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Energy- and moisture performance considering future climate change

Berggren, Björn

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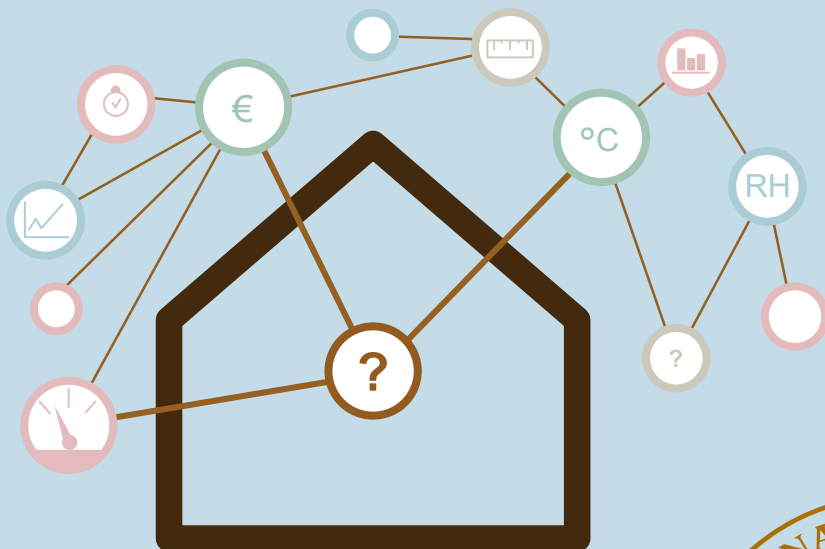
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Evaluating energy efficient buildings

Energy- and moisture performance considering future climate change

Björn Berggren

Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2019
Report EBD-T-19/23



Evaluating energy efficient buildings

Energy- and moisture performance considering future climate change

Errata

<i>Page</i>	<i>Reads</i>	<i>Shall read</i>
Page 11, line 2	... en av de största utmaningarna som världens står inför idag.	... en av de största utmaningarna som världen står inför idag
Page 11, line 29	Simuleringar visar dock att klokt utformade och konstruktioner och där byggproduktion haft fokus på att minimera byggfukt...	Simuleringar visar dock att klokt utformade konstruktioner och där byggproduktion haft fokus på att minimera byggfukt...
Page 14, line 29	R Discount rate	<i>The abbreviation is written twice and should be removed from the nomenclature</i>
Page 21, line 14	Berggren, B. & Davidsson, H: (2013)	Berggren, B. & Davidsson, H. (2013)
Page 22, line 18	Berggren, B., & Olofsson, T. (2017)	Berggren, B. & Olofsson, T. (2017)
Page 23, line 26	The Energy Performance of Buildings Directive EPBD, the first version of came in force in January....	The Energy Performance of Buildings Directive (EPBD), the first version came into force in January....
Page 36-38, Figure 2.2-2.4	A: Non-metropolitan regions B: Malmö region; C: Göteborg region D: Stockholm region	A: Non-metropolitan regions; B: Malmö region; C: Göteborg region; D: Stockholm region
Page 60, line 24	... weekly results are presented in Figure 3.16.	... weekly results are presented in Figure 3.9.
Page 65, Equation 3.8	$E_{norm}=E_{meas,DHW^-}-E_{corr,DHW^+}...$	$E_{norm}=E_{meas,DHW^+}+E_{corr,DHW^+}...$
Page 81, line 6	... local generation covers the building load.	... local generation does not cover the building load.
Page 140, line 2	... it may be easier to find it is profitable...	... it may be easier to find it profitable...

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 116 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 7 500 employees and 47 700 students attending 287 degree programmes and 2 200 subject courses offered by 69 departments.

Division of Energy and Building Design

Reducing environmental effects of construction and facility management is a central aim of society. Minimising the energy use is an important aspect of this aim. The recently established division of Energy and Building Design belongs to the department of Architecture and Built Environment at the Lund University, Faculty of Engineering LTH in Sweden. The division has a focus on research in the fields of energy use, passive and active solar design, daylight utilisation and shading of buildings. Effects and requirements of occupants on thermal and visual comfort are an essential part of this work. Energy and Building Design also develops guidelines and methods for the planning process.

Evaluating energy efficient buildings

Energy- and moisture performance
considering future climate change

Björn Berggren

Doctoral Thesis

Keywords

Net Zero Energy Building, passive house, thermal bridge, building envelope, energy performance, moisture performance, multi criteria decision making, climate change, climate scenarios, EN ISO 13789, EN ISO 10211

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Abstract

One of the greatest challenges the world is facing is climate change. The need of reduction of energy use and an increased use of renewable energy in buildings constitutes important climate change mitigation measures.

The objective of this research is to investigate methodologies and performance indicators for the evaluation of energy and moisture performance of buildings, including co-benefits which may occur in “green buildings”. Furthermore, the objective is to identify a methodology for evaluation of the energy and moisture performance of buildings, including co-benefits.

This work was set out with a historical review of building envelopes for residential buildings followed by a literature review and case studies to investigate how energy performance, moisture conditions and green co-benefits may be calculated. An evaluation method based on multi criteria decision analysis (MCDA) was developed and tested.

The study of the existing residential building stock shows that it is not possible to analyse a single reference building that would cover a majority of the existing buildings, e.g. renovation potentials. A set of different reference buildings and constructions are needed to enable further studies, which may investigate different possibilities related to renovation.

Results also show that the relative share of transmission heat transfer losses due to thermal bridges increases when the heat resistance of a building envelope is increased. Hence, thermal bridges must be given more attention in the design of buildings.

The term “energy performance” of buildings is often used today, and it is generally alleged that it refers to the annual energy use per conditioned living area. However, differences exist in building regulations in different countries and in definitions of Net Zero Energy Buildings. In relation to “moisture performance”, no international or European standard or framework for assessing and presenting moisture performance has been found within this study. Quantifying and including green co-benefits may be very profitable.

Common for all calculations and investigations presented—regardless if it is energy performance of building envelopes, buildings’ energy performance, hygrothermal simulations, quantification of green co-benefits

or a life cycle assessment—is the need to clearly state the boundary conditions when the results are presented, as they may have a major impact on the results.

A model based on MCDA was proposed and tested. The tests of the model showed that it is possible to handle a large set of criteria and to weight them into one value. Hence, it should be possible to use the model to assist with decision-making.

Recommendations for future research are to further develop calculation and evaluation methods for energy and moisture performance in buildings, including co-benefits that may arise in green buildings. Finally, there is a need for an MCDA software tailored for the construction industry to facilitate more use of MCDA. The software could be based on the method presented in this thesis.

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Finally, Lotta and Estrid. You give me more support than you ever can imagine.

With your support and love, everything is possible.

Stockholm, April 2019

Björn Berggren

Sammanfattning

Den pågående klimatförändringen på vår planet är en av de största utmaningarna som världens står inför idag. Misslyckas vi med att begränsa klimatförändringarna kan det ge allvarliga och oåterkalleliga konsekvenser för vår planet och för oss människor. Nästan en femtedel av all generering av växthusgaser kan härledas till byggnaders drift (energianvändning, renovering m.m.). Därför är minskad energianvändning och användande av förnybar energi mycket viktiga åtgärder för att begränsa pågående klimatförändring.

En åtgärd för att minska byggnaders energianvändning är att förbättra värmeisoleringen av det omslutande klimatskalet. Emellertid kan förbättrad värmeisolering och förändrat klimat förändra mikroklimaten inne i byggnadens konstruktioner och öka risken för fuktrelaterade problem. Därför är det viktigt att kunna utvärdera byggnader och konstruktioner som både tar hänsyn till energi- och fuktprestanda.

Denna avhandling undersöker metoder och indikatorer för att utvärdera energi- och fuktprestanda i byggnader, inklusive mervärden som kan uppstå i s.k. ”gröna byggnader”. Vidare har en modell för utvärdering av byggnaders energi- och fuktprestanda, inklusive mervärden som kan uppstå, tagits fram.

Resultaten visar att det är möjligt att bygga netto-nollenergibyggnader med den teknik som finns kommersiellt tillgänglig idag. Det finns dock kunskapsbrist bland svenska ingenjörer och arkitekter när det gäller att beräkna energiförluster genom byggnaders klimatskal. Det råder oklarheter om hur en köldbrygga definieras samt hur byggnadsdelar ska kvantifieras för energiberäkningar.

Genomförda simuleringar av olika träkonstruktioner med nuvarande och framtida klimat visar att risken för mögel kan öka både på grund av ökad värmeisolering och/eller framtida klimat. Simuleringarna visar dock att klokt utformade och konstruktioner och där byggproduktionen haft fokus på att minimera byggfukt och kvalitet i anslutningar ger minskad risk för mögel, där denna minskning är större än ökningen på grund av ökad isolering och/eller framtida klimat. Följaktligen är det fullt möjligt att bygga välisolerade träkonstruktioner som klarar framtida klimat,

men det kan kräva att man inte utformar konstruktionerna enligt gamla erfarenheter och tumregler.

En modell för utvärdering har tagits fram och testats för en begränsad del av ett klimatskal och en hel byggnad. Testerna visar att det är möjligt att hantera ett stort antal indikatorer och sammanväga dem till ett enda prestandatal. Modellen innehåller en prestandafaktor som säkerställer att det sammanvägda resultatet av en utvärdering visar att det är oacceptabelt om någon av de utvärderade indikatorerna är under acceptabel nivå. Detta innebär att det inte är möjligt att överkompensera ett undermåligt resultat för en indikator genom att uppnå ett mycket högt värde för en annan indikator.

Rekommendationer för fortsatt arbete är att beräknings- och utvärderingsmetodiker för energi- och fuktprestanda i byggnader, inklusive mervärden som kan uppstå i gröna byggnader, bör vidareutvecklas. Vidare så skulle byggbranschen kunna ha stor nytta av en mjukvara som skulle kunna stödja sammanvägning av flera olika prestandaindikatorer, anpassad för branschen.

Nomenclature

AC	Advertising costs
A	Area
AIP	Article in press
CDQ	Critical Duration Quota
c_i	Charging energy of carrier, i , to storage
DC	Decommissioning cost and/or duration curve
dc_i	Discharge energy of carrier, i , from storage
DE	Demolition energy
d_i	Delivered energy of carrier, i , from the grid
Dn	Mould dose after n days
D_{RH}	Mould dose component based on RH
D_T	Mould dose component based on temperature
$E_{corr,solar}$	Normalise divisor for deviating solar radiation
E_{aux}	Auxiliary energy use, e.g. fans, pumps, elevators
$E_{corr,DHW}$	Normalise term for domestic hot water
$E_{corr,IL}$	Normalise term for deviating internal loads
EE	Embodied energy and/or Increased exported energy
EE_i	Initial embodied energy
EE_r	Recurring embodied energy
e_i	Exported energy of carrier, i
EI	Reduced imported energy and/or Energy index
EI_{meas}	Energy index, measured heating degree days, adjusted for solar radiation and wind
EI_{α}	Energy index, normal heating degree days adjusted for solar radiation and wind.
$E_{meas,C}$	Measured energy use for cooling
$E_{meas,DHW}$	Measured energy use for domestic hot water
$E_{meas,IL}$	Measured energy use for plug loads and lighting
$E_{meas,SH}$	Measured energy use for space heating
Emp	Quantity of employees
E_{norm}	Normalised energy performance
$E_{\alpha,DHW}$	Normal energy use for domestic hot water
$E_{\alpha,IL}$	Normal energy use for plug loads and lighting

f_{grid}	Grid interaction
f_{load}	Load match
g_i	Generation of energy carrier, i
$G_{meas,solar}$	Measured global solar radiation
G_{α}	Normal global solar radiation
H_a	Transmission heat transfer coefficient to adjacent buildings
H_d	Direct heat transfer coefficient
H_g	Steady-state ground heat transfer coefficient
H_{tr}	Transmission heat transfer coefficient
H_u	Transmission heat transfer coefficient through unconditioned places
i	Inflation rate
IC	Introduction course for new employee
I_b	Share of internal loads assumed to affect the heating or cooling
IP	Increased productivity per employee
IPV	Increased productivity value
k	performance failure indicator
L_{2D}	Thermal coupling coefficient obtained from a 2-D calculation
L_{3D}	Thermal coupling coefficient obtained from a 3-D calculation
l_i	Load of energy carrier, i
LI	Lost income during vacancy
l	Length
m_{DC}	Parameter, m , for duration curve, DC
OCD	Normalise divisor for deviating outdoor climate
OE	Operating energy
PPV	Public publicity value
R	Discount rate
r	Nominal discount rate
R	Discount rate
RC	Recruitment cost per employee
REC	Reduced energy costs
$RETC$	Reduced employee turnover costs
RH	Relative humidity
$RH(t)$	Relative humidity at time, t
$RH_{crit}(T(t))$	Critical relative humidity at temperature, T , and time, t
RPC	Reduced productivity cost (new employee and supervisor)
$RSAC$	Reduced sickness absence costs
$RSAS$	Reduced sickness absence salary
S	Salary
SC	Salary costs
$SCOP$	Seasonal coefficient of performance
T	Temperature
t	Time

TAF	Normalise factor for deviating indoor temperature
T_e	External/outdoor temperature
T_i	Interior/indoor temperature
T_{meas}	Measured temperature
t_{ms}	Critical time for onset of mould growth (n, days)
$T\alpha$	Normal temperature
U	Thermal transmittance
$V(a)$	Total value of alternative a
V_{DHW}	Volume hot water use
v_e	Moisture content by volume
v_i	Relative value for criterion i
w_i	Weighting factor for criterion i
v_s	Vapour content, by volume, at saturation for the temperature T
WW	Quantity of wagedworkers
Δv	Local moisture supply (g/m^3)
α	Energy tariff for EI
β	Retardation factor or energy tariff for EE
γ	Increase in energy tariffs
ε	Reduced employee turnover
κ	Reduced sickness absence
ξ	Relative temperature factor
φ	Average sickness absence
χ	Point thermal transmittance, point thermal bridge
Ψ	Linear thermal transmittance, linear thermal bridge
\overline{RH}	Average relative humidity
\overline{RH}_{crit}	Average critical relative humidity

List of publications

This thesis is a collection of the 18 publications produced during the PhD. All publications except for XLI and XLII, two reports in Swedish, are included as appendices.

Other publications where the author has been the main author or contributor, produced during the PhD, are also listed.

The main author is listed first of the listed author in relation to each publication.

Peer reviewed articles included in this thesis

- I PR Berggren, B., Wall, M., Flodberg, K. & Sandberg, E. (2012). Net ZEB Office in Sweden - a case study, testing the Swedish Net ZEB definition. *International Journal of Sustainable Built Environment*, 1(2) 217-226. <https://doi.org/10.1016/j.ijbsbe.2013.05.002>
Björn Berggren was the main author; responsible for the writing process, calculations and simulations. Co-authors assisted with writing, analysis of data and discussion of results.
- II PR Berggren, B., Hall, M. & Wall, M. (2013). LCE analysis of buildings - Taking the step towards Net Zero Energy Buildings. *Energy and Buildings*, 62 (May 2013). 381 - 391. <https://doi.org/10.1016/j.enbuild.2013.02.063>
Björn Berggren was the main author; responsible for the writing process. The literature review and compilation of data from case studies were carried out in collaboration with Monica Hall. Monica Hall and Dr. Maria Wall assisted with writing, analysis of data and discussion of results.
- III PR Berggren, B. & Wall, M. (2013) Calculation of thermal bridges in (Nordic) building envelopes – Risk of performance failure due to inconsistent use of methodology. *Energy and Buildings*, 65 (October 2013) 331-339. <https://doi.org/10.1016/j.enbuild.2013.06.021>

Björn Berggren was the main author; responsible for the writing process, administration of the survey and thermal bridges calculations. Dr. Maria Wall assisted with writing, analysis of data and discussion of results.

- IV PR Berggren, B. & Wall, M. (2017) Two methods for normalisation of measured energy performance – a test on a net zero-energy building in Sweden. *Buildings*, 7 (4). <https://doi.org/10.3390/buildings7040086>

Björn Berggren was the main author; responsible for the writing process, measuring and compiling data. Dr Maria Wall assisted with writing, analysis of data and discussion of results.

- V PR Berggren, B. & Wall, M. (2018) State of knowledge of thermal bridges – a follow up in Sweden and a review of recent research. *Buildings*, 8 (11). <https://doi.org/10.3390/buildings8110154>

Björn Berggren was the main author; responsible for the writing process, administration of survey and the review of previous research. Dr Maria Wall assisted with writing, analysis of data and discussion of results.

- VI PR Berggren, B. & Wall, M. (2019) Review of constructions and materials used in Swedish residential buildings during post-war peak of production. *Buildings*, 9 (4). <https://doi.org/10.3390/buildings9040099>

Björn Berggren was the main author; responsible for the writing process and compiling data. Dr Maria Wall assisted with writing, analysis of data and discussion of results.

Conference proceedings included in this thesis

- VII CP Berggren, B., & Wall, M. (2011) The importance of a common method and correct calculation of thermal bridges. Proceedings of the 9th Nordic Symposium on Building Physics, Tampere, Finland.

Björn Berggren was the main author; responsible for the writing process and administration of the survey. Dr. Maria Wall assisted with writing, analysis of data and discussion of results.

- VII CP Berggren, B., Stenström, H., & Wall, M. (2011). A parametric study of the energy and moisture performance in passive house exterior walls. Proceedings of the 4th Nordic Passive House Conference, Helsinki, Finland.

Björn Berggren was the main author; responsible for the writing process, thermal bridges calculations and energy simulations.

- Hygrothermal simulations were conducted in collaboration with Håkan Stenström. Håkan Stenström and Dr. Maria Wall assisted with writing, analysis of data and discussion of results.
- IX CP Berggren, B., & Wall, M. (2011). Thermal bridges in passive houses and nearly zero-energy buildings. Proceedings of the 4th Nordic Passive House Conference, Helsinki, Finland.
Björn Berggren was the main author; responsible for the writing process, thermal bridges calculations and energy simulations. Dr. Maria Wall assisted with writing, analysis of data and discussion of results.
- X CP Berggren, B., & Wall, M. (2012). Hygrothermal conditions in exterior walls for passive houses in cold climate considering future climate scenario. Proceedings of the 5th Nordic Passive House Conference, Trondheim, Norway.
Björn Berggren was the main author; responsible for the writing process, production of climate scenario weather files and hygrothermal simulations. Dr. Maria Wall assisted with writing, analysis of data and discussion of results.
- XI CP Berggren, B., & Wall, M. (2012). Moisture Conditions in Exterior Walls for Net Zero Energy Buildings in Cold Climate Considering Future Climate Scenario. Proceedings of the 7th International Cold Climate HVAC Conference, Calgary, Canada.
Björn Berggren was the main author; responsible for the writing process, description of mould models and hygrothermal simulations. Dr. Maria Wall assisted with writing, analysis of data and discussion of results.
- XII CP Berggren, B., Wall, M., Karlsson B., Widén J. (2012). Evaluation and optimization of a Swedish NetZEB, Using Load matching and Grind interaction Indicators, Proceedings of the First Building Simulation and Optimization Conference BSO 12, Loughborough, Great Britain.
Björn Berggren was the main author; responsible for the writing process, calculations and simulations. Co-authors assisted with writing, analysis of data and discussion of results.
- XIII CP Berggren, B., Wall, M., Togerö, Å. (2017) Profitable Net ZEBs – How to break the traditional LCC analysis, Proceedings of the International Conference on Energy, Environment and Economics (ICEEE), Edinburgh, Great Britain.
Björn Berggren was the main author; responsible for the writing process and calculations. Dr. Åse Togerö gathered increased

construction costs. Dr. Maria Wall and Dr. Åse Togerö assisted with writing, analysis of data and discussion of results.

- XIV CP Berggren, B. (2018) A Net ZEB Case Study—Experiences from Freezing in Ventilation Heat Exchanger and Measured Energy Performance, Proceedings of the Cold Climate HVAC 2018, Kiruna, Sweden.

Björn Berggren was the only author; responsible for all results in the paper.

- XV CP Berggren, B., Wall M., Davidsson H., Gentile N. (2018) Normalisation of Measured Energy Use in Buildings—Need for a Review of the Swedish Regulations, Proceedings of the Cold Climate HVAC 2018, Kiruna, Sweden.

Björn Berggren was the main author; responsible for the writing process and literature review. Co-authors assisted with writing, analysis of data and discussion of results.

- XVI CP Berggren, B., Wall, M., Weiss, T., Garzia, F., Perneti, R. (2018) LCC analysis of a Swedish Net Zero Energy Building – Including Co-benefits, Proceedings of the International Sustainable Energy Conference, Graz, Austria.

Björn Berggren was the main author; responsible for the writing process and gathering of construction costs. Co-authors assisted with writing, analysis of data and discussion of results.

Other publications produced during the PhD

- XVII Berggren, B., Togerö Å., Tengberg Svensson C (2010) Fuksäkerhet och isolering i välisolerade hus - hur kan takkonstruktioner optimeras?, Bygg och Teknik 4/10.

- XVIII Marszal A. J., Bourrelle J., Nieminen J., Berggren B., Gustavsen A., Heiselberg P., Wall M. (2010) North European Understanding of Zero Energy/Emission Buildings, in Zero Emission Buildings, Proceedings from Renewable Energy Research Conference 2010,

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1 Introduction

This chapter introduces the background to this research. Furthermore, it presents the objective of the study, the methodology and the structure of this thesis.

1.1 Background

1.1.1 Energy and environmental issues

One of the greatest challenges the world is facing is climate change. The human influence on the climate system is clear and the warming of the climate system is unambiguous. Sea levels have risen, the atmosphere and oceans have warmed and the amounts of snow and ice have declined (Intergovernmental Panel on Climate Change, 2014). Greenhouse gas (GHG) emissions are the dominant driver for climate change and their concentration in the atmosphere are now at their highest level over the 800,000 last years. Failure to fight climate change will likely result in severe, irreversible and pervasive impacts for people and ecosystems.

More than 30% of the globally consumed primary energy is used in commercial and residential buildings in operation (Hong, 2018) and roughly 18% of the GHG emissions can be related to buildings (Intergovernmental Panel on Climate Change, 2014). The population of the world and the need for buildings are growing.

The overall goal within the European Union (EU) is to reduce greenhouse gas emissions by 20% by 2020 as compared to 1990 and it is proposed to enhance the target to 40% by 2030 (European Parliament, 2016). Within the EU buildings account for approximately 40 % of the total energy consumption and roughly 30% of the CO₂-emissions (European Commission, 2018). Almost 75% of the building stock is energy inefficient and about 35% is more than 50 years old. The Energy Performance of Buildings Directive EPBD, the first version of came in force in January 2003 (European Parliament, 2002), is the main legislative instrument in EU to improve the energy performance of buildings within the Union.

A recast of the EPBD came in place in June 2010 (European Parliament, 2010) and as of July 2018 an amendment is also in force (European Parliament, 2018).

The EPBD states, in short, that member states shall ensure that all new buildings are nearly zero- energy buildings after 31 December 2020 and that all new buildings occupied and owned by public authorities are nearly zero-energy buildings after 31 December 2018. Furthermore, each member state shall form a long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings into a highly energy efficient and decarbonised building stock by 2050. Additionally, the amendment (European Parliament, 2018) declares a minimum number of recharging points for parking spaces and a voluntary smart readiness indicator.

In Sweden, the overall goal is to strive towards 50% more efficient energy use as compared to 2005 by 2030. Furthermore the proportion of renewables in the national electricity production should be 100% (Sveriges Riksdag, 2018). In Sweden, the residential sector accounts for roughly 20% of the total energy consumption. Including the public and commercial sector, altogether they all together accounts for roughly one-third of the energy consumption in Sweden (Swedish Energy Agency, 2018b). Roughly half of the energy use in the building stock is for space heating and the heating of water (Swedish Energy Agency, 2018a).

Hence, reduction of energy use and the use of renewable energy in buildings constitutes important climate change mitigation measures.

1.1.2 Moisture related damages in buildings

The building sector in Sweden has a rather long history of moisture related damages. For example, crawl space foundations with high relative humidity resulting in mould and rot damage, impregnated wood which prevented the wood from rot damages but endured mould damages, autoclaved aerated concrete constructions which absorb more water than expected, etc. (Boverket, 2010a; Nilsson, 2006b). More recently, severe moisture problems have also been discovered in exterior walls with wooden framing and exterior insulation and plaster (Samuelson, Mjörnell, & Jansson, 2007), commonly called EIFS (Exterior Insulation and Finish Systems) or ETICS (External Thermal Insulation Cladding System).

Investigations conducted by the National Board of Housing Building and Planning in Sweden (Boverket) 2006-2009 show that roughly one-third of the Swedish buildings have moisture and mould damages which may have a negative effect on the indoor environment. Roof constructions have the highest share of damaged constructions, followed by foundations

and bathrooms (Boverket, 2010a). A more recent investigation, mainly based on interviews and a survey, show that the most common problems, defaults and defects in buildings are related moisture and water (Boverket, 2018b).

Improving the energy performance of buildings by means of increased thermal resistance, is frequently introduced in order to achieve a lower energy demand for buildings, both for renovation and new buildings. However, increased thermal resistance of the building envelope will result in a different microclimate within it. Parametric studies have shown that increased amounts of insulation in building envelopes results in increased relative humidity in these constructions (Geving & Holme, 2010; Samuelson, 2008). For example, the outer parts of a wall will have hygrothermal conditions more similar to the exterior climate and moisture may take longer time to dry out. Thus, increasing the risk of moisture related performance failure.

1.1.3 Need for assessment of buildings considering energy and moisture performance using a life-cycle perspective

Traditionally, buildings and their components are often designed based on a mix of experience, rules of thumb and implicit rules (Alsaadani & Souza, 2012; Isaksson, Thelandersson, Ekstrand-Tobin, & Johansson, 2010). Hence, the expected result cannot always be described in quantitative terms. In regard to energy performance, the result can often be calculated or measured. However, this is a challenge related to moisture safety, but it is also related to other values that may be associated with so-called “green buildings”, which here are referred to as buildings with high performance within the aspects of energy, thermal comfort, indoor air quality, building materials etc. For example, a healthier indoor climate may result in reduced sickness absence. Thus, it is a challenge to describe the effect of changes in design considering both energy and moisture performance.

Furthermore, as experience, rules-of-thumb and implicit rules are based on history, they do not take into account future climate change. In conclusion, there is a need to develop robust buildings and building envelopes where moisture safety is valued as an important factor, which also can meet future demands for energy performance, considering future climate change.

1.2 Objective of the study

1.2.1 Hypothesis and objective

The hypothesis behind this research is as follows:

- The demand for more energy efficient buildings will lead to a need of increased thermal resistance in building envelopes, both in new construction and renovation.
- Due to climate change, building envelopes will face new boundary conditions.
- Increased thermal resistance and new boundary conditions will change the hygrothermal conditions within building envelopes. This may have the result that technical solutions and principles—confirmed as best practice by history—may suffer from moisture related damage, in both new construction and renovation.

The objective of this research is firstly to investigate methodologies and performance indicators for evaluation of energy and moisture performance in buildings, including co-benefits which may occur in “green buildings”.

Secondly, the objective is to identify a methodology for evaluation of energy and moisture performance of buildings, including co-benefits. The methodology should make it easier for stakeholders in the construction- and real estate industry to make informed decisions regarding their buildings for the entire life cycle. The results of the research are aimed at researcher, consultants, contractors and building owners.

1.2.2 Research questions

Based on the background, hypothesis and objective, the following research questions were formulated.

1. Is it possible to distinguish between different typical buildings and/or building techniques in the existing building stock?
2. Will the importance of thermal bridges in building envelopes increase?
3. How may energy- and moisture performance and green co-benefits be evaluated?
4. Will increased thermal resistance and new boundary conditions increase the risk for mould growth?

5. How could a method which may combine the different performance indicators, expressed in different units be used in the evaluation?

The first research question mainly relates to the hypothesis of the research. Different typical buildings and/or building techniques may enable strategic development of more cost-effective and robust renovation methods or prefabricated building elements that substantially can increase the thermal resistance of building envelopes in existing buildings from this period. Furthermore, it may enable investigation of how climate change may change the hygrothermal conditions within building envelopes in the existing building stock.

Research Questions 2-4 relate to the first part of the objective of the research, to investigate methodologies and performance indicators for evaluation of energy and moisture performance in buildings, including co-benefits.

The fifth research question relates to the second part of the objective of the research—to identify a methodology for evaluation of energy and moisture performance of buildings, including co-benefits.

1.3 Methodology and simulations

1.3.1 Methodology

The work was set out with a historical review of building envelopes for residential buildings. The review is mainly based on data from Statistics Sweden, SCB, published 1967-1995, containing data on multi-dwelling buildings and one- or two-dwelling buildings between 1960 and 1994.

A literature review was conducted to investigate how energy performance and moisture conditions may be calculated. Since transmission heat transfer losses may be calculated different, a survey was conducted among Swedish engineers and architects. Based on this questionnaire, studies were made regarding possible performance failure scenarios due to misunderstandings and misinterpretations that may occur. The survey was repeated five years later, in order to investigate whether the state of knowledge among Swedish consultants had increased since the previous study.

Critical moisture levels for building materials and models for the onset of mould growth were reviewed.

In order to gather knowledge and experience of the different calculations and evaluation methodologies, various case studies were conducted during the project. The case studies focused mainly on possible lateral effects of increased amounts of insulation and more energy efficient buildings con-

sidering a future climate scenario and the performance of energy efficient buildings in the user stage.

Also, publications concerning climate change and Multi-Criteria Decision-Making (MCDM) were reviewed, and a method to evaluate energy and moisture performance, based on MCDM was developed. The method was tested by conducting hygrothermal and energy simulations on a limited part of a building envelope as well as for an entire building. The results from the simulations were converted into performance criteria and used as input data for the model.

The research was partly carried out within the international project IEA SHC Task 40/ECBCS Annex 52; Towards Net Zero Energy Solar Buildings. This project involved researchers and practitioners from 19 countries within the framework of the International Energy Agency. The project started in 2008 and ended in 2013.

1.3.2 Simulations

The thermal transmittance for building elements and thermal bridges was calculated using HEAT 2.8 and HEAT 3.6 (Blocon AB, 2019). HEAT is a computer program for two- and three-dimensional transient and steady-state heat transfer calculations. The program is validated against the standard EN ISO 10211 (Swedish Standards Institute, 2017).

Hygrothermal simulations were conducted using the numerical computer program WUFI (Fraunhofer Institute for building physics, 2019), which is designed to calculate hygrothermal processes. It includes 1D or 2D coupled heat and moisture transport, and considers both vapour diffusion and capillary conduction.

Simulations related to energy performance and indoor climate of buildings were conducted using IDA Indoor Climate and Energy 4.5, IDA ICE (EQUA Simulation AB, 2019) and VIP Energy (Strusoft, 2019). IDA ICE is a dynamic multi-zone simulation computer program which calculates thermal indoor climate and energy use of a whole building, and VIP Energy is a dynamic software focusing on energy use in buildings.

1.4 Content and limitations of the thesis

1.4.1 Thesis structure in relation to research questions

Figure 1.1 presents an overview of the thesis structure and the relation to the research questions.

Chapter 1 introduces the challenges the building sector is facing due to climate change. Furthermore the objective, methodology and structure of the thesis is presented.

Chapter 2 relates to the first research question and presents a bottom-up analysis of existing buildings in Sweden from the 1960s to the 1990s. The analysis is based on data from Statistics Sweden which were previously only available in historical reports. The data and metadata are available for further studies.

Chapter 3 relates to the second and third research questions and presents results in three main parts. Firstly, the importance and state of knowledge related to thermal bridges are presented. This is followed by investigating the energy performance of Net Zero Energy Buildings (Net ZEBs) from a Swedish perspective including experiences from different case studies. The third part covers embodied energy (EE) and the effect of different weighting factors and methods for evaluating environmental impact.

Chapter 4 relates to the third and fourth research questions, and four different models for assessment of risk of mould growth are presented. Two of the models are used to analyse the risk of mould growth in an exterior wooden wall, using different approaches to increase the thermal resistance of the wall.

Chapter 5 relates to the fourth research question and presents the risk of performance failure in an exterior wooden wall construction, due to mould growth based on the possible future climate scenario A1B.

Chapter 6 relates to the third research question and investigates different co-benefits, which may be expected in green buildings such as Net ZEBs. Furthermore, methods to quantify the co-benefits are presented and applied on two case studies.

Chapter 7 relates to the fifth research question and presents an overview of multi criteria decision analysis followed by a proposed model which could be used by stakeholders in the construction- and real estate industry to evaluate different options for their buildings, enabling informed decisions regarding their buildings for the entire life cycle.

Chapter 8 presents the main conclusions from the research in relation to the five research questions presented in the introduction.

Chapter 9 gives recommendations for future research.
References and publications are found in the end of this thesis.

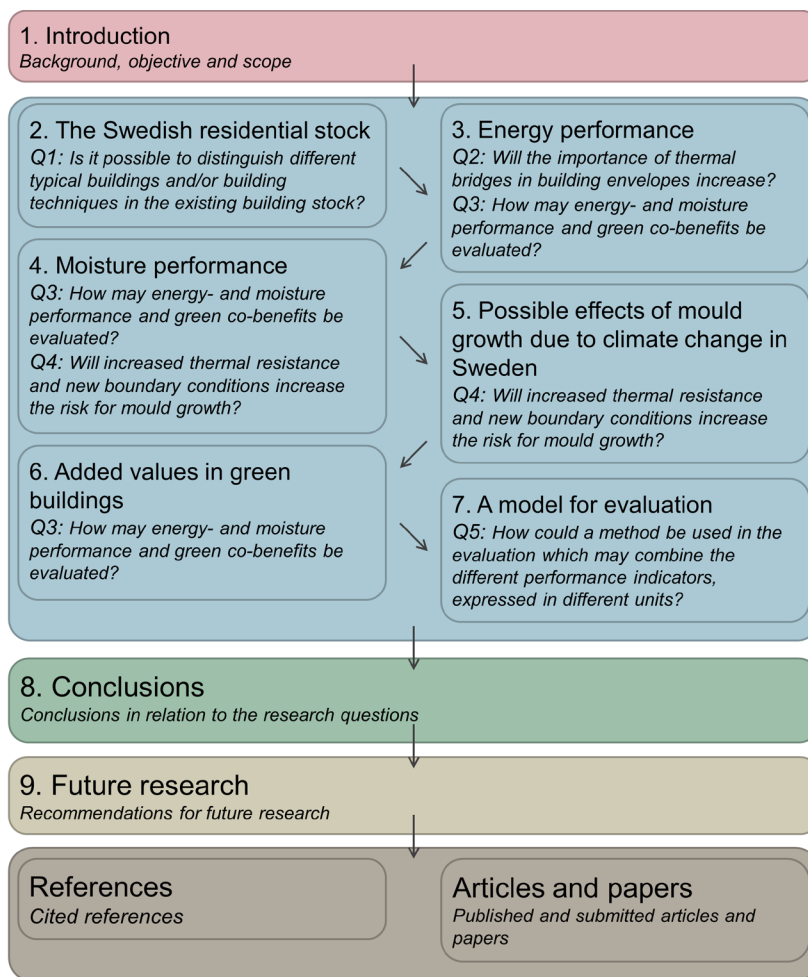


Figure 1.1 Overview of thesis structure, related to the research questions

1.4.2 Limitations

This research focuses on building envelopes and buildings for residential purposes in a Nordic climate, specifically Sweden.

This thesis presents a method for evaluations of buildings, both in new construction and renovation.

The developed evaluation method does not claim to be able to judge whether a design will or will not withstand future climate. Rather, it will help stakeholders to make informed decisions and to compare different design options.

1.4.3 Thesis structure in relation to research publications

This thesis is a collection of the 18 publications produced during the PhD studies. Figure 1.2 presents an overview of Chapter 2-7 and the relation to the research publications.

All publications except for XLI and XLII, two reports in Swedish, are included as appendices.

Results from investigating the Swedish residential building stock were presented in PR VI, where a bottom-up analysis was conducted based on data from Statistics Sweden.

Thermal bridges in building envelopes were investigated in four publications. In CP VII, results from a questionnaire conducted in 2010 investigating the state of knowledge in Sweden related to thermal bridges were presented, and in PR III and CP IX, the results from the questionnaire were further investigated. Furthermore, the relative importance of thermal bridges and the possible performance failure due to incorrect calculations were calculated. In PR V, a follow up on the previously conducted questionnaire and a review of recent research were conducted.

Definitions of Net ZEBs and the interaction with the existing energy grid were investigated in two publications. In PR I, a case study was conducted, investigating the Swedish Net ZEB definition in relation to the framework developed within IEA SHC Task 40/ECBCS Annex 52; Towards Net Zero Energy Solar Buildings. In CP XII, different load matching and grid interaction indicators were studied and the impact of different design strategies were investigated.

Evaluation and normalisation of energy use in buildings in the user stage were investigated in four publications. In PR IV, two methods of normalisation of measured energy use were tested for a case study. In CP XIV and CP XV, this was further investigated and experiences from the user stage were documented. Results from a literature review and a workshop, focusing on boundary conditions which may have a great impact on the energy use in the user stage, are presented in a Swedish report, XLI (Berggren, 2018).

Embodied energy and environmental impact of energy use in the user stage were investigated in two publications. In PR II, a literature review of EE in buildings was conducted and the relative share of EE in relation to

the total energy use through a buildings' lifecycle was conducted. This was based on both the literature review and detailed calculations for 11 Net ZEBs constructed in Switzerland. In a Swedish report, XLII, the environmental impact of energy use in user stage was investigated, using different evaluation methods and boundary conditions related to the Nordic energy grid (Erlandsson, Sandberg, Berggren, Francart, & Adolfsson, 2018).

Moisture performance and possible effects of mould growth due to climate change were investigated in three publications. In CP VIII, a parametric study was carried out, investigating the increased risk for mould growth in an exterior wooden wall, using different approaches to increase the thermal resistance of the wall. In CP X and CP XI, weather files for one climate scenario were created and the possible effects due to mould growth for the same exterior wall, based on scenario data, were further investigated.

Possible co-benefits and values in green buildings were investigated in two publications, CP XIII and CP XVI. Previous research related to possible co-benefits were investigated and quantification of the co-benefits in monetary terms were carried out.

The proposed model for evaluation was published in the licentiate thesis (Berggren, 2013) and is also presented and discussed in this thesis in relation to other research and models.

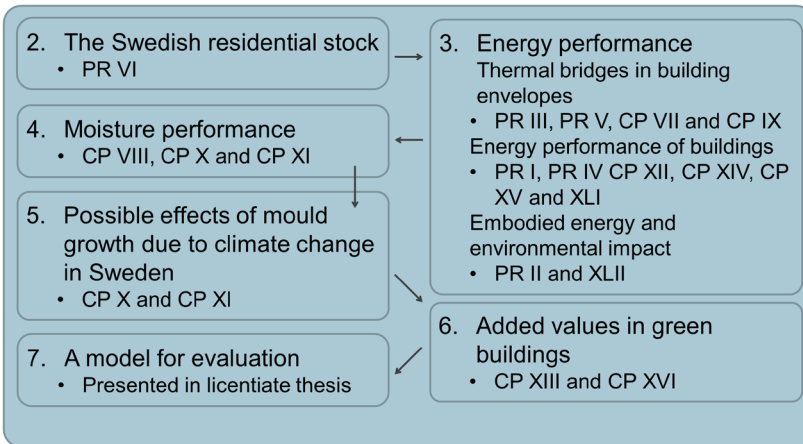


Figure 1.2 Overview the publications in relation to Chapter 2-7

2 The Swedish residential building stock

This chapter presents a bottom-up analysis of existing buildings in Sweden from the 1960s to the 1990s, which was studied in PR VI. After an introduction, the major findings are presented followed by a discussion and conclusions. The analysis is based on data from Statistics Sweden, which were previously only available in historical reports. The data and metadata are made available by the author for further studies.

2.1 Introduction

The largest part of the European housing stock is found in residential buildings, but the current growth rate is low (Economidou et al., 2011). Reducing the energy use in the existing building stock is, therefore, an important action for climate change mitigation. In Sweden, the pace of renovation of existing buildings must increase since roughly 3.3 million homes - 75% of existing residential buildings - must undergo major renovations before 2050 (Boverket & Energimyndigheten, 2013).

In this chapter, results from a bottom-up analysis, based on data from reports published by SCB (SCB, 1967-1994) is presented. The data is from applications for state loans, where a technical description of the building was required based on a predefined template and cover residential buildings from 1960 to 1993. The loans, granted by the state, ended in 1992 (Boverket, 2007).

The data are available for further studies (Berggren & Wall, 2019). This may enable strategic development of more cost-effective and robust renovation methods or prefabricated building elements that can substantially increase the thermal resistance of building envelopes in existing buildings from this period.

2.2 Bottom-up analysis

From 1960 through 1990, more than 2 million dwellings were produced in Sweden—1.3 million of which were produced in multi-dwelling buildings and about 0.9 million produced in one- or two-dwelling buildings. Sweden has roughly 4.6 million dwellings, where 3.9 million of these were built before 1991 (Statistics Sweden, 2018). As such, dwellings built during this period cover the majority of the buildings built before 1991. The available data cover 92% of the produced dwellings in multi-dwelling buildings and 69% of the one- or two-dwelling buildings from this period. There are mainly two reasons for the lower coverage of data for one- or two-dwelling buildings. Firstly, SCB did not publish statistics from state loans for one- or two-dwelling buildings during from 1960 to 1965. Secondly, during 1988 to 1990, they only published data for dwellings were situations in which the applicant of a state loan was not the same as the final resident. During 1966 to 1987, the published data covers 83% of the dwellings (see Figure 2.1).

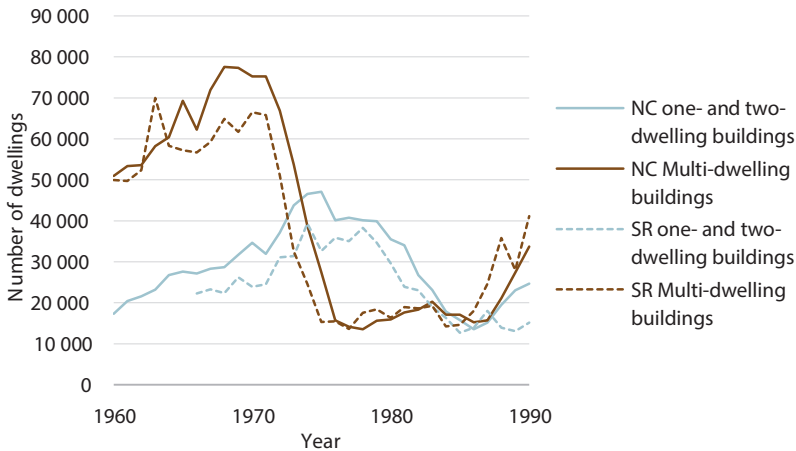


Figure 2.1 *New construction of dwellings in Sweden. Comparing data for new construction, NC, statistics (Statistics Sweden, 2016) and Statistical Reports, SR (SCB, 1967-1994)*

A large part of the existing buildings in Europe were built between 1940 and 1980. In Sweden, a very large number of the existing dwellings were built during the so-called “Miljonprogrammet”, the Million Homes programme. Figure 2.1 shows that roughly 70% of the dwellings in Sweden were built as multi-dwelling buildings during the 1960s and early

1970s. In the beginning of the 1970s, the production of dwellings in multi-dwelling buildings dropped significantly. Instead, the production of one- or two-dwelling buildings increased, and, in 1974, the production of dwellings in one- or two-dwellings buildings became higher compared to multi-dwelling buildings.

2.2.1 Multi-dwelling buildings

During the Million Homes programme, almost 60% of the dwellings in multi-dwelling buildings were produced in non-metropolitan regions, which means that they were not produced in the regions of Malmö, Göteborg or Stockholm.

During this period, more than 80% of the dwellings were slab block buildings (see Figure 2.2). After the mid-1970s the number of dwellings in slab block buildings were on a rather constant low level for a long period, with a small increase in the end of the 1980s. Instead, other building types became more usual. The share of point block buildings and balcony access buildings increased, but other types of buildings also saw an up-rise.

The distribution of different types of buildings in different regions were rather equal during the Million Homes programme with the exception of the Stockholm region, where the share of balcony access buildings and point block buildings dwellings were higher compared to the rest of Sweden, as shown in Figure 2.2.

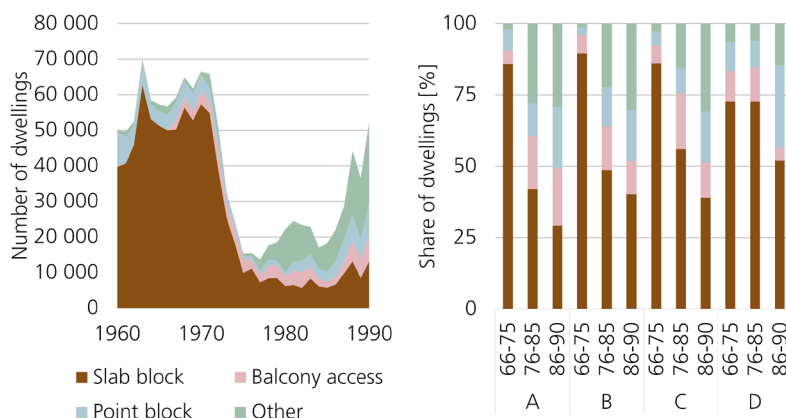


Figure 2.2 *Left: Distribution of dwellings in multi-dwelling buildings by type of building and year of state loan. Right: Share of dwellings in multi-dwelling buildings by type of buildings for different periods and regions. A: Non-metropolitan regions B: Malmö region C: Göteborg region D: Stockholm region*

The type of superstructure was only presented by SCB for the period of 1968 to 1972. However, even though it was a short period of time, this was during the peak of production of multi-dwelling buildings—the Million Homes programme. Therefore, it is interesting to review the data (see Figure 2.3). There was roughly a 50/50 distribution of the use of longitudinal load bearing construction and transverse load bearing construction in the Malmö region and non-metropolitan regions. The use of transverse load bearing was roughly 10%-points higher in the Göteborg region and 10%-points lower in the Stockholm region. The roughly 50/50 distribution shows that a type of building, e.g. slab block building, may not be expected to have a specific type of superstructure.

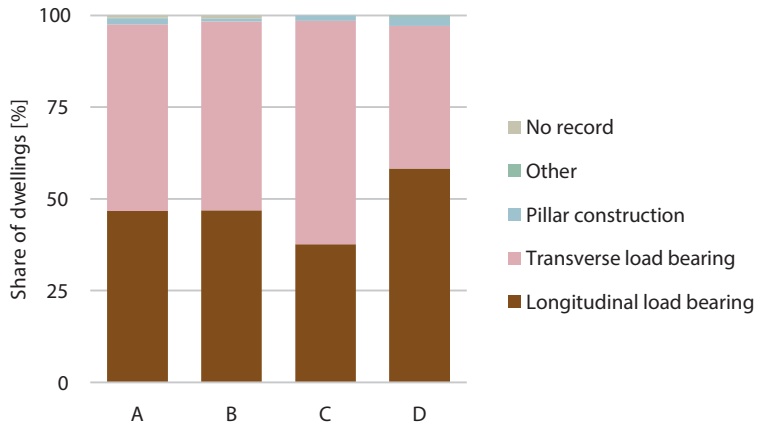


Figure 2.3 Share of dwellings in multi-dwelling buildings by type of superstructure for different regions, 1968-1972. A: Non-metropolitan regions B: Malmö region C: Göteborg region D: Stockholm region

Facade materials and the type of inner materials used in exterior walls are presented in Figure 2.4. Data for the facade material used in different regions is available for the period of 1968 to 1987, and data describing the combination of facade material and inner material in exterior walls is available for the period of 1963 to 1979. In general, clay brick facades were the most common facade material used from the early 1960s to 1990. However, the data shows that clay brick facades were not the most common facade throughout Sweden for the whole analysed period. From the late 1960s to mid-1970s, clay brick facades were common in non-metropolitan regions and the Malmö region. In the Stockholm region, render was the most common facade; and, in the Göteborg region, clay brick facades were the most common but were just slightly more used compared to concrete facade.

Clay brick facades, the most common facade material, were commonly used on walls with an inner material of wood, followed by lightweight concrete, clay bricks and concrete. Rendered facades material—the second most common—was usually applied on walls of lightweight concrete or concrete. Concrete facades were almost solely constructed with an inner material of concrete. Facades of sand-lime brick, wood or sheet metal were commonly designed in combination with wood as the inner material within the walls.

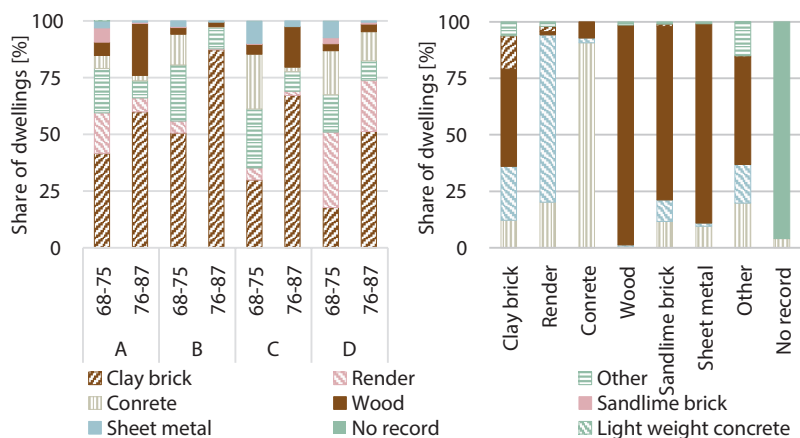


Figure 2.4 Left: Share of dwellings in multi-dwelling buildings by facade material for different periods and regions. A: Non-metropolitan regions B: Malmö region: C: Göteborg region D: Stockholm region. Right: Share of dwellings by different inner material in exterior walls for different facade materials, 1963-1979

2.2.2 One- and two-dwelling buildings

The process for state loans differed for one- and two-dwelling buildings—depending on whether the applicant of the state loan was the final resident or not. If the applicant was the same as the final resident, the process was simple, and the decision regarding the state loan was given before the start of the construction work. If the applicant was not the final resident, the applicant was given a preliminary decision before the start of the construction work. A second and final decision regarding state loans was given when the building was completed (SCB, 1967-1994). For buildings with two decisions, more data was gathered. Throughout the period where data from both one and two decisions was gathered (1966-1987), dwellings with two decisions cover 53% of the total data (see Figure 2.5).

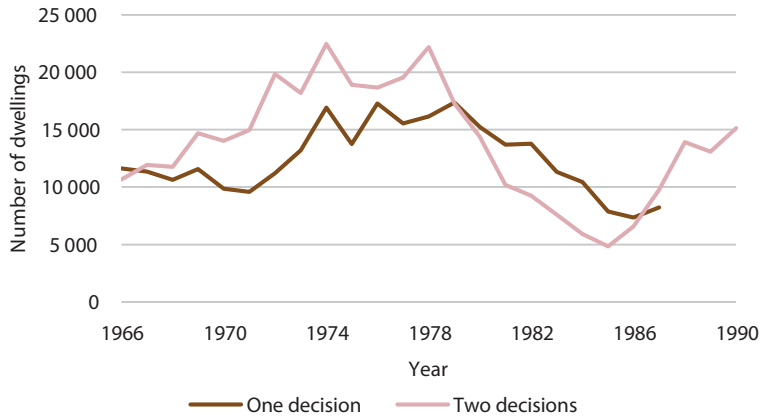


Figure 2.5 *Distribution of dwellings in one- or two-dwellings buildings by one or two decisions and year of state of loan*

Data regarding different types of buildings in which the process of obtaining a state loan was completed by one decision was only gathered from 1966 to 1967. However, 99% of the dwellings with one decision during that period were one-dwelling buildings. One may, therefore, assume that more than 95% of the dwellings with one decision are one-dwelling buildings.

In Figure 2.6, different types of buildings from two-decision loans are presented together with the quantity of dwellings with one decision. One-dwelling buildings together with one-decision dwellings contributed to the largest share of dwellings from this period. Together, they varied between 60% and 70% of the dwellings. The largest part of the dwellings with two decisions were terraced buildings, which increased significantly in the end of the 1980s. Linked buildings were rather common from the late 1960s to the mid-1970s but dropped in the late 1970s and remained rather uncommon through the 1980s.

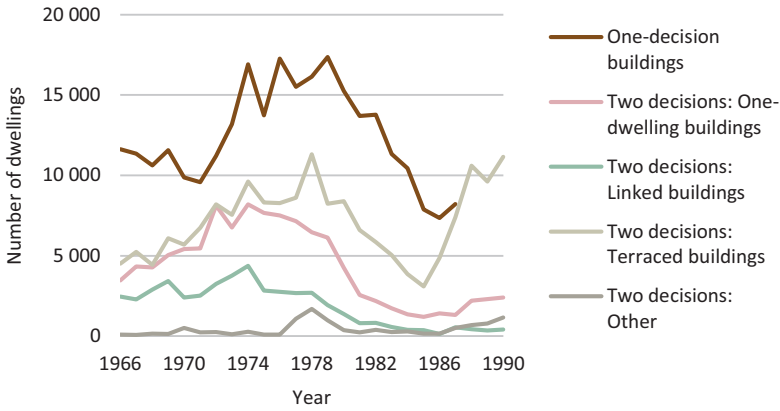


Figure 2.6 *Distribution of dwellings in one- or two-dwelling buildings by type of building and year of state loan. More than 95% of the dwellings with one decision may be assumed to be one-dwelling buildings*

Material used in load-bearing walls in one- or two-dwelling buildings are presented in Figure 2.7, and facade materials used are presented in Figure 2.8. Information regarding material used for the load-bearing structure in exterior walls and facade materials were gathered for 1966 to 1987 and 1966 to 1990, respectively. That is, the combination of facade material and inner material for exterior walls is not available. However, as Figure 2.6 shows, wood was the dominant material throughout the period. Regarding facade material, wood and clay brick facades were the most common materials. Together, the share varies between 70-95% of the dwellings during 1966-1990. In the mid-1960s facades with clay bricks were most common and accounted for almost 70% of the dwellings. The use of wood became more common, and, in the beginning of the 1980s, wood was used for more than 70% of the dwellings.

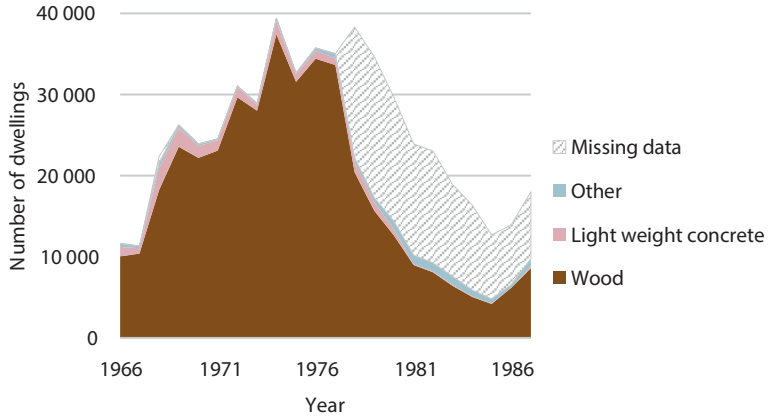


Figure 2.7 *Distribution of dwellings in one- or two-dwelling buildings based on material used for load-bearing in exterior walls. Missing data refers to dwellings that provided data to SCB but did not specify information load-bearing material*

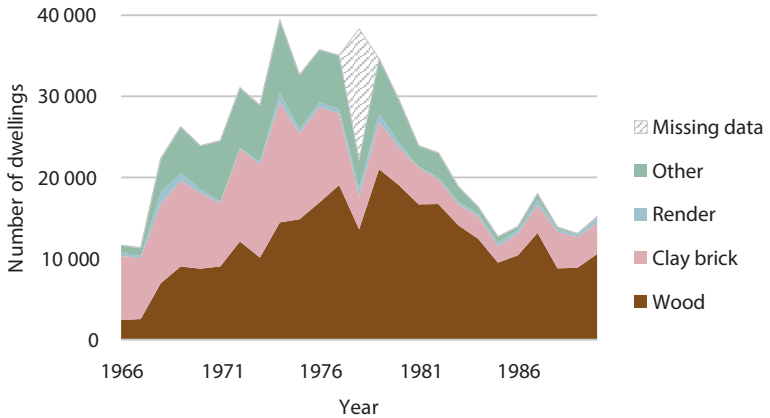


Figure 2.8 *Distribution of dwellings in one- or two-dwelling buildings based on facade material. Missing data refers to dwellings that provided data to SCB but did not specify information regarding facade material*

2.3 Discussion and conclusions

The data from SCB, based on Swedish state loans, does not cover all dwellings built during this period of time and covers a limited period of time in the Swedish history. However, the information covers, to a large extent, the peak of production of dwellings built in Sweden, enabling a bottom-up analysis. Hence, it is interesting to compare these results with previous research related to building typology and to discuss differences.

It should be noticed that previous research, creating building typologies, may have had a different purpose compared to this research (gathering, describing and sharing data to enable further studies), i.e. if the purpose of a study is to make a rough assessment of the energy performance of a building stock, not to discuss applicable refurbishment measures in detail, detailed information regarding materials used are not necessary.

The large share of dwellings built during the Million Homes programme have been identified in previous studies as an important part of the Swedish building stock to focus on, as a reduction of the energy use in these dwellings has great potential as a climate mitigation measure (Berggren, Janson, & Sundqvist, 2008; Boverket & Energimyndigheten, 2013; Mjörnell & Werner, 2010). The distribution of regions found in this study corresponds rather well with previous findings (Hall & Vidén, 2005) that state that 65% of the dwellings built during the Million Homes programme were built in non-metropolitan regions. However, when separating all the dwellings into multi-dwelling buildings and one- or two-dwelling buildings, the data from state loans shows that 59% of the multi-dwelling buildings were in non-metropolitan regions and 70% of the one- or two-dwelling buildings were built in non-metropolitan regions. The rather large share of dwellings built in non-metropolitan regions is important to highlight since the economic conditions, available capital for renovation, are likely to be different in these regions compared to metropolitan regions.

The distribution of type of multi-dwelling buildings (slab block, point block and balcony access buildings) found in this study correspond well to previous studies (Berggren et al., 2008; Mjörnell & Werner, 2010). Furthermore, findings regarding the number of storeys also correspond rather well with previous studies (Berggren et al., 2008; Hall & Vidén, 2005; Mjörnell & Werner, 2010; Wittchen et al., 2012). However, it is important to highlight that even if the largest part of the dwellings in multi-dwelling buildings from the Million Homes programme is to be found in slab block buildings with three or four storeys, roughly 50% of the dwellings were designed in another way.

Regarding inner material in exterior walls and facade materials used, the results show that, while there are prevailing materials, there exists a

rather large diversity for multi-dwelling buildings. For example, the most common material in a wall behind a clay brick facade is wood (43%). However, almost 25% of the dwellings with clay brick facades has an inner material of lightweight concrete. Clay bricks (15%) and concrete (12%) as an inner wall material also make up for more than 25%. There are rather large regional differences regarding common facade materials. Pertaining to one- or two-dwelling buildings, almost all buildings included in the data were built with wooden constructions, which means that it is mainly variations of facade material which need to be considered in future work.

The fact that there is a roughly 50/50 distribution of the type of superstructure used in multi-dwelling buildings is important due to that it will give different possibilities for energy renovation. A multi-dwelling building with a transverse load-bearing system allows for renovation measures for the exterior walls with less effects on the superstructure compared to a building with a longitudinal load-bearing system. Previous studies have concluded, based on statistics regarding the frequency of slab block buildings, that such buildings all used the same building technique with a transverse load-bearing system and light infill walls (Boverket, 2013; Mjörnell & Werner, 2010; Spets, 2012). However, such a conclusion is wrong.

The TABULA study regarding potential energy savings in the Swedish building stock from 2012 (Spets, 2012) defined multi-dwelling buildings built between 1961 and 1975 as three-storey buildings and did not define the exterior wall constructions. It should be interpreted that, in this study, it was assumed that energy-saving measures may be possible to apply regardless of wall construction. This is a simplification which is likely not true. The TABULA study defined one- or two-dwelling buildings from the selected time period as one-storey buildings with exterior walls of lightweight concrete covered with render. This definition is unfortunate since it covers less than 5% of the existing one- or two-dwelling buildings.

Boverket conducted an extensive review, completed during 2007-2008, of the existing building stock in Sweden in which inspections of 1,386 residential buildings were carried out in order to create a detailed description of the existing buildings (Boverket, 2009). Based on the available collected data, Boverket concluded that the average multi-dwelling building and average one- or two-dwelling building in Sweden were built in 1959 and 1953, respectively (Boverket, 2010b). These are likely to be the mean values of all residential buildings in the study, and they are an incorrect description of the most common buildings in Sweden. If an analysis would be based on median values instead of mean values, it would show that the most common multi-dwelling building was built during the Million Homes programme (Statistics Sweden, 2018).

In 2013, Boverket conducted another study to analyse cost-optimal energy requirements (Boverket, 2013). Regarding energy requirements

on existing residential buildings, Boverket defined four different reference buildings. Two were multi-dwelling buildings, where one was defined as a three-storey multi-dwelling building from the 1950s with lightweight concrete exterior walls, and the other as a nine-storey multi-dwelling building from the 1970s with concrete sandwich walls. The chosen types of exterior walls cover approximately 25% of the existing multi-dwelling buildings built during the Million Homes programme in Sweden. The most common exterior wall construction—wooden infill walls with clay brick facades—is not included. The other two reference buildings were defined as one-dwelling buildings with wooden facades. By only including wooden facades, here, roughly 50% of the facade constructions were excluded.

A recent study describes 46 typical buildings for the Swedish building stock (Gontia, Nägeli, Rosado, Kalmykova, & Österbring, 2018). Considering multi-dwelling buildings built during the 1970s, the study defined three different buildings, two point block buildings and one slab block building, all with six storeys or more. These buildings represent less than 10% of the dwellings in multi-dwelling buildings in the Swedish dwelling stock in this period. The study further discusses that the 1.5-storey building was the most common building type during the 1970s. This is incorrect, as the most common building type in the collected data from SCB has one storey.

The analysed data for the existing building stock and reference buildings in previous studies show the complexity of the existing building stock and the challenge to describe it with a set of reference buildings. The study described in this chapter will hopefully contribute to improve future definitions of typical buildings in the Swedish residential building stock.

3 Energy performance

This chapter presents research related to the energy performance of buildings. After an introduction, the importance and state of knowledge related to thermal bridges, studied in PR III, PR V, CP VII and CP IX, are presented. This is followed by the energy performance of Net Zero Energy Buildings, studied in PR I, PR IV, CP XII, CP XIV CP XV and XLI, including experiences from different case studies. Before discussion and conclusions, embodied energy in buildings and different methods for evaluating the environmental impact of energy use, studied in PR II and XLII, are presented.

3.1 Introduction

The share of dwellings constructed with energy requirements that are $\geq 25\%$ tougher compared to building regulations has increased markedly in recent years in Sweden, with an all-time high in 2013 in which 7% of the dwellings were produced as low-energy buildings, compared to 1% in 2008 (Lantz & Wahlström, 2018). If one considers only the segment of multi-dwelling buildings, the share was higher than 10% in 2013. The EPBD recast states that all new buildings must be nearly Zero-Energy Buildings, nZEBs, by 2020 (European Parliament, 2010). Furthermore, EPBD2 states that member states shall set energy requirements for building elements and/or building envelope. Methodology for calculations should take into account European standards and be expressed in a transparent manner. A review including 26 of the 28 member countries from 2016 (Papadopoulos, 2016) shows that all countries have regulations regarding energy performance of the building envelope. Furthermore, 23 of 26 countries include thermal bridges.

Many stakeholders are already, today, making an effort to outperform the nZEB concept, designing and building Net ZEBs (Berggren, Dokka, & Lassen, 2015; Garde et al., 2014; Lenoir, Garde, & Wurtz, 2011; Musall et al., 2010; Sørensen, Mysen, Andresen, Hårklau, & Lunde, 2017). At a first glance, the “zero energy concept” seems simple and intuitive. However, there may be significant differences between definitions that seem similar

(BPIE, 2011; Kurnitski et al., 2011; Marszal et al., 2011; Sartori et al., 2010; Sartori, Napolitano, & Voss, 2012).

Whether a stakeholder chose to design a nZEB or Net ZEB, the design strategy is, in general, to apply energy conservation and efficiency measures coupled with renewable energy generation. In designing a building according to these principles, the major part of the energy needed for space heating will be related to thermal transmission through building elements and thermal bridges. Hence, calculation of transmission heat transfer in a correct way is vital. Poor calculation of thermal bridges may, therefore, lead to an increased space heating demand and poor indoor climate. Further, this may lead to economic consequences for the builder, the client and/or the consultants.

While pushing boundaries of energy efficiency in buildings, it is of growing importance that predicted energy performance is actually achieved during the user stage and that the intended environmental benefit is obtained. Performance gaps related to energy performance have been identified in earlier studies (Bordass, Cohen, & Field, 2004; Branco, Lachal, Gallinelli, & Weber, 2004; Carbon Trust, 2011; de Wilde, 2014; Demanuele, Tweddell, & Davies, 2010; Guerra-Santin & Itard, 2012; Janson, 2010; Kampelis et al.; Mahapatra & Olsson, 2015; D. Majcen, L. Itard, & H. Visscher, 2013; D. Majcen, L. C. M. Itard, & H. Visscher, 2013; Menezes, Cripps, Bouchlaghem, & Buswell, 2012; Norbäck & Wahlström, 2016; Rekstad, Meir, Murtnes, & Dursun, 2015; Wall, 2006), showing that predicted energy use is often not achieved during the user stage. One way to overcome this and to identify actual performance gaps is to normalise the measured energy use. Indeed, in the cited works, a smaller performance gap is generally found when measured energy use is normalised.

In regard to the expected environmental benefit, it is of growing importance that the energy use is evaluated in a way that consider the environmental impact, commonly done today by using different weighting factors (Sartori et al., 2012), which may affect and reduce the number of feasible or favoured building energy system solutions (Beerepoot & Beerepoot, 2007; Sartori, Dokka, & Andresen, 2011). Also, the energy use for producing, maintaining and demolishing—embodied energy—should be considered. In the beginning of this millennium, it was generally alleged that energy use in the user stage of a building accounted for 70-90% of the energy used during its life cycle (Adalberth, 1997, 1999; Sartori & Hestnes, 2007; Winther & Hestnes, 1999). However, when buildings are more energy efficient and, as such, use less energy in the user stage, the relative share of EE will increase.

In this section, results from research related to how transmission heat transfer for a building envelope may be calculated and expressed are presented. This is followed by investigating the definition of Net ZEBs from a

Swedish perspective, including experiences from the case studies, i.e. Väla Gård, Glasbruket and Solallén focusing on measurement and verification. The last section covers EE and the effect of different weighting factors and methods for evaluating environmental impact.

3.2 Thermal bridges in building envelopes

The energy performance of a building envelope is usually expressed by calculating the average thermal transmittance, U_{mn} , which includes the thermal transmittance from building elements, linear thermal bridges and point thermal bridges. As mentioned in Chapter 3.1, the EPBD states that member states shall set energy requirements for building elements and/or the building envelope. Furthermore, the methodology for calculations should take into account European standards and be expressed in a transparent manner.

A commonly used standard to calculate transmission heat transfer through a building envelope is EN ISO 13789 (Swedish Standards Institute, 2017c), which, in turn, refers to EN ISO 6946 (Swedish Standards Institute, 2017a) regarding thermal transmittance of building elements and to two standards regarding thermal bridges, EN ISO 14683 (Swedish Standards Institute, 2017d) and EN ISO 10211 (Swedish Standards Institute, 2017b).

The transmission heat transfer coefficient, H_{tr} , for an entire building envelope calculated, according to EN ISO 13789, is shown in Equation 3.1.

$$H_{tr} = H_d + H_g + H_u + H_a \quad \text{Equation 3.1}$$

where

- H_{tr} Transmission heat transfer coefficient (W/K)
- H_d Direct heat transfer coefficient, defined in Equation 3.2 (W/K)
- H_g Steady-state ground heat transfer coefficient (W/K)
- H_u Transmission heat transfer coefficient through unconditioned places (W/K)
- H_a Transmission heat transfer coefficient to adjacent buildings (W/K)

$$H_d = \sum_i A_i U_i + \sum_k l_k \Psi_k + \sum_j \chi_j \quad \text{Equation 3.2}$$

where

- A_i Area of element, i (m^2)
- U_i Thermal transmittance of element, i (W/m^2K)
- l_k Length of linear thermal bridge, k (m)
- Ψ_k Linear thermal transmittance of thermal bridge, k (W/mK)
- χ_j Point thermal transmittance through point thermal bridge, j (W/K)

To calculate the transmission heat transfer coefficient for the entire building envelope, the building envelope needs to be divided into different building elements. Measuring in order to quantify the building elements may be conducted in different ways. Three different ways are clearly defined and referred to in all the standards mentioned above—internal, overall internal and external dimensions. The different methods are visualized in Figure 3.1.

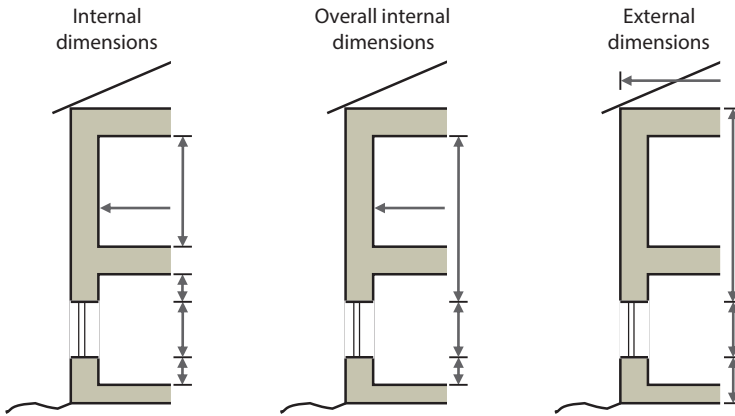


Figure 3.1 Three different methods of measuring according to EN ISO 10211, EN ISO 13789 and EN ISO 14683

Thermal bridges are defined as part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, a change in thickness of the fabric and/or a difference between internal and external areas, such as an occurrence at wall/floor/ceiling junctions according to EN ISO 10211.

The linear thermal transmittance of the thermal bridge, Ψ , is calculated according to Equation 3.3. The point thermal transmittance of the thermal bridges, X , is calculated according to Equation 3.4.

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \quad \text{Equation 3.3}$$

where

L_{2D} Thermal coupling coefficient obtained from a 2-D calculation (W/mK)

U_j Thermal transmittance of 1-D component, j (W/m²K)

l_j Length over which U_j applies (m)

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot l_i - \sum_{j=1}^{N_j} \Psi_j \cdot l_j \quad \text{Equation 3.4}$$

where

L_{3D} Thermal coupling coefficient obtained from a 3-D calculation (W/K)

U_i Thermal transmittance of 1-D component, i (W/m²K)

A_i Area over which U_i applies (m²)

Ψ_j Linear thermal transmittance calculated according to Equation 3.3 (W/mK)

l_j Length over which Ψ_j applies (m)

The sum of transmission losses through building elements, the term $\Sigma(A_i \cdot U_i)$, will vary depending on the chosen measuring method. Consequently, the thermal bridges, Ψ -values and X -values, will vary. However, the transmission heat transfer coefficient will be the same provided that the same measuring method is consistently used in all calculations.

As the measuring of areas and lengths may be conducted in three different ways (Figure 3.1), the specific values for thermal bridges may differ. In order to avoid misunderstanding and enable comparison, the chosen measuring method should always be included when specific values of thermal bridges are reported. Subscripts presented in Table 3.1 should be used.

Table 3.1 Subscripts to clarify used method for measuring to avoid misunderstandings

Subscript	Definition
i	Internal
oi	Overall internal
e	External

Different stakeholders may apply measuring methods differently, imposing a risk of misunderstanding. To investigate the state of knowledge, a survey was conducted twice (2010, 2016) in Sweden among consultants who work with energy calculations. The results were published in peer reviewed journals, scientific conferences and also in Swedish trade journal (Berggren & Wall, 2012, 2017) and has also been the basis for a handbook in Swedish (Larsson & Berggren, 2015). Despite the effort made to communicate the results, comparing the results from the two surveys shows little progress. There is a big spread among the answers related to how to quantify building elements and the buildings' enclosing areas, see Figure 3.2.

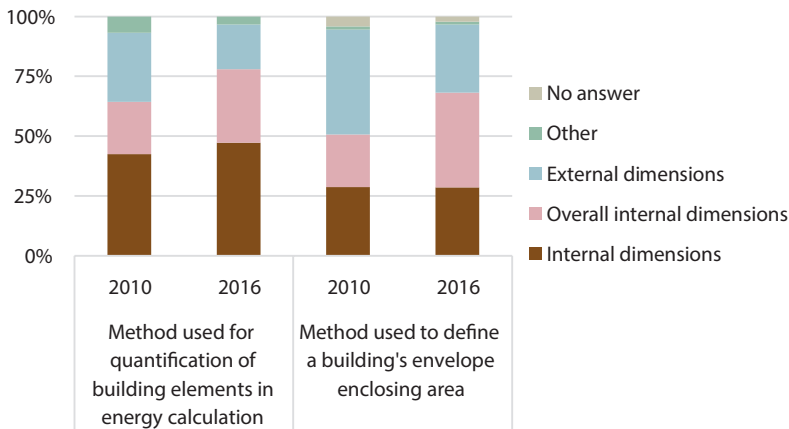


Figure 3.2 Distribution of answers on how to quantify building elements and envelopes. Comparing the old survey (2010) and the new survey (2016)

Regarding how thermal bridges are handled in general, there is a shift towards simplifications. Almost half of the respondents (49%) consider thermal bridges by increasing the thermal transmittance from the building elements by a certain percentage, compared to the old survey (22%).

Based on which method of measurement for building elements the respondents chose, it is also possible to quantify if the respondents assess typical junctions in a correct way. Additionally, little progress is seen here. The share of correct answers was 58% in the new survey, compared to 56% in the old survey.

Based on a case study building presented when the results from the first survey was introduced, the transmission heat transfer through building elements and thermal bridges is presented in Figure 3.3. As can be seen, for a specific building category with a specific type of external wall construction, the total transmission heat transfer coefficient is the same. However, the share related to thermal bridges varies. Additionally, the share of transmission heat transfer due to thermal bridges is the highest in the best practice building category for all three building systems.

The share of thermal bridges is always the highest if internal measuring is used, regardless of exterior wall construction and building category.

The share of transmission heat transfer losses due to the thermal bridges varies as follows: between 2% and 17% when external walls are concrete with external insulation; between 7% and 27% in wooden frame walls with insulation and the highest shares, between 14% and 39%, in cases with precast concrete sandwich walls.

The corresponding increase in percentage factor, which should be used if one is only increasing the transmission heat transfer coefficient by a certain percentage instead of analysing thermal bridges, is consequently even higher. In the worst case, the corresponding increase is 64%. This applies to precast concrete sandwich walls and insulation thickness equivalent to best practice.

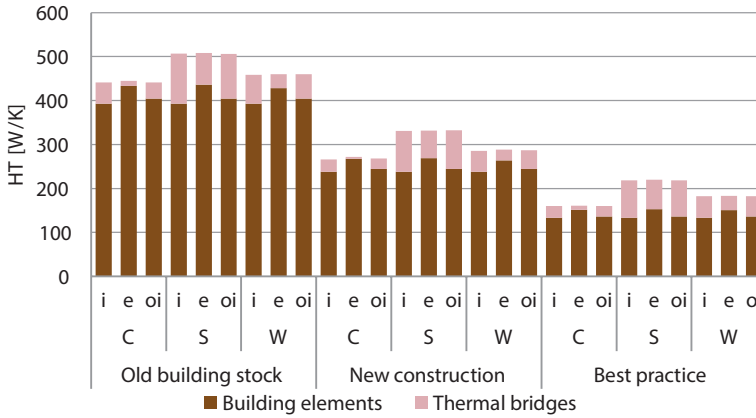


Figure 3.3 Calculated transmission heat transfer coefficient, HT , by different measuring method (i , e and oi), exterior wall constructions (C =Concrete walls, S =Sandwich walls and W =Wooden walls) and building categories

Several consultants are usually involved in the design and construction stage of a building. Hence, it is possible to imagine a scenario in which an architect will be asked to provide quantities of building elements and junctions, a construction engineer to calculate U-values and specific values for thermal bridges and an HVAC-consultant to carry out energy calculations and sizing of heating and cooling system. In such a scenario, misinterpretations and, therefore, incorrect calculations of transmission heat transfer losses may occur. In Figure 3.4, results from calculated energy demand and peak load for heating is presented based on five different scenarios:

- Scenario 1
External dimensions used to determine A_i , no thermal bridges added
- Scenario 2
Overall internal dimensions used to determine A_i , thermal bridges considered by increasing thermal transmittance by 15%
- Scenario 3
Internal dimensions used to determine A_i , thermal bridges considered by increasing thermal transmittance by 15%

- Scenario 4
Internal dimensions used to determine A_i , thermal bridges added by applying values for Ψ_e
- Scenario 5
Internal measuring used to determine A_i , thermal bridges added by applying values for Ψ_i

In the scenarios described above, Scenario 5 is an example of the correct treatment of thermal bridges, and all other scenarios are examples of possible misunderstandings. Correct treatment would also be to apply overall or external measuring as long as the chosen measuring method is applied consistently.

As can be seen in Figure 3.4, misinterpretations and incorrect calculations may result in underestimations of space heating energy demand and peak load by roughly 30%.

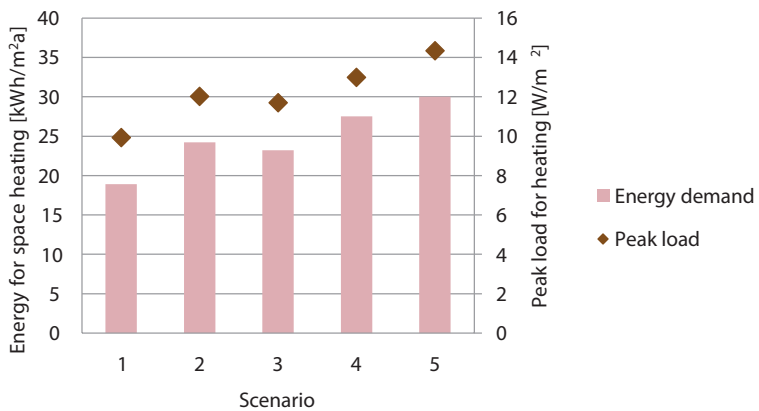


Figure 3.4 Annual energy demand and peak load for heating based on different scenarios

3.3 Energy performance of (Net-zero energy) buildings

Four main concepts and definitions may be distinguished related to “zero energy buildings” (including the EPBD definition):

- **Zero Energy Building, ZEB:**
A building where renewable energy generation covers the energy use. The building is autonomous and does not interact with any external energy supply system, such as district heating, gas pipe network, electricity or similar.
- **Net-Zero Energy Buildings, Net ZEBs:**
A building where renewable energy generation covers the energy use. The building interacts with an energy supply system and can export energy when the building’s system generates a surplus and import energy when the building’s system does not produce the quantities of energy required.
- **Net-Zero Energy Clusters, Net ZECs:**
A cluster of buildings (more than one) where the buildings interact with each other. Renewable energy generation covers the energy use within the cluster.
- **Nearly Zero Energy Buildings, nZEBs:**
A building with very high energy performance in which the energy required should, to a very significant extent, be covered by energy from renewable sources, including sources on-site or nearby.

Regardless of the concept applied, to design an energy efficient building, one should always start by applying energy efficiency measures to reduce the energy demand, followed by dimensioning and installing an energy supply system to generate energy, exploiting renewable energy sources. The concept is graphically presented in Figure 3.5.

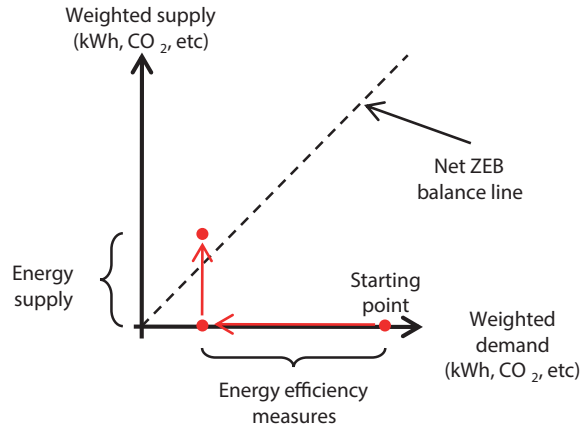


Figure 3.5 Graph representing the Net ZEB balance concept (Sartori et al., 2012)

The sketch shown in Figure 3.6 gives an overview of the relevant terminology addressing the energy use in buildings and the connection between buildings and energy grids. The building's load refers to the energy demand, which may not match the delivered energy due to self-consumed on-site generation.

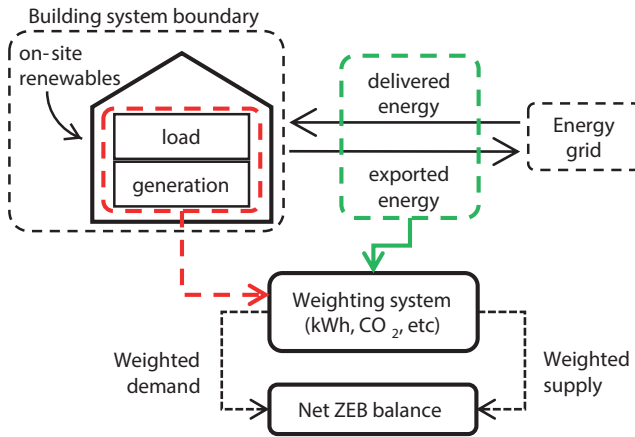


Figure 3.6 Connection between building and energy grid (Sartori et al., 2012)

To clearly define and communicate a Net ZEB definition, different aspects recommended to be addressed within the Net ZEB framework were developed in the context of the joint IEA SHC Task40/ECBCS Annex52 (International Energy Agency (IEA), 2013; Sartori et al., 2012):

- Building system boundary
- Weighting system
- Net ZEB balance
- Energy match characteristics
- Verification and measurements

Defining the building system boundary should include the physical and balance boundaries and boundary conditions. The physical boundary should be defined in order to be able to quantify energy flows delivered and exported to the building and also to define “on-site”. The term “balance boundary” refers to defining which energy uses are included in the Net ZEB balance, i.e. whether or not all the energy use related to building operation is included in the balance. Boundary conditions include defining the external climate and the use of the building, e.g. indoor temperature, air change rate, etc.

Defining the weighting system should include the choice of metrics and weighting factors. Today, there are projects claiming Net ZEB balance based on delivered energy, primary energy, CO₂ credits and costs, etc.

Defining the Net ZEB balance should include the balancing period, type of balance, energy efficiency requirements and energy supply requirements. Often, an annual balance is applied for Net ZEBs, but there are also cases where the balance is calculated monthly, seasonally or over several decades. “Type of balance” refers to whether the balance is based on delivered/exported balance or load/generation balance. Energy efficiency requirements may be set for U-values of building elements and performance of HVAC systems but can also be design requirements relating to other qualities (e.g. thermal comfort or acoustic requirements). “Energy supply requirements” refer to which renewable energy generation options that may be included in the definition.

Energy match characteristics may be described in different ways, usually expressed in terms of load match and grid interaction (LMGI) indicators. Load match index usually refers to how much of the local energy generation may cover the energy load (see Equation 3.5), which also includes the effect of an energy storage. The load match may be calculated in different time resolution and for different energy carriers.

$$f_{load,i,T} = \min \left[1, \frac{g_i + dc_i - c_i}{l_i} \right] \quad \text{Equation 3.5}$$

where

g_i Generation of energy carrier, i

dc_i Discharge energy of carrier, i

c_i Charging energy of carrier, i

l_i Load of energy carrier, i

Equation 3.6 describes the energy exchange with the grid, compared to the maximum exported/delivered energy. The average stress on the grid—grid interaction index—is described in Equation 3.7 using the standard deviation of the grid interaction over the period of a year.

Several other indicators exist to analyse load match and grid interaction.

$$f_{grid,i,T} = \frac{(e_i - d_i)}{\max[e_i - d_i]} \quad \text{Equation 3.6}$$

$$f_{grid,i,year,T} = \text{STD}(f_{grid,i,T}) \quad \text{Equation 3.7}$$

where

e_i Exported energy of carrier, i

d_i Delivered energy of carrier, i

Lastly, Net ZEB definitions should also include how to verify the performance of the building. This may include calculations procedures and/or how to measure the energy performance in the user stage.

3.3.1 Case study: Väla Gård – Net ZEB definition and interaction with energy grid

A two-storey office building, Väla Gård, situated in the south of Sweden, was used to study the Net ZEB definition in Sweden and its interaction with the energy grid using LMGI indicators. The overall design concept of Väla Gård may be described as two main buildings with double pitched roofs, connected by a smaller building with a flat roof. The smaller building serves as an entrance and reception (see Figure 3.7 and Figure 3.8).

The strategy for reaching the Net ZEB balance for the case study utilizes a three-step approach. Firstly, heating and cooling load were reduced, mainly by reducing thermal losses and solar heat gains. Secondly, a ground source heat pump (GSHP) was chosen in order to lower the need for imported energy. Lastly, the building was equipped with photovoltaic (PV) panels on the roof facing southwest to generate sufficient renewable energy in order to reach the Net ZEB balance. The technical description is summarized in Table 3.2.

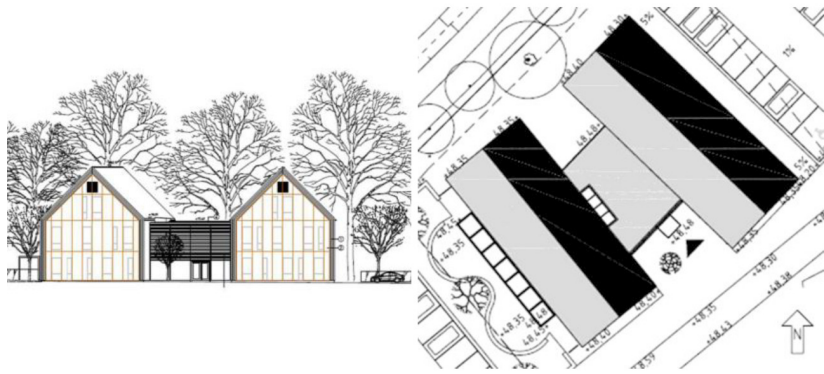


Figure 3.7 Väla Gård. Left: facade facing southeast; right: orientation of building



Figure 3.8 Photo of Väla Gård. Facade towards northwest and southwest.

Table 3.2 Summary of technical description of case study, Våla Gård. All values are design values

Type of Data/Description	Value
Conditioned area	1 670 m ²
Indoor air volume	6 492 m ³
Enclosed area/indoor air volume	0.42 m ⁻¹
Enclosed area/conditioned area	1.64
Window area/wall area	0.29
Foundation, 350 mm insulation, U-value	0.08 W/m ² K
Exterior wall, 295 mm insulation, U-value	0.11 W/m ² K
Flat roof, 370 mm insulation, U-value	0.10 W/m ² K
Double pitched roof, 520 mm insulation, U-value	0.08 W/m ² K
Windows, U-value	0.90 W/m ² K
Glazed entrance, U-value	1.00 W/m ² K
Total thermal bridges/enclosed area	0.03 W/m ² K
Air tightness (q50/n50)	0.3 l/s, m ² / 1.0 h ⁻¹
Ventilation heat recovery	82%
Ventilation specific fan power	0.8 kW/(m ³ /s)
Geothermal heat pump, SCOP _{heating}	3.0
Geothermal heat pump, SCOP _{cooling}	20.0
Photovoltaic panels, 450 m ²	70 kW _p

A summary of the predicted energy performance compared to measured results in 2013-2014 is presented in Table 3.3, and weekly results are presented in Figure 3.16. The measured results have not been normalised.

The total measured energy load is lower compared to predicted results. Additionally, the measured generation of electricity is higher compared to measured results, which leads to both a total energy export higher than predicted and a total energy import lower than predicted. However, the measured import of energy, according to Swedish building regulations and excluding plug loads and lighting, is higher compared to predicted. This is mainly due to higher measured energy load during night compared to predicted values.

Table 3.3 Comparison of predicted energy performance and measured results (not normalised), Väla Gärd

Energy use	kWh/m ² a	
	Predicted	Measured
Energy load, excl. plug loads and lighting	19	16
Plug loads and lighting load	29	26
Photovoltaic panels	38	40
Imported energy excl. plug loads and lighting	10	11
Total imported energy	29	26
Total exported energy	19	24

Studying the weekly values in Figure 3.9, it should be noted that the expected low energy load during summer vacation, Weeks 27-30, is not seen in the measured results. This is mainly due to the presence-controlled ventilation and lighting because only a few persons need to attend the office to start the ventilation and lighting (which was the case). Except for Weeks 27-30, less solar energy is, in general, used on-site compared to simulated.

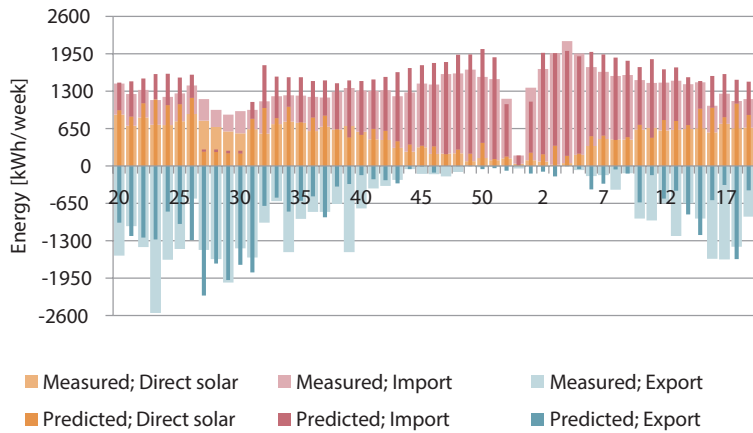


Figure 3.9 Weekly results from simulations compared with measurements, Väla Gärd (Year 2013-2014)

Load match and grid interaction were also evaluated (see Figure 3.10) (Berggren, Kempe, & Togerö, 2014). Analysing the load match, the complexity of the interaction between load/generation and delivered/exported energy can be seen. There are periods every day, except for a short period in January, where the load match is both 100% and 0%. Analysing the load match on a weekly basis indicates that the generated electricity from the PV panels may cover the required energy load from the building during summer if a one-week storage could be used/implemented.

The analysis of grid interaction shows the complexity of the interaction between delivered and exported energy. The hourly analysis shows that electricity is delivered to the building as well as exported from the building several times a day, and the weekly analysis shows that the stress could be reduced. The maximum peak is also shifted from summer (export of electricity) to winter (delivered electricity).

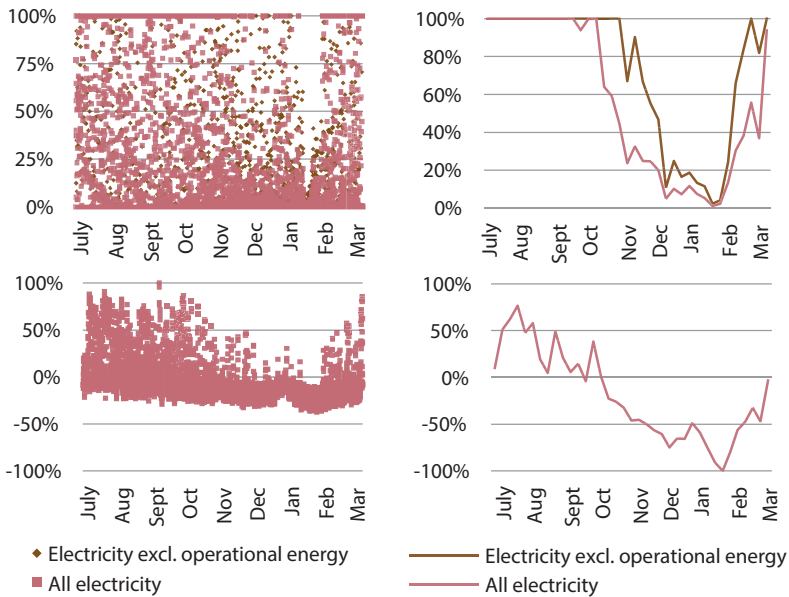


Figure 3.10 Load match and grid interaction for Väla Gärd (2013-2014). Top left: load match based on hourly resolution; top right: load match based on weekly resolution; bottom left: grid interaction based on hourly resolution; bottom right: grid interaction based on weekly resolution

3.3.2 Case study: Glasbruket – interaction with energy grid

LMGIs were further studied for a residential building, Glasbruket, in the design phase (Glasbruket was never built). The case study is summarised in Table 3.4 and presented in Figure 3.11. In this study, different options, such as increased/decreased roof slope, orientation of building, energy storage etc., were investigated. The parametric study showed that changes such as increased/decreased roof slope, orientation of building and increased/decreased area of solar thermal collectors and PV-panels have a low impact on load match if the time resolution is less than one year. Furthermore, it has a low impact on the grid interaction, i.e. stress on the grid. The only significant impact on grid interaction is seen when the option to export heat to the district heating network is terminated.

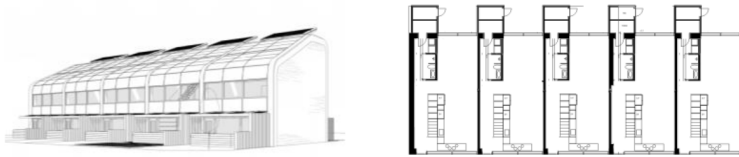


Figure 3.11 Glasbruket. Left: facade facing south; right: layout of building

Table 3.4 Summary of technical description of case study, Glasbruket. All values are design values

Type of Data/Description	Value
Conditioned area	703 m ²
Indoor air volume	2 102 m ³
Enclosed area/indoor air volume	0.52 m ⁻¹
Enclosed area/conditioned area	1.55
Window area/wall area	0.30
Foundation, 300 mm insulation, U-value	0.09 W/m ² K
Exterior wall, 310 mm insulation, U-value	0.11 W/m ² K
Roof, 370 mm insulation, U-value	0.09 W/m ² K
Windows, U-value	0.90 W/m ² K
Glazed entrance, U-value	1.00 W/m ² K
Total thermal bridges/enclosed area	0.05 W/m ² K
Air tightness (q50/n50)	0.2 l/s, m ² / 0.4 h ⁻¹
Ventilation heat recovery	80%
Ventilation specific fan power	1.5 kW/(m ³ /s)
Solar thermal collectors, area	108 m ²
Photovoltaic panels, 240 m ²	34 kWp

3.3.3 Case study: Solallén – normalising measured energy use

As mentioned in the introduction in this chapter, it is important that predicted energy performance is actually achieved during the user stage. One way to overcome and to identify actual performance gaps is to normalise the measured energy use. In Sweden, the building regulations (Boverket, 2018a) require verification of energy performance by calculations in the design stage and by measuring the energy use in the user stage. The measured energy use should be normalised according to a specific provision called BEN (Boverket, 2017). BEN includes two different methods for normalisation of measured energy use—static normalisation and dynamic normalisation.

The static normalisation is carried out in four steps, including the effect of hot water use, deviating indoor temperature, deviating internal loads and deviating external climate. The static normalisation is graphically summarised in Figure 3.12, and it follows Equation 3.8.

$$E_{norm} = E_{meas,DHW} - E_{corr,DHW} + \frac{E_{meas,SH} \cdot TAF + E_{meas,C} - E_{corr,IL}}{OCD} + E_{aux}$$

Equation 3.8

where

E_{norm}	Normalised energy performance
$E_{meas,DHW}$	Measured energy use for domestic hot water (excluding energy losses for hot water circulation)
$E_{corr,DHW}$	Normalise term for domestic hot water (Equation 3.9)
$E_{meas,SH}$	Measured energy use for space heating
TAF	Normalise factor for deviating indoor temperature (Equation 3.11)
$E_{meas,C}$	Measured energy use for cooling
$E_{corr,IL}$	Normalise term for deviating internal loads (Equation 3.12)
OCD	Normalise divisor for deviating outdoor climate (Equation 3.13)
E_{aux}	Measured auxiliary energy use, e.g. fans, pumps, elevators

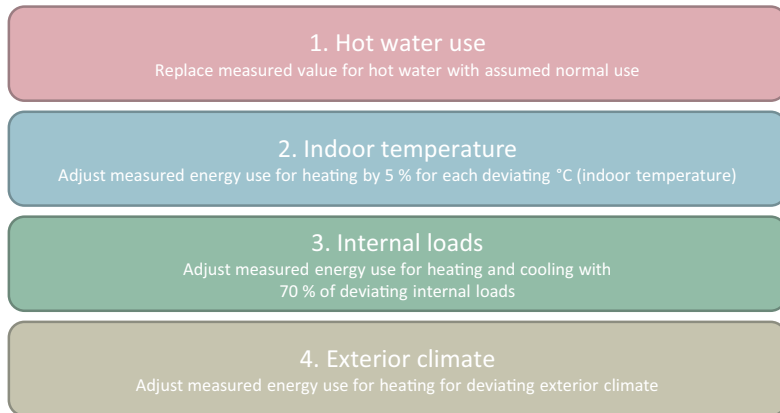


Figure 3.12 Summary of static normalisation, according to the Swedish national board of planning and housing (Boverket)

The first step of static normalisation is related to hot water use, see Equation 3.9.

$$E_{corr,DHW} = E_{\alpha,DHW} - E_{meas,DHW} \quad \text{Equation 3.9}$$

where

$E_{\alpha,DHW}$ Normal energy use for domestic hot water
 $E_{meas,DHW}$ Measured energy use for domestic hot water

If $E_{meas,DHW}$ is measured including energy losses for hot water circulation, Boverket requires that 25% of the energy use for domestic hot water heating should be assumed to be energy losses due to hot water circulation. These energy losses are expected to heat the building and should, therefore, be included in space heating energy. If domestic hot water is measured by volume, $E_{meas,DHW}$ may be calculated according to Equation 3.10.

$$E_{meas,DHW} = \frac{V_{DHW} \cdot 55}{SCOP_{DHW}} \quad \text{Equation 3.10}$$

where

V_{DHW} Measured volume hot water use (m³)
 $SCOP_{DHW}$ Seasonal coefficient of performance for hot water heating

The second step of static normalisation is related to indoor temperature (see Equation 3.11).

$$TAF = 1 + (T_{\alpha} - T_{meas}) \cdot 0.05 \quad \text{Equation 3.11}$$

where

T_{α} Normal indoor temperature
 T_{meas} Measured indoor temperature

The third step of static normalisation is related to internal loads (see Equation 3.12).

$$E_{corr,IL} = \frac{(E_{\alpha,IL} - E_{meas,IL}) \cdot I_h}{SCOP_{heating/cooling}} \quad \text{Equation 3.12}$$

where

$E_{\alpha,IL}$	Normal energy use for plug loads and lighting
$E_{meas,IL}$	Measured energy use for plug loads and lighting
I_h	Share of internal loads assumed to affect the heating or cooling
$SCOP$	Seasonal coefficient of performance for space heating and space cooling

According to Boverket, $E_{corr,IL}$ is applied/used if energy for plug loads and lighting deviates more than 3 kWh/m²a. Furthermore, they recommend that I_h may be assumed to be 70% when adjusting energy use for heating. No recommendation is given for the adjustment of cooling.

The fourth and final step relates to deviating exterior climate. Boverket recommends normalisation by using the method of energy index (SMHI, 2017a) from SMHI (SMHI, 2017b). The energy index, OCD_{EI} (see Equation 3.13), gives a weighted adjustment divisor based on outdoor temperature, solar radiation and wind.

$$OCD_{EI} = \frac{EI_{meas}}{EI_{\alpha}} \quad \text{Equation 3.13}$$

where

EI_{meas}	Measured heating degree days, adjusted for solar radiation and wind
EI_{α}	Normal heating degree days adjusted for solar radiation and wind.

It is also allowed to normalise the measured energy use based on repeated simulation. This means that the initial simulation, carried out during the design phase, is repeated with updated conditions regarding the actual use of the building and the exterior climate. The ratio between the first and second simulations is used as a factor for normalisation. Boverket states that the initial simulation and the repeated simulation has to be carried out in the same way. Furthermore, they clarify that technical parameters, such as quantities of insulation, etc., must not be changed and that this method of normalisation is only allowed when actual use (plug loads, lighting, etc.) is verified.

A one-storey terraced house with three dwellings, Solallén, was used to test the normalisation methods described above (see Figure 3.13 and

Figure 3.14). Both static and dynamic normalisations were tested. The strategy for reaching a Net ZEB balance for the case study comprises a three-step approach. Firstly, the thermal losses were reduced in order to have a low heating demand. Secondly, a GSHP was chosen in order to lower the need for imported energy. Lastly, the building was equipped with PV panels on the roof facing south to generate sufficient renewable energy in order to reach the Net ZEB balance. The technical description is summarised in Table 3.5.



Figure 3.13 Solallén. Left: layout of the house; right: facade towards the south



Figure 3.14 Photo of Solallén. Facade towards south

Table 3.5 Summary of technical description of case study, Solallén. All values are design values except for air tightness

Type of Data/Description	Value
Conditioned area	258m ²
Indoor air volume	667 m ³
Enclosed area/indoor air volume	1.11 m ⁻¹
Enclosed area/conditioned area	2.88
Window area/wall area	0.19
Foundation, 300-mm insulation, U-value	0.11 W/m ² K
Exterior wall, 455-mm insulation, U-value	0.09 W/m ² K
Roof, 500–600 mm insulation, U-value	0.07 W/m ² K
Windows and doors, U-value	0.90 W/m ² K
Total thermal bridges/enclosed area	0.02 W/m ² K
Measured air tightness (q ₅₀ /n ₅₀)	0.21l/s, m ² / 0.84 h ⁻¹
Ventilation heat recovery	90%
Ventilation specific fan power	1.5 kW/(m ³ /s)
Geothermal heat pump, SCOP _{heating}	3.0
Photovoltaic panels, 66 m ²	10 kW _p

As the static normalisation from Boverket does not give instructions regarding how to normalise solar energy, normalisation was carried out using a divisor, as defined in Equation 3.14.

$$E_{corr,solar} = \frac{G_{meas,solar}}{G_{\alpha,solar}} \quad \text{Equation 3.14}$$

where

$G_{meas,solar}$ Measured global solar radiation
 G_{α} Normal global solar radiation

The normalisations were done on both a monthly and a yearly basis, and the results are presented in Figure 3.15. Before normalisation, the measured energy use for a GSHP was 12% higher compared to simulation. After static normalisation, the corresponding values are 5% and 7% for yearly and monthly normalised values, respectively. After dynamic normalisation, the corresponding value is 1% for both yearly and monthly normalisation. The measured energy from the PV panels was 17% higher compared to the simulation. After static normalisation, the corresponding value was 6% for both yearly and monthly normalised values; and, after dynamic normalisation, the corresponding value is 5% for both yearly and monthly normalised values.

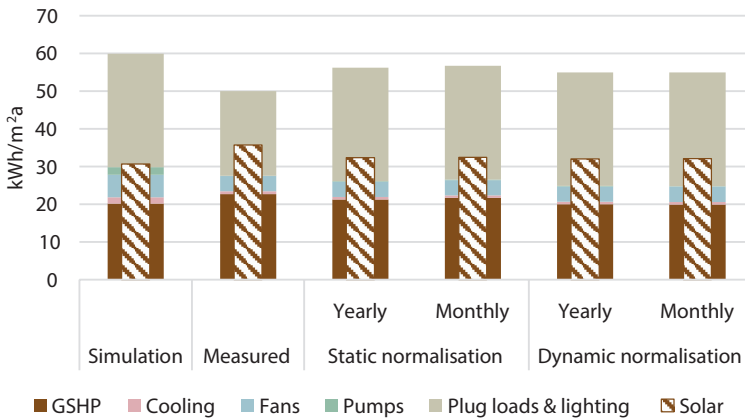


Figure 3.15. Results from simulations and measurements together with static and dynamic normalisation

Examining existing literatures which investigate different input parameters related to the user stage of the building show that there are a large set of parameters which may affect the energy use in the user stage. These parameters may be divided into three main groups— operation adjustments, user behaviour and exterior climate.

“Operation adjustments” is defined as parameters which may be affected by an organisation or person which/who are responsible for the operation of the building. Examples of operation adjustments may be adjusting set point temperatures, operation time for ventilation, etc. In existing literature, changing the set point for indoor temperature by 1°C may affect the energy use for heating by 7-40% and cooling by 25-33%.

“User behaviour” is defined as parameters which may be affected by the users of the building. Examples of parameters may be occupancy presence, airing, use of electronic equipment, etc. In existing literature, the share of energy use which may affect the energy use for heating varies between 35-90%.

“Exterior climate” is defined as parameters which relate to the exterior climate, temperature, relative humidity, wind, solar radiation, etc.

3.4 Embodied energy and environmental impact

As mentioned in the introduction in this chapter, the relative share of EE will increase as the total life cycle energy, LCE, decreases when the operational energy use, OE, decreases.

Today, no international definition of EE exists. To ensure transparency, the international guidelines may be used, EN ISO 14040 and EN ISO 14044 (Swedish Standards Institute, 2006a, 2006b), where LCE analysis or other life cycle analysis, LCA, is reported. Furthermore, the European norm, EN 15978, may be used to assess the environmental performance of buildings (Swedish Standards Institute, 2011).

The total LCE of a building may be divided into the following:

- Initial embodied energy, EE_i ,
where EE_i includes the initial embodied energy within a material or a product plus the energy used for transportation and assembly on site
- Recurring embodied energy, EE_r ,
where EE_r includes energy within materials and processes due to renovation and refurbishments

- Operating energy, OE,
where OE is the energy consumed to maintain the desired indoor environment in a building
- Demolition energy, DE,
where DE is the energy required to demolish the building and to transport materials to a land fill or recycling centre. The quantities of energy recycled should be subtracted from DE

The European norm EN 15978 divides the life cycle into more fractions compared to the more general breakdown described above. A comparison of the European norm and the breakdown presented above is presented in Figure 3.16.

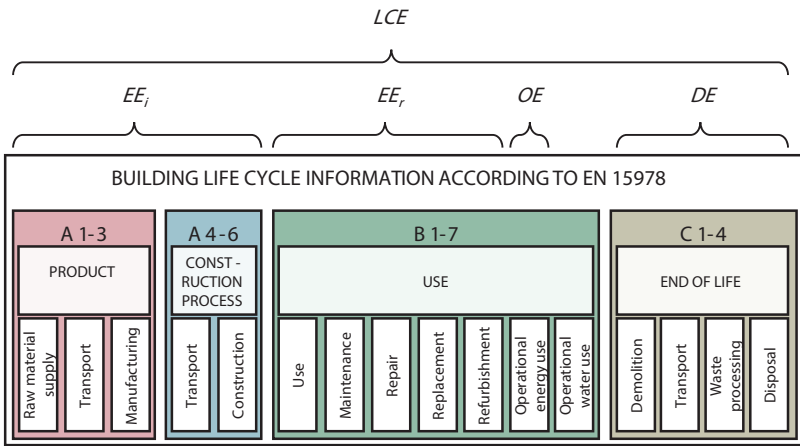


Figure 3.16 Comparison of general breakdown of LCE and fractions defined in EN 15978

Figure 3.17 shows the relationship between OE and LCE based on 154 gathered case studies. All data from the case studies were normalized into kWh/m²a. Only data based on primary energy were used, and all energy use related to building operation was included in OE. However, primary energy factors used were not always presented, and it was not always clear whether the data were in total primary energy or non-renewable primary energy.

The relationship between OE and LCE is almost linear. This data correspond previous studies (Ramesh, Prakash, & Shukla, 2010; Sartori & Hestnes, 2007). Low energy buildings and Net ZEBs usually require more material in the form of insulation and installations (PV panels, solar thermal collectors, heat pumps, etc.). Hence it could be logical to assume that

the linear relationship between OE and LCE would flatten out. However, the tendency is that the linear relationship is constant. This may be due to that design and construction in Net ZEBs and/or nZEBs has a focus on sustainable material management.

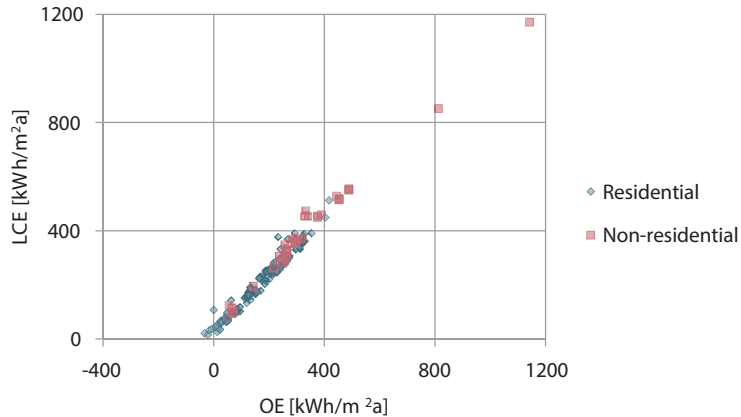


Figure 3.17 Relationship OE and LCE, primary energy, for 154 case studies.

In Figure 3.18, case studies with $OE > 100 \text{ kWh/m}^2\text{a}$ are excluded, and the relationship between the OE and the embodied energy as percentage share of LCE are shown. As there are no case studies for non-residential buildings where $OE \leq 0 \text{ kWh/m}^2\text{a}$, data for a fictitious building is incorporated.

Using the exponential regression formulas presented in Figure 3.18, the embodied energy exceeds 50% of the life cycle energy use when the annual operating energy use is $\leq 33 \text{ kWh/m}^2\text{a}$ and $\leq 45 \text{ kWh/m}^2\text{a}$ for residential and non-residential buildings, respectively. It may appear odd that embodied energy as a share of life cycle energy exceeds 100% when the operating energy $< 0 \text{ kWh/m}^2\text{a}$. But this effect is due to buildings that annually supply more energy than the annual energy demand generating a surplus each year and, thus, reducing the total life cycle energy use.

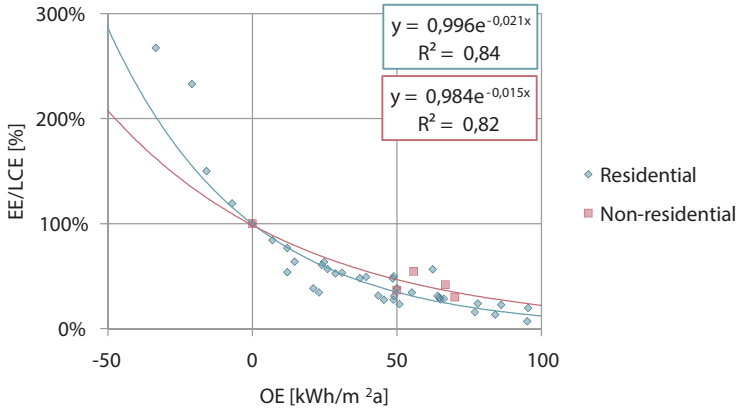


Figure 3.18 Relationship between OE and EE/LCE

As highlighted in EN 15978, the assessments of environmental performance of buildings are, to a large extent, based on predicted use of the building in the user stage; e.g. quantities of energy delivered to the building, energy generation, maintenance, demolition, etc.

A large part of the environmental impact is related to energy delivered to the building during the user stage. This is commonly considered by calculating the weighted demand, applying different weighting factors for different types of energy carriers. A European parametric analysis was conducted for six different case studies using different weighting factors and different energy supply options (Noris et al., 2014). Table 3.6 and Table 3.7 show a summary of the different weighting factors from different countries, and Table 3.8 and Table 3.9 summarise the case studies and the different energy supply options considered by said case studies, respectively.

Table 3.6 Quasi-static weighting factors for EU electricity in 2010 and 2050 in carbon equivalent emissions (g CO_{2-e}/kWh). The first line represents each month, and second and third lines represent emissions in 2010 and 2050, respectively.

J	F	M	A	M	J	J	A	S	O	N	D
378	377	367	349	342	346	350	345	354	357	370	377
49	51	41	18	12	13	15	13	18	23	40	46

Table 3.7 Static and symmetric weighting factors for primary energy (PE) and carbon equivalent emissions (CO_{2-e})

Energy carrier	DK	E	D	S	EN
					15603
Electricity					
PE [-]	2.5	2.6	2.6	2.7	3.14
CO ₂ [gCO ₂ /kWh]	505	649	633	360	617
Gas					
PE	1	1.1	1.1	1.1	1.36
CO ₂	204	240	244	250	277
Biomass					
PE	1	0	0.2	0.2	0.09
CO ₂	0	0	41	50	14

Table 3.8 Summary of case studies

Case study	Location	Building type	Gross floor area (m ²)
Kleehäuser	Freiburg, D	Residential	2 965
EnergyFlexHouse	Taastrup, DK	Residential	216
Glasbruket	Malmö, S	Residential	703
Die Sprösslinge	Monheim, D	Nursery	1 218
Circe	Zaragoza, E	Office and labs	1 700
Väla Gärd	Helsingborg, S	Office	1 670

Table 3.9 Summary of different energy supply options. HP=Heat pump, CHP= Combined heat and power generation, PV=Photovoltaic panels

Case study	Energy supply				
	HP (SCOP)	Gas boiler (%)	Biomass boiler (%)	CHP (%)	PV (%)
Kleehäuser	4.3	94	67	36e/51t	15.0
EnergyFlexHouse	3.5	98/107	90	NA	15.5
Glasbruket	3.5	95	90	NA	14
Die Sprösslinge	4.3	94	67	36e/51t	15
Circe	3.5	98	88	30e/40t	15
Väla Gärd	3.0	95	90	NA	14

Table 3.10 summarizes, for all case studies, which energy supply option would be most favoured under the different weighting options. Bio is the most preferred solution, and two aspects are interesting to highlight. Firstly, the fact that Bio is the preferred energy supply raises questions regarding whether, in the context of EPBD implementation, the low weighting factors chosen for biomass are in line with sustainability of forest and agriculture. Furthermore, this energy supply option is not always possible to choose in urban areas. Secondly, when the future emission scenario is applied (EU 2050), heat pump is the most preferred energy supply, which raises the question whether we should already use scenario data when we evaluate different options, as we, otherwise, may base our decisions on weighting factors which do not consider the future energy grid.

Table 3.10 Summary of different energy supply options. N=National weighting, EN=EN 15603

Case study	Weighting option					
	Primary energy		Carbon emissions			
	N	EN	N	EN	EU 2010	EU 2050
Kleehäuser	Bio	Bio	Bio	Bio	Bio	HP
EnergyFlexHouse	Bio	Bio	Bio	Bio	Bio	HP
Glasbruket	HP	Bio	Bio	Bio	Bio	Bio
Die Sprösslinge	Bio	Bio	Bio	Bio	Bio	HP
Circe	Bio	Bio	Bio	Bio	Bio	Bio
Väla Gård	Bio	Bio	Bio	Bio	Bio	HP

Studying the effect of the environmental impact from a Nordic perspective, a parametric analysis was conducted for a single family house (SFH) and a multi dwelling building (MDB) (Erlandsson, Sandberg, Berggren, Francart, & Adolfsson, 2018). Both houses were evaluated with an energy performance according to the Swedish building regulations and an energy performance class of A and C according to SS 24300-2:2012 (Swedish Standards Institute, 2012). A summary of the case studies is presented in Table 3.11.

Table 3.11 Summary case studies

Abbreviation	Type of building	Energy supply	Energy class
SFH1A	Single family house	Heat pump	C
SFH1B	Single family house	District heating	C
SFH2A	Single family house	Heat pump	A
SFH2B	Single family house	District heating	A
MDB1A	Multi dwelling building	Heat pump	C
MDB1B	Multi dwelling building	District heating	C
MDB2A	Multi dwelling building	Heat pump	A
MDB2B	Multi dwelling building	District heating	A

The global warming potential (GWP) due to energy use in the user stage is calculated based on four different methods, which are described in short below:

- GWP1: Attributional LCA without time-dependent accounting
I.e. static and symmetric weighting factors, Nordic grid.
- GWP2: Attributional LCA with time-dependent accounting.
I.e. dynamic weighting factors, hour-by-hour, Nordic grid.
- GWP3: Consequential LCA without substitution effect.
I.e. dynamic weighting factors, hour-by-hour.
Import/export from/to the Nordic grid is not included.
- GWP4: Consequential LCA with substitution effect.
I.e. dynamic weighting factors, hour-by-hour.
Import/export from/to the Nordic grid is included.

Furthermore, the analysis is carried out both for the energy supply in the grid today (2015) and future scenario (2050).

In Figure 3.19 and Figure 3.20, energy performance and GWP is presented based on energy supply in the grid today. The figures clearly illustrate that the choice of method has a great impact on the calculated GWP. Based on GWP1 and GWP2, SFH2A and MDB2A constitute to slightly less GWP compared to the other buildings, and, based on GWP3 and GWP4, SFH2B and MDB2B are more favourable. Differences between GWP1 and GWP2 are low; i.e. using dynamic weighting factors based on attributional LCA seem to have a low effect.

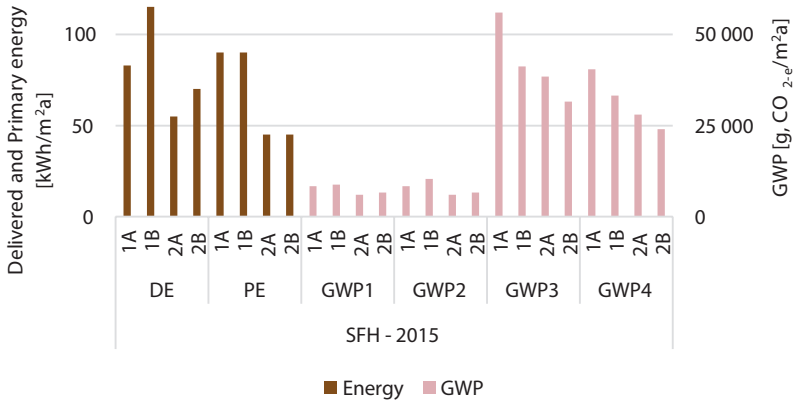


Figure 3.19 Energy performance and GWP for different SFHs and calculation methods based on energy supply in the grid today (2015)

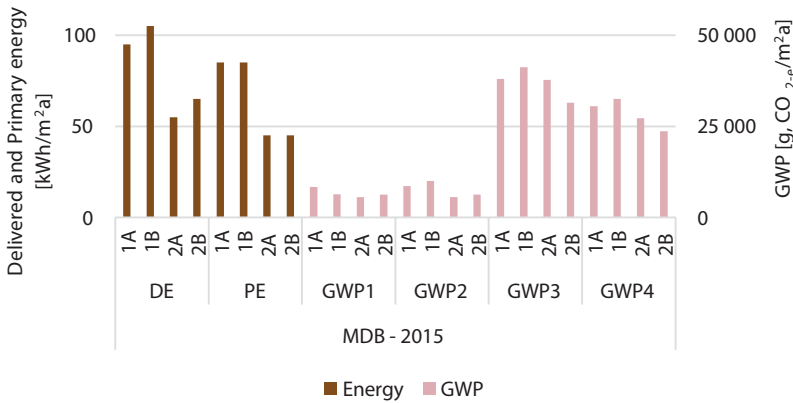


Figure 3.20 Energy performance and GWP for different MDBs and calculation methods based on energy supply in the grid today (2015)

In Figure 3.21 and Figure 3.22, energy performance and GWP is presented based on future scenario of energy supply in the grid. Also, here, the figures clearly illustrate that the choice of method has a great impact on the calculated GWP. It should also be noted that the GWP is considerably

lower, especially for GWP4. SFH2A and MDB2A show the lowest GWP regardless of method for calculating GWP.

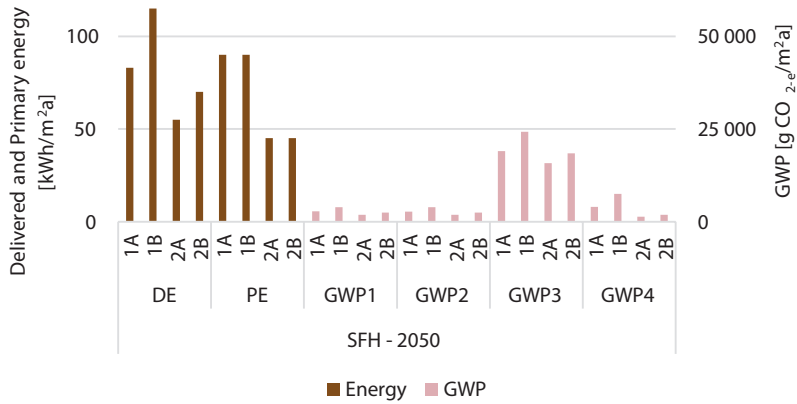


Figure 3.21 Energy performance and GWP for different SFHs and calculation methods based on a scenario for energy supply in the future grid (2050)

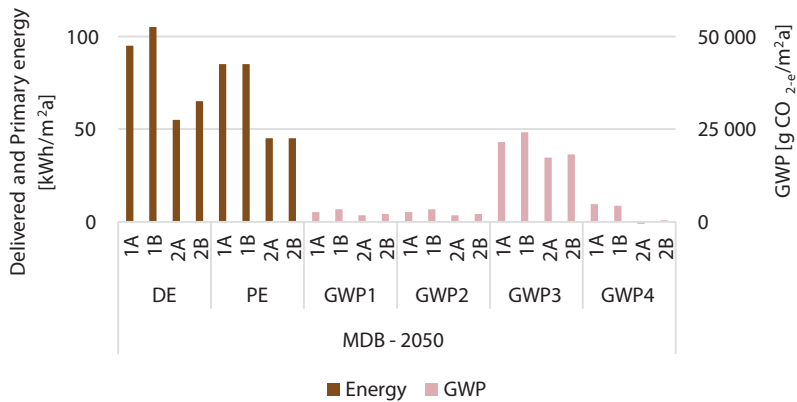


Figure 3.22 Energy performance and GWP for different MDBs and calculation methods based on a scenario for energy supply in the future grid (2050)

3.5 Discussion and conclusions

3.5.1 Thermal bridges in building envelopes

Regarding energy performance of building envelopes, the relative share of transmission heat transfer due to thermal bridges increases when the heat resistance is increased. However, the case studies show that it is possible to design and construct buildings where the relative impact of thermal bridges is low.

The surveys show that there is still a large spread among consultants related to how they choose to quantify a building envelope. As several consultants are typically involved in the design phase, there is a risk for misunderstandings, which may, in severe cases, result in calculation errors over 30%, creating undersized/oversized heating systems and energy use in the user stage far from expected. An increased use of Building Information Modelling may result in more standardized and automatic ways to gather input data. However, this may also be a source of error if data from models are used by users who do not fully understand the software, e.g. how a wall area is defined, etc.

The trend towards simplifications and increased use of percentage factors to consider thermal bridges are worrying. Reviewing recent research in the field, they mainly discuss the impact of thermal bridges in relative terms. As the results show, the impact from thermal bridges may be below 10% and above 30%. It should, therefore, not be recommended to use relative terms in energy calculations and sizing of heating and cooling systems for buildings. Still, an overwhelming majority of the research fails to include information related to which measuring method was applied when they present their results. This underlines the need to increase knowledge and compliance related to standards among researchers, reviewers and editors.

The surveys were carried out among Swedish engineers and architects, and the results should, therefore, be viewed from that perspective. From a more global perspective, it would be beneficial to carry out a global survey based on the survey used here.

3.5.2 Energy performance of (Net-zero energy) buildings

Regarding energy performance of buildings, the case studies show that is possible to build Net ZEBs with technologies available on the market today. Väla Gård and Glasbruket highlight the complexity of load match and grid interaction. In a Nordic climate, it is difficult to achieve a high load

match unless it is based on a yearly resolution. More recent research has investigated and defined more LMGI-indicators (Dávi, Caamaño-Martín, Rütther, & Solano, 2016; Lindberg et al., 2016; Salom, Marszal, Widén, Candanedo, & Lindberg, 2014). One example of an indicator which may be useful is the LOLP indicator, which describes the percentage of time that the local generation covers the building load.

3.5.3 Verification of energy performance

Measurement and verification of energy performance in the user stage is important, and measured values should be normalised in order to clarify whether energy use in the user stage is due to different conditions or actual performance failures. Normalisation due to changes in the actual use of the building show greater impact compared to normalisation due to deviating exterior climate.

There are a large number of parameters that affect a building's energy performance, and the static method from Boverket does not fully take all these parameters into account. However, the static method from Boverket is the most complete method identified during this work. Regarding dynamic normalisation, there is much work needed to clarify this method because, if the method is allowed to be vague, there is a big risk that different stakeholders will apply and use the method differently.

Detailed measurements and follow-ups of buildings in the user stage may not only gain experiences related to energy performance; it may also give important knowledge related to how specific products behave under certain temperatures, user patterns etc. Detailed measurements and verification in the user stage are important.

3.5.4 Embodied energy and environmental impact

Regarding embodied energy and environmental impact, it becomes growingly important to not only consider the user stage when Net ZEBs or similar buildings are designed. In conventional buildings, the environmental impact from the user stage dominates the environmental impact. However, in Net ZEBs, the impact from the user stage is very low, and, consequently, the relative impact from the product and construction stages is dominant. Taking the step from a conventional building to a Net ZEB shows a small increased impact in the product and user stages. However, the increased impact is very small compared to the reduced impact in the user stage.

The conclusions above are also highlighted in more recent research. Case studies and reviews show that environmental impact from the user

stage dominates in conventional buildings (Cellura, Guarino, Longo, & Mistretta, 2015; Chastas, Theodosiou, & Bikas, 2016; Chau, Leung, & Ng, 2015; Stephan & Stephan, 2016). Net ZEB case studies show that the relative impact from the product and construction stages is dominant (Chastas et al., 2016; Georges, Haase, Houlihan Wiberg, Kristjansdottir, & Risholt, 2015). Case studies also highlight the effect of different weighting factors, methods and/or scenarios for future environmental impact from energy use in the user stage (Cellura et al., 2015; Chau et al., 2015; Georges et al., 2015).

Common for all calculations and investigations presented—regardless if it is energy performance of building envelopes, buildings' energy performance or a life cycle assessment—is the need to clearly state the boundary conditions when the results are presented, as they may have a major impact on the results.

4 Moisture performance

This chapter presents four different models for assessment of risk of mould growth, studied in CP VIII, CP X and CP XI. After an introduction, the different models are presented. Two of the models have been used to analyse the effect of increased insulation in exterior wooden walls.

4.1 Introduction

As mentioned in the introduction, the building sector in Sweden has a rather long history of moisture-related damages, which may have negative effects on appearance, indoor environment and durability, e.g. mould, bad smell and adhesives losing their performance. Furthermore, human health may be adversely affected.

The costs related to moisture-related damages are substantial. Calculations made by Boverket in 2010 conclude that the costs for remediation of Swedish moisture related-damages existing in residential buildings would be close to 100 billion Swedish crowns (Boverket, 2010a). A more recent study by Boverket estimates that costs for defaults and defects in buildings in the user stage—most commonly, water and moisture related—amount to 5-6% of the production costs in Sweden, corresponding to roughly 20 billion Swedish crowns per year (Boverket, 2018b). Hence, there are both economic and health-related arguments to take moisture performance into account for buildings and building envelopes.

When the term “EP” is used in relation to buildings, it generally refers to energy use related to a conditioned area, as once defined in the EPBD. However, the definition of “moisture performance” is not that clear, as use of this term may refer to the hygrothermal characteristics of a specific building component or material. It may also refer to the risk of performance failure due to exceeding a critical hygrothermal condition. There is no international or European standard for assessing and presenting moisture performance.

When the Swedish building regulations were changed in accordance with EPBD, changes were also made in regulations related to hygiene,

health and environment. In short, the new regulations advised that moisture levels within a building component should be lower than the critical moisture level. Furthermore, if the critical moisture level was not well investigated and documented, a relative humidity (RH) of 75% should be used as a critical moisture level. Initially, these requirements were interpreted by many in the construction industry, as the RH in a construction layer containing organic material was not allowed to exceed 75% RH at any time. As 75% RH is a rather strict demand and moisture related damage is very much not only dependent on RH but also on temperature and duration, there is a need to evaluate risks by considering all of these parameters.

In Sweden, wood is easily available and, as shown in Chapter 2 related to the Swedish dwelling stock, there is a tradition of wooden constructions in buildings, especially for one- and two-dwelling buildings.

In this chapter, results from examining four different models for assessment of the risk of mould growth are presented. Three of the models have been developed in Sweden: the “Dose-model” developed at Lund university (Isaksson, Thelandersson, Ekstrand-Tobin, & Johansson, 2010); the “m-model” developed at Skanska Sverige AB (Tengberg & Togerö, 2010; Togerö, Tengberg, & Bengtsson, 2011); the “Hagentoft-method” developed at Chalmers University (Hagentoft, 2010). The fourth model is a plug-in to the software WUFI Pro (Fraunhof-Institut für Bauphysik, 2012) called WUFI Bio.

Two of the models have been used to analyse the effect of increased insulation in exterior wooden walls.

4.2 Models for investigating risk of mould growth

The Dose model is based on the critical time, t_{ms} , for the onset of mould growth (Level 1) for different climate conditions (constant time) based on response time for mould growth spine and spruce sapwood (Viitanen, 1997), as defined in Equation 4.1.

$$t_{ms} = \exp(-0.74 \ln T - 15.53 \ln RH + 75.736) \quad \text{Equation 4.1}$$

where

t_{ms}	Critical time for onset of mould growth (n, days)
T	Temperature (°C)
RH	Relative humidity (%)

By choosing a reference climate as $T_{ref}=20^{\circ}\text{C}$ and $RH_{ref}=90\%$, mould is, in theory, initiated after 38 days. The total mould dose, D , is then described as in Equation 4.2-4.5 below. Input data for calculations are daily averages.

$$D_n = \sum_1^n D_{RH}(RH) \cdot D_T(T) \quad \text{Equation 4.2}$$

where

D_n Dose after n days

D_{RH} Dose component based on RH , defined in Equation 4.3

D_T Dose component based on temperature, defined in Equation 4.4

$$D_{RH} = \exp \left[15.53 \cdot \ln \left(\frac{RH}{90} \right) \right] \quad \text{for } 75 < RH \leq 100$$

$$D_{RH} = \left(-2.7 + \frac{1.1RH}{30} \right) \quad \text{for } 60 < RH < 75 \quad \text{Equation 4.3}$$

$$D_{RH} = -0.5 \quad \text{for } RH < 60$$

$$D_T = \exp \left[0.74 \cdot \ln \left(\frac{T}{20} \right) \right] \quad \text{for } 0.1 \leq T \quad \text{Equation 4.4}$$

$$D_T \cdot D_{RH} = -0.5 \quad \text{for } T < 0.1 \quad \text{Equation 4.5}$$

where

RH Relative humidity (%)

T Temperature ($^{\circ}\text{C}$)

Negative “doses” are added when conditions for mould growth is unfavourable, i.e. when RH is below 60% or T is below 0.1°C . The accumulated mould dose, D_n , never falls below zero. To calculate the relative dose, the accumulated dose may be divided with the reference climate for which mould, in theory, is initiated, i.e. in this case, 38 days. Mould is, in theory, initiated when the relative mould dose ≥ 1 .

The m-model was originally developed at Skanska Sverige AB to assess and compare different design solutions with respect to the risk of mould growth. The m-model is similar to the Dose Model, as the model also is based on calculating the critical time for when mould, in theory, is initiated. However, the m-model calculates in shorter time steps—one to three hours—and uses six different duration curves for which mould, in theory, is initiated, as shown in Figure 4.1.

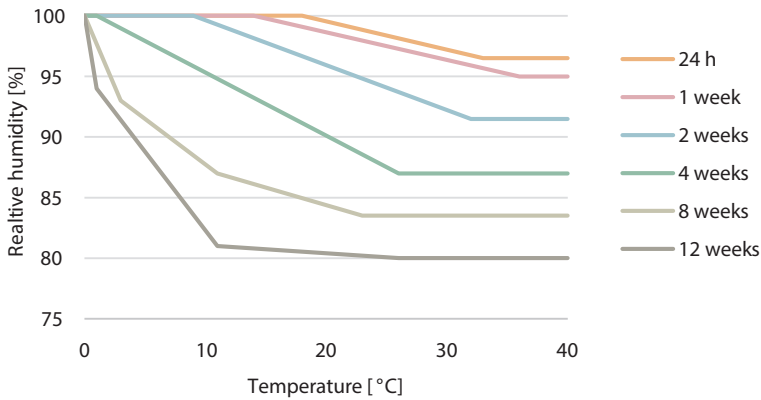


Figure 4.1. Different critical moisture levels for wood (Togerö et al., 2011)

At each time step, m is calculated according to Equation 4.6 for all six critical duration curves.

$$m_{DC} = \frac{RH(t)}{RH_{crit}(T(t))\gamma} \quad \text{Equation 4.6}$$

where

- m_{DC} Parameter, m , for each duration curve, DC (-)
- $RH(t)$ Relative humidity at time, t (%)
- $RH_{crit}(T(t))$ Critical relative humidity at temperature, T , and time, t (%)
- T Temperature (°C)

If $m \geq 1$, conditions for mould growth have occurred in one time step. All time steps where $m \geq 1$ are summarized separately for each duration curve and constitute the accumulated risk time. The m -model considers dehydration according to Equation 4.7 and 4.8.

$$m_{DC\ reduced} = \beta \cdot \sum m_{DC} \quad \text{Equation 4.7}$$

where

- β Retardation factor according to Equation 4.8.

$$\begin{aligned}
\beta_{m_{24h}} &= \left(\frac{\overline{RH}}{RH_{crit}} \right)^{4.5} & \text{for } \frac{RH}{RH_{crit}} < 1 > 6 \text{ h} \\
\beta_{m_{1w,2w,3w}} &= \left(\frac{\overline{RH}}{RH_{crit}} \right)^{1.7} & \text{for } \frac{RH}{RH_{crit}} < 1 > 168 \text{ h} \\
\beta_{m_{8w,12w}} &= \left(\frac{\overline{RH}}{RH_{crit}} \right)^{1.2} & \text{for } \frac{RH}{RH_{crit}} < 1 > 168 \text{ h} \\
\beta_{m_{all}} &= 0 & \text{for } \frac{RH}{RH_{crit}} < 1 > 504 \text{ h}
\end{aligned}
\tag{Equation 4.8}$$

where

\overline{RH} Average relative humidity

\overline{RH}_{crit} Average critical relative humidity

I.e. if RH is below RH_{crit} for >6 hours, the accumulated m_{24h} is reduced, multiplying m_{24} by $\beta_{m_{24h}}$. If RH is below RH_{crit} for >168 hours, the accumulated m_{1w} , m_{2w} and m_{3w} is reduced, multiplying m_{1w} , m_{2w} and m_{3w} by $\beta_{m_{24h}}$, etc. Averages of RH and RH_{crit} are only used to calculate β , not to define if unfavourable conditions have occurred.

The accumulated risk time for each duration curve is divided with the critical risk time, and the quota is called critical duration quota (CDQ). Mould will, in theory, be initiated when $CDQ \geq 1.0$.

A straightforward and simplified method for risk assessment was introduced at the 3rd Nordic Passive House Conference 2010 (Hagentoft, 2010). The model uses a non-dimensional temperature factor, ξ , to calculate the relative humidity at any point in a construction, as shown in Equation 4.9.

The model may be used for static and/or quasi-static analysis. When the relative humidity is calculated, it may be compared to the critical relative humidity for the material in the investigated point.

$$RH = \frac{v_e + \Delta v}{v_s(T_e + \xi \cdot (T_i - T_e))} \tag{Equation 4.9}$$

where

RH Relative humidity (%)

v_e Outdoor humidity by volume (g/m^3)

Δv Local moisture supply (g/m^3)

v_s Saturation vapour content for the temperature T (g/m^3)

T_e External/outdoor temperature ($^{\circ}\text{C}$)

T_i Interior/indoor temperature ($^{\circ}\text{C}$)

ξ Relative temperature factor (-)

In addition to the software WUFI Pro, a plug-in to assess the risk of mould growth is available—WUFI Bio. This model is different from the models described above in which whether the conditions have been favourable or unfavourable was investigated. WUFI Bio uses a hypothetical mould spore, which is given the characteristics for sorption of water and diffusion of water vapour. If the water content within the mould spore exceeds critical levels, mould growth is initiated. The pace of mould growth is related to the level water content. The model was developed in the beginning of the 2000s (Sedlbauer, 2001, 2003). The result of the evaluations is presented on a seven-point scale, presented in Table 4.1.

Table 4.1 Mould index (Viitanen & Ritschkoff, 1991)

Index	Description
0	No mould growth
1	Some mould growth, visible under microscope
2	Moderate mould growth, visible under microscope – coverage >10%
3	Growth detected visually, thin hyphae found under microscope
4	Visual coverage of mould growth >10%
5	Visual coverage of mould growth >50%
6	Visual coverage of mould growth 100%

4.2.1 Case study: Risk of mould growth in exterior wall

A case study was conducted for an exterior wooden wall construction. The case study investigated takes the step from a wall with standard amounts of insulation to a wall with low thermal transmittance, comparing two different approaches:

- Decreasing the thermal transmittance by increasing the amount of insulation on the interior side of the load bearing structure—w1 in Figure 4.2
- Decreasing the thermal transmittance where insulation is added on both sides of the load bearing structure—w1 and w2 in Figure 4.2

The different cases are summarised in Table 4.2.

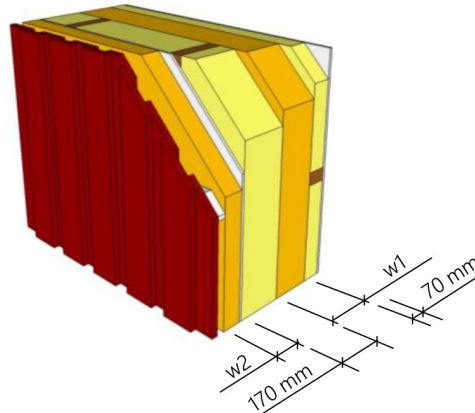


Figure 4.2 Description of wall used in the case study

Table 4.2 Different external walls in the different cases studies (w_1 and w_2 are according to Figure 4.2)

Case	Description		
Base line	$w_1=0$ mm	$w_2=0$ mm	$U=0.17$ W/m ² K
Scenario 1.1	$w_1=70$ mm	$w_2=0$ mm	$U=0.13$ W/m ² K
Scenario 1.2	$w_1=0$ mm	$w_2=70$ mm	$U=0.13$ W/m ² K
Scenario 2.1	$w_1=220$ mm	$w_2=0$ mm	$U=0.09$ W/m ² K
Scenario 2.2	$w_1=145$ mm	$w_2=70$ mm	$U=0.09$ W/m ² K

The maximum CDQ and accumulated dose, calculated using the m- and Dose-models, respectively, are presented in Figure 4.3. The chosen point of investigation is the interior side of the wind barrier.

The analysis shows that adding insulation in moderate quantities on the interior side of the load bearing construction (Scenario 1.1) increases both the CDQ and accumulated mould dose. If more insulation is added on the interior side (Scenario 2.1), $CDQ > 1$, which means that mould growth is theoretically initiated, and the accumulated mould dose also increases. However, the accumulated dose is below 38 days; i.e. mould growth is not initiated, according to this model.

If insulation is added on the exterior side of the load-bearing construction (Scenario 1.2), both the CDQ and the accumulated mould dose decreases. When more insulation is added on the interior side after adding insulation on the exterior side (Scenario 2.2), the CDQ is slightly

increased, and the accumulated mould dose is slightly decreased, compared to the base line.

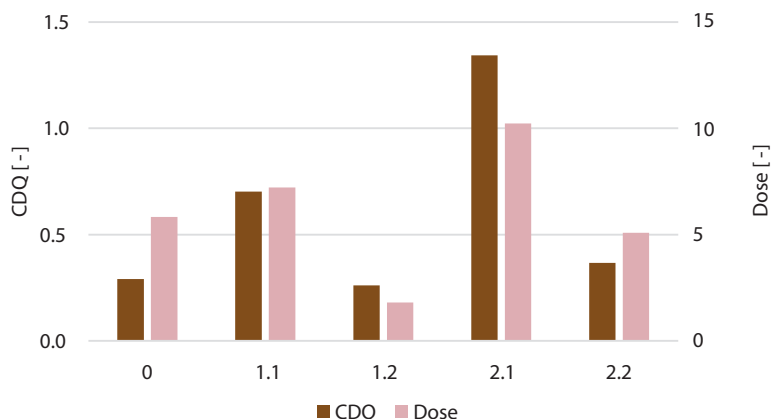


Figure 4.3 Maximum CDQ and accumulated mould dose for the different wall assemblies

4.3 Discussion and Conclusions

The case study shows that it is possible to increase the amounts of insulation in a wooden construction without increasing the risk for mould growth. However, it is important to point out that the case study, of course, has specific boundary conditions. In other words, the case study does not claim to show that a certain construction will suffer from mould growth or not. It does, however, show that, by applying simple measures, it is possible to substantially reduce the risks of mould growth. The importance of boundary conditions—indoor and outdoor climate—is also pointed out in a thesis from Lund University (Mundt-Petersen, 2015), which highlights that mean or standard outdoor climate boundary conditions should not be used.

Four different models have been investigated in this section. However, a thorough literature review conducted in Norway (Gradeci, Labonnote, Time, & Köhler, 2017) has identified six additional mould models. The review concludes that humidity, temperature, time/duration and material are the most important factors to consider, and the largest difference between the different models are found in relation to time. Differences are found related to time step, assessment of duration and fluctuating condi-

tions. The Norwegian review also concludes that, despite the advancement within computation, mould models and design, there is a continuous flow of reports on mould growth problems in the building industry.

The m-model, originally developed by Skanska, has recently been thoroughly tested with data from both laboratory and field measurements (Johansson, Wadsö, Johansson, Svensson, & Bengtsson, 2018). The results, overall, confirm that the results from the m-model, in general, are true to reality. The model has also been programmed in MATLAB and is made freely available (Fuktcentrum, 2018).

It is not only wood that may suffer from performance failure due to moisture. Critical moisture levels for onset of mould growth for ten commonly used building materials were published in 2012 (Johansson, 2012). The results show that wood, in general, is affected by mould growth before other common building materials, such as insulation, gypsum boards, etc. Furthermore, performance failure may not only appear in the form of mould growth. Problems with swelling and shrinking, carbonation, corrosion, etc. may also occur for different materials (Nilsson, 2006a). In general, these problems usually occur after mould growth is initiated. Consequently, evaluation of the risk of mould growth is important, as it is likely to be the first performance failure that may appear.

5 Possible effects of mould growth due to climate change in Sweden

This chapter presents results from investigating the increased risk for mould growth based on climate scenario data, investigated in CP X and CP XI. After an introduction, the major findings are presented, followed by discussion and conclusions.

5.1 Introduction

There are a number of boundary conditions needed in order to evaluate the energy and moisture performance of a building or its elements. As buildings have a long lifespan, it is necessary to consider the future climate when conducting evaluations. There are different methods to generate future climate data for simulations and estimations of building performance in respect to climate change. These may be divided into four groups, from simple to complex: extrapolating statistical methods, imposed offset methods, stochastic weather models and climate models (Guan, 2009).

The extrapolating statistical method, also called the degree-day method, has the benefits of being simple and fast. However, it has been proven to be fairly coarse and often not suitable as input data for simulations (Guan, 2009).

The imposed offset method bases the climate data on a typical year, meteorological (TMY) or reference (TRY). Known parameters that are expected to be affected by climate change are adjusted by offsetting the parameters based on the results from climate models. This method has been used in many studies and has the benefit that it can be used even if changes of some parameters are unknown (Cox, Drews, Rode, & Nielsen, 2015; Jiang, Zhu, Elsafty, & Tumeo, 2018).

Stochastic weather models have the benefit of being possible to use if climate scenario data is not available. However, the method has difficulties in accurately modelling several climate variables (Guan, 2009).

Using data from a regional climate model (RCM) has the benefit of being physically consistent data, and there is no need to apply modification methods (Nik, Sasic Kalagasidis, & Kjellström, 2012b). However, RCMs are not always available.

Climate models are used to simulate and produce climate scenario data which are not weather forecasts. The climate scenarios answer the question, “If the atmosphere is changing in a certain way, how will the climate change?” As input, the climate models use emissions scenarios from IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000) or Representative Concentration Pathways (RCPs) (IPCC, 2014), which describe different greenhouse concentration scenarios. RCPs replaced SRES in 2014, but SRES may still be used; for example, in publicly available climate scenario data from the Swedish Metrological Institute (SMHI) (SMHI, 2018).

In this chapter, the risk of performance failure in a building construction due to mould growth based on possible future climate scenario is investigated, using the four different evaluation models for mould growths, presented in Chapter 4.

5.2 Investigations based on future data generated with imposed offset method

To generate future climate scenario data for simulations, the imposed offset method was applied. Climate scenario data were obtained for four different locations in Sweden, based on the scenario A1B, with monthly resolution for the period 1985-2098 (SMHI, 2012). The locations are given in Figure 5.1. The A1B scenario represents a future world of very rapid economic growth, rapid introduction of new and more efficient technologies, relying both on fossil and non-fossil energy sources and a global population that peaks in mid-century and declines thereafter (IPCC, 2000).

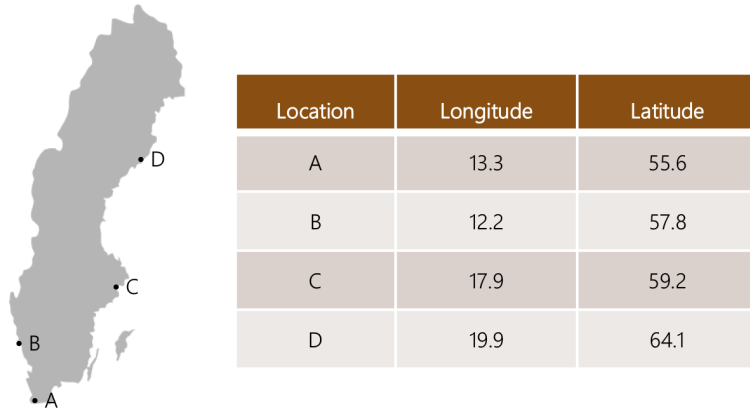


Figure 5.1 Geographical presentation of locations included in the study

The same type of walls as included in the case study for risk of mould growth in Chapter 4 were used. However, only the baseline and the alternatives with most insulation were included, i.e. one exterior wall construction with standard amounts of insulation, $U_c=0.17 \text{ W/m}^2\text{K}$, and two alternative wall constructions with more insulation, $U_c=0.09 \text{ W/m}^2\text{K}$. The wall constructions are presented in Figure 5.2.

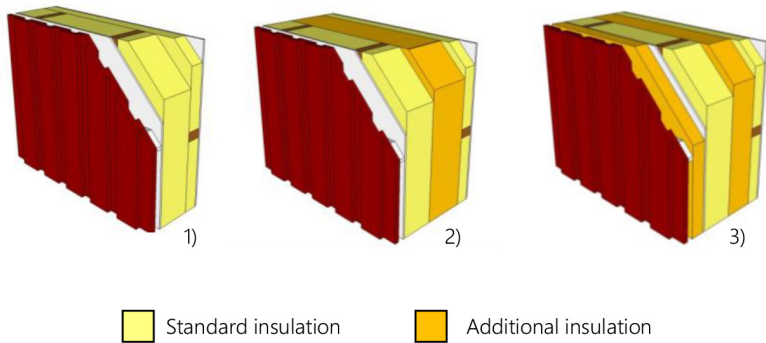


Figure 5.2 Alternative 1 - Standard wall constructions. Alternative 2 – Additional insulation on the interior side of the wood frame construction. Alternative 3 – Additional insulation on the exterior and interior side of wood frame construction

Hygrothermal simulations was conducted using the numerical software WUFI Pro 5.1 1D (Fraunhof-Institut für Bauphysik, 2012). To analyse the risk for mould growth, data for RH and temperature at the interior side of the wind barrier were extracted from WUFI Pro 1D and analysed, using the Dose- and m-models. Furthermore, the position was also evaluated using WUFI Bio based on Substrate Class 1, which corresponds to building products made out of biologically degradable materials. To enable detailed analysis using the Hagentoft model, all constructions were 3D-modeled in HEAT 3 6.0 (Blocon Sweden, 2011), and monthly averages from climate scenario data were used. The same position as for the other models was examined.

Due to limitations in computing power, the investigated period was divided into time series of three years, i.e. 1985-1987, ..., 2096-2098, and, for or each series, the highest CDQ, relative mould dose, mould index and RH in relation to RH_{crit} is presented.

The investigation was carried out in two steps. As a first step, all walls were investigated for all locations. As a second step, the two most unfavourable locations were further investigated, investigating the effect of less built-in moisture and increased driving rain penetration.

Results from the first step are presented in Figures 5.3-5.6. Numbers represent the studied wall assemblies (1-3, according to Figure 5.2). Letters represent geographical location (A-D, according to Figure 5.1).

Overall, the risk of mould growth increases over time due to climate change, and the most unfavourable climate is at locations A and B.

When compared to all other results, data from 2B analysed with an m-model show a decreasing risk for mould growth for future climate scenarios. The reason for this has not been determined.

Using the Dose-model to analyse the hygrothermal conditions, the conditions for mould growth is increasing over time regardless of location and construction. The increase is more evident at Location B, and adding more insulation to the exterior side of the wood frame construction clearly reduces the conditions for mould growth at this location; the mould dose decreases when comparing 1B and 3B even though more insulation is used in the construction. At the most northern location, D, the relative mould dose is always ≤ 1 , regardless of type of wall assembly.

The CDQ, calculated using the m-model, shows similar results as the Dose-model. The conditions for mould growth increase at all locations and constructions except for 2B. However, the risk for mould growth is the highest in 2B. At the more northern latitudes, C and D, CDQ is always ≤ 1 , regardless of construction chosen and examined year.

The analysis based on WUFI Bio also shows that conditions for mould growth is increasing over time regardless of location and construction. The effect of external insulation at Locations A and B is lower compared to the

results shown using Dose- and m-models. In Locations C and D, mould index is usually <1 , regardless of wall assembly.

The Hagentoft model also shows increased risk of mould growth over time based on the climate scenarios. Furthermore, it indicates that exterior insulation is preferable in Location A but has little effect on other locations.

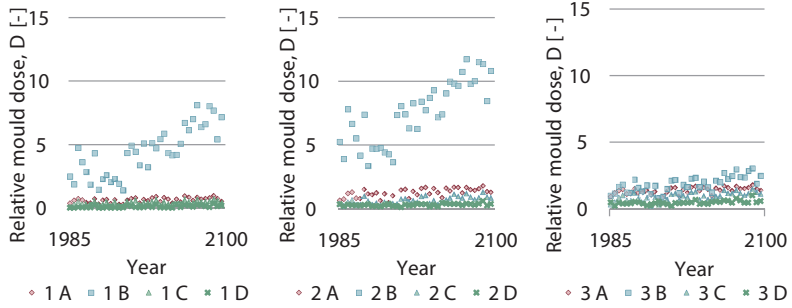


Figure 5.3 Evaluation of hygrothermal conditions using the Dose-model

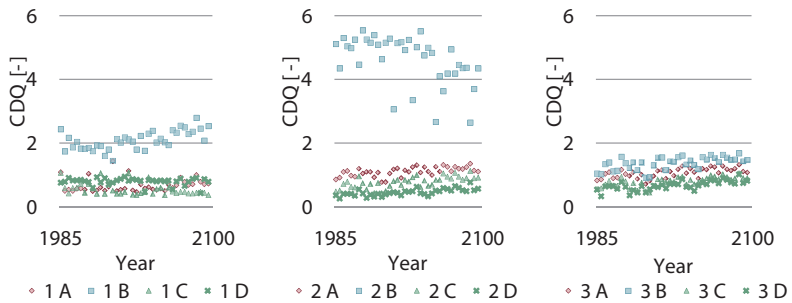


Figure 5.4 Evaluation of hygrothermal conditions using the m-model

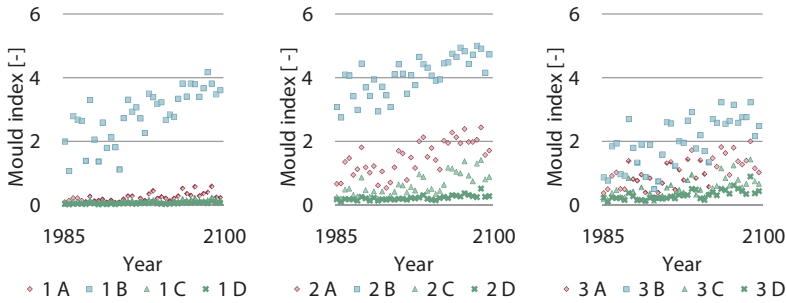


Figure 5.5 Evaluation of hygrothermal conditions using WUFI Bio

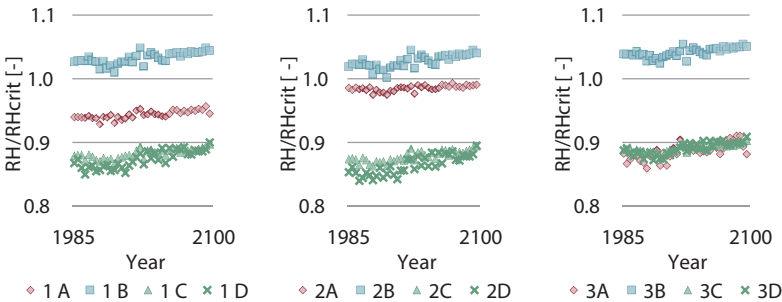


Figure 5.6 Evaluation based on the Hagentoft model

Results from the second step are presented in Figures 5.7-5.9. Numbers represent the studied wall assemblies (1-3, according to Figure 5.2), and letters represent geographical location (A-D, according to Figure 5.1). The Hagentoft model is not used in this step.

Using the Dose-model to analyse the hygrothermal conditions, the conditions for mould growth decrease when built-in moisture is reduced and increase when rain penetration is increased. The effect is most evident for 3B, and, when built-in moisture is reduced, the relative mould dose is ≤ 1 for both 3A and 3B.

The m-model shows similar results as the Dose-model. Reducing built-in moisture shows a greater impact for 2A compared to results from the Dose-model. Furthermore, when rain penetration is increased, some results for 3B show higher risk of mould growth compared to 2B. This result is not seen when the data is analysed using the Dose-model.

Using WUFI Bio results in a very clear indication that using external insulation and keeping the built-in moisture to a minimum is favourable. Comparing 3B, with low built-in moisture, a very low mould index is shown as with 1B and 2B. WUFI Bio also indicates (as when the m-model was used) that external insulation may result in higher risk for mould growth if the rain penetration is high.

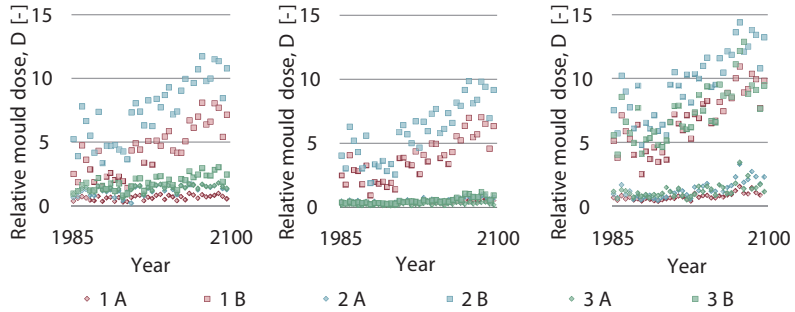


Figure 5.7 Evaluation of hygrothermal conditions using the Dose-model. Left - Base case; middle - minimizing built-in moisture; right - minimizing built-in moisture and increased driving rain penetration

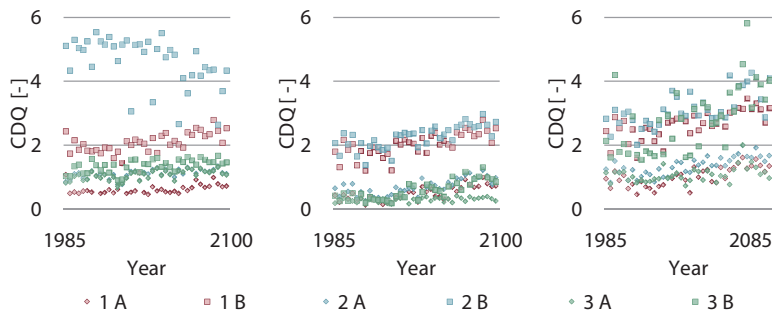


Figure 5.8 Evaluation of hygrothermal conditions using the m-model. Left - base case; middle - minimizing built-in moisture; right - minimizing built in moisture and increased driving rain penetration

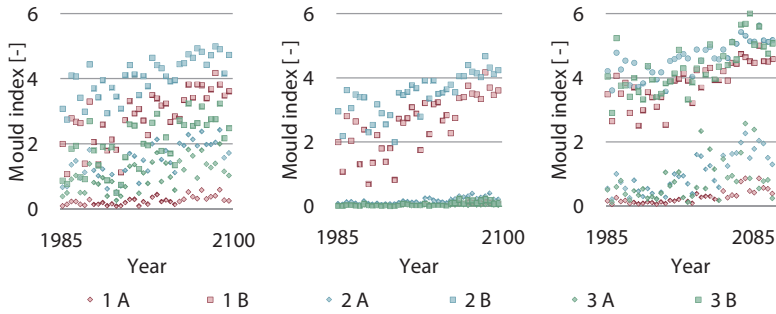


Figure 5.9 Evaluation of hygrothermal conditions using WUFI Bio. Left - base case; middle - minimizing built-in moisture; right - minimizing built-in moisture and increased driving rain penetration

5.3 Discussion and conclusions

These results are based on one climate scenario, but several other climate scenarios exist. Furthermore, a climate scenario is not a forecast, i.e. it is not showing expected climate conditions. However, a similar study investigating the risk for mould growth in attics in Sweden showed slight difference between different climate scenarios (Nik, Sasic Kalagasidis, & Kjellström, 2012a).

The results show an increased risk of mould growth considering the ongoing climate change according to the climate scenario used. The above-mentioned study, which investigates Swedish attics with different climate scenarios, and more recent studies show similar results (Bylund Melin, Hagentoft, Holl, Nik, & Kilian, 2018; Nik, 2017; Nik & Arfvidsson, 2017; Sehizadeh & Ge, 2016). As buildings are expected to have a long lifespan, climate change should be considered in the design of buildings and building elements.

Construction materials based on biodegradable materials, e.g. wooden studs, should always be given exterior insulation to decrease the risk of mould growth. However, poor assembly, i. e. enabling driving rain to penetrate exterior walls, most likely at junctions, may actually increase the risk for mould growth.

As can be seen, reducing built-in moisture has a positive effect, decreasing the risk for mould growth. Hence, measures to decrease the amount of moisture added in the construction stage should always be considered.

The simulations conducted in this investigation were time consuming, as they included climate scenario data for 115 years at 4 different location. In two of the more recent studies mentioned above (Nik, 2017; Nik & Arfvidsson, 2017), three representative one-year data sets, including both typical and extreme weather, were used. Using this methodology would substantially reduce simulation time. Furthermore, these studies show that the extreme years have a greater impact compared to a typical year, which further underlines the conclusion made in the thesis mentioned in Chapter 4 (Mundt-Petersen, 2015), which highlights that mean or standard outdoor climate boundary conditions should not be used in simulations.

As also mentioned in Chapter 4, other problems in addition to mould growth may occur. As an example, one of the studies mentioned above highlights that climate change may cause swelling and shrinking of wood, resulting in permanent damage in historical buildings (Bylund Melin et al., 2018).

6 Added values in green buildings

This chapter presents results from investigating co-benefits, which may occur in green buildings, which were studied and applied on two case studies in CP XIII and CP XVI. After an introduction, methods to quantify the co-benefits are presented and applied on two case studies.

6.1 Introduction

Net ZEBs are usually also “green buildings”, which, here, are referred to as buildings with high performance within the aspects of energy, thermal comfort, indoor air quality, building materials, etc. To design and construct buildings with additional insulation, more energy-efficient HVAC systems, etc. are usually coupled to increased investment costs. Despite that construction of Net ZEBs has been proven possible, it may be difficult to justify investments in these solely based on cost savings related to energy savings. The Swedish law, Planning and Building Act (2010:900) (Sveriges Riksdag, 2018b), was changed in 2015, prohibiting municipalities in Sweden to set tougher energy requirements than the requirements in the national building regulations. The law was changed based on a Swedish Government Official Report, “Bygghkravsutredningen” (Regeringskansliet, 2012), which concluded that incurring additional costs of 10-15% were unprofitable. However, other studies and evaluations estimates the additional costs to be 0-10% (Janson, 2010; Nordling & Carlsson, 2013; Sveriges Centrum för Nollenergihus, 2012) in order to design and construct buildings with significantly better energy performance than in the mentioned official report (Regeringskansliet, 2012).

A narrow concept and a short time perspective for evaluating profit, only focusing on increased investment costs and decreased energy costs, may be wrong from both a strict business perspective and from a socio-economic perspective.

This chapter, therefore, investigates and presents different co-benefits, which may be expected in green buildings such as Net ZEBs. Furthermore, methods to quantify the co-benefits are presented and applied on two case studies.

6.2 Co-benefits in two case studies

Quantifying added value in green buildings in monetary terms, except for energy savings, may be complex. The calculation procedure in itself may not be complex, but the research on green buildings and environmental and green benefits is still in its early stage. Still, it is important to quantify added value in green buildings in monetary terms, communicating and presenting business opportunities in a business language that potential investors are familiar with, as technical performance is less likely to attract their interest (Bleyl et al., 2017).

Studies which may be used as a basis for analysing added values do exist. Studies mainly based on questionnaires show that employees in green buildings may perceive a positive effect of their work environment and productivity (Bleyl et al., 2017; Hedge, Miller, & Dorsey, 2014; Singh, Syal, Grady, & Korkmaz, 2010; Thatcher & Milner, 2014). In two of these studies, reduced absenteeism is also found (Singh et al., 2010; Thatcher & Milner, 2014); and one American study showed that roughly 20% of 534 tenants/companies perceived higher employee morale, more effective client meetings, ease in recruiting employees and lower employee turnover after moving to a green office (Miller, Pogue, Gough, & Davis, 2009).

In addition to well-being and productivity, higher revenues from rent or sales may be expected. A review in Austria concluded that higher rent income may range roughly in between 5% and 20%, and higher market valuations may range from below 10% to up to 30% in green offices (Bleyl et al., 2017).

The value of a positive news article about a specific building or a specific project could also be comparable to advertising costs in the specific source in which the article is published.

One way to structure different co-benefits may be to rank them as presented in Figure 6.1. The classification is based on subjective judgement, highlighting the relevance and the difficulty to value the co-benefits discussed above. As can be seen, many of the highlighted co-benefits in the studies mentioned above have high relevance for a business case but may be perceived as difficult to quantify.

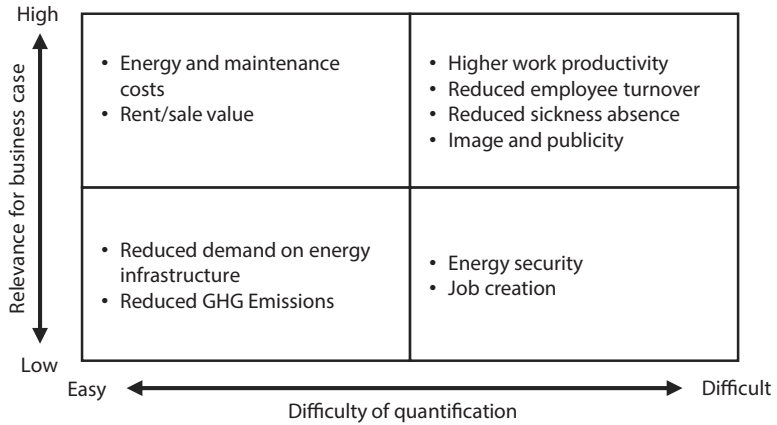


Figure 6.1 Co-benefits classifications, based on (Bleyl et al., 2017)

The profitability of the increased costs related to increased energy efficiency and green co-benefits related to the building were evaluated for two of the case studies described in Chapter 3: Väla Gård and Solallén. The increased costs for production were compared to the value of energy efficiency and green co-benefits, quantified as described below.

Quantification of energy efficiency is described in Equation 6.1, which summarize the net present value of reduced energy costs (REC).

$$REC = \sum \frac{EI \cdot \alpha + EE \cdot \beta}{\left(1 + \frac{r - i - \gamma}{1 + i + \gamma}\right)^t} \quad \text{Equation 6.1}$$

where

- REC* Reduced energy costs
- EI* Reduced imported energy
- α Energy tariff for *EI*
- EE* Increased exported energy
- β Energy tariff for *EE*
- r* Nominal discount rate (%)
- i* Inflation rate (%)
- γ Increase in energy tariffs (%)
- t* Time

In order to widen the economic concept, the net present value of five additional values may be quantified according to Equations 6.2-6.6: reduced employee turnover costs (RETC), reduced sickness absence costs (RSAC), increased productivity value (IPV), public publicity value (PPV) and reduced sickness absence salary (RSAS). Equations 6.1-6.5 were used for Väla Gård, the office building, and Equation 6.1 and 6.6 were used for Solallén, the residential building.

$$RETC = \sum \frac{\varepsilon \cdot Emp(RC + IC + RPC + LI + DC)}{(1 + R)^t} \quad \text{Equation 6.2}$$

where

<i>RETC</i>	Reduced employee turnover costs
ε	Reduced employee turnover (%)
<i>Emp</i>	Quantity of employees
<i>RC</i>	Recruitment cost per employee
<i>IC</i>	Introduction course for new employee
<i>RPC</i>	Reduced productivity cost (new employee and supervisor)
<i>LI</i>	Lost income during vacancy
<i>DC</i>	Decommissioning cost
<i>R</i>	Discount rate, as presented in Equation 6.7.

$$RSAC = \sum \frac{Emp \cdot 0.8SC \cdot \phi \cdot \kappa}{(1 + R)^t} \quad \text{Equation 6.3}$$

where

<i>RSAC</i>	Reduced sickness absence costs
<i>SC</i>	Salary costs
ϕ	Average sickness absence
κ	Reduced sickness absence (%)

Other symbols as described in previous equations. The reason for the reduction of the salary in Equation 6.3 is due to that wageworkers in Sweden usually get only 80% of their salary when they are on sick leave (Sveriges Riksdag, 2018c).

$$IPV = \sum \frac{Emp \cdot SC \cdot IP}{(1 + R)^t} \quad \text{Equation 6.4}$$

where

IPV Increased productivity value
IP Increased productivity per employee (%)

Other symbols as described in previous equations.

$$PPV = \sum AIP \cdot AC \quad \text{Equation 6.5}$$

where

PPV Public publicity value
AIP Article in press
ACA Advertising costs in the specific source

$$RSAS = \sum \frac{WW \cdot 0.2S \cdot \phi \cdot \kappa}{(1 + R)^t} \quad \text{Equation 6.6}$$

where

RSAS Reduced sickness absence salary
WW Quantity of wageworkers
S Salary

Other symbols as described in previous equations.

$$R=(r-i)/(1+i) \quad \text{Equation 6.7}$$

where

R Discount rate (%)
r Nominal discount rate (%)
i Inflation

In Solallén and Väla Gård, productivity, sickness absence, etc. were not measured. In order to enable quantification of green values, input data regarding reduced employee turnover, reduced sickness absence and increased productivity were based on previous studies presented above and on Swedish literature and databases.

Increased costs for the case studies, to achieve their green and Net ZEB targets, were gathered from the project managers in each project. Improved energy performance is based on the verified energy performance in the user

stage. For all input data except investments and energy performance, base case data were defined together with a best and worst cases.

Increased costs in Väla Gård amounted to 268 €/m², an increase of roughly 11% of costs compared to if the office would have been a “normal office”; and, in Solallén, increased costs amounted to 164 €/m², an increase of roughly 8% of costs compared to if it would have been a “normal residential building”. In Väla Gård, a state grant was given for PV panels, equal to 49 €/m² floor area. In Solallén, a municipal discount on land was given, equal to 92 €/m² floor area.

The accumulated discounted value for the cost reductions in Väla Gård and Solallén, normalised by the conditioned area, is presented in Figure 6.2. For both buildings, four different scenarios were considered. The traditional scenario includes increased costs for production and the value of reduced energy costs, and the other scenarios include value of co-benefits quantified as described above.

Results show that, for Väla Gård, in analysing the green investments in a traditional way, the investments were not profitable if the calculation period was ≤ 20 years. A period of 35 years would need to be considered in order to reach a break even. However, including green co-benefits, a period of 3-9 years would be enough to reach breakeven.

As the green co-benefits are fewer in Solallén compared to Väla Gård, the difference between the traditional scenarios and the other scenarios are smaller. In Solallén, a calculation period of 20 years would have to be considered to value the green investments as profitable. However, including green co-benefits, a period of 5-11 years would be enough to reach breakeven.

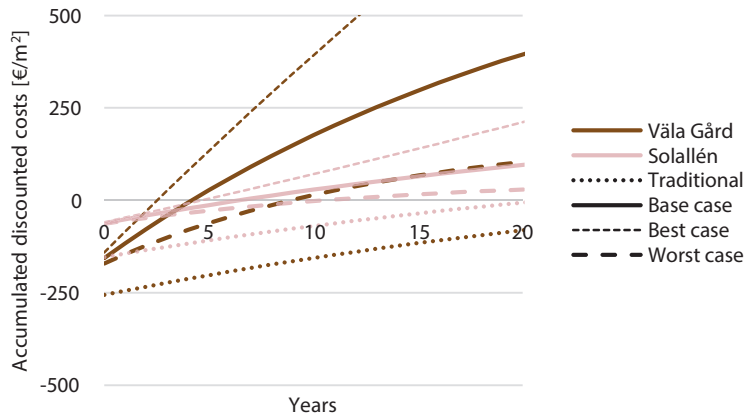


Figure 6.2 Accumulated value considering investments and green co-benefits

6.3 Discussion and conclusions

In the analysis of Våla Gård and Solallén, reduced employee turnover, reduced sick absence and increased productivity are based on assumptions, i.e. should not be mistaken for verified results. Furthermore, a recent study has pointed out that social factors may have a greater impact, in monetary terms, compared to environmental factors (Hugh & Eziaku Onyeizu, 2016). However, even if the value of green co-benefits are assumed to be low, it still has a great impact on the profitability. Furthermore, it would be possible to quantify more green co-benefits, which are not included here; e.g. increased value of building, less costs for moving/changing homes (if one is satisfied with its home, one should stay there for a longer time), etc.

In the previous studies mentioned in Section 6.1, co-incurring additional costs amount to 0-15%. Here, the corresponding value is 11% and 8% for Våla Gård and Solallén, respectively. Results showing increased costs of 0% are unlikely to be due to the lack of investment to achieve “green performance”. Most likely, these projects have prioritized “green investment” and saved money in other parts of the project. Thus, the projects have not become more costly than expected.

In this study, examples were shown of how green co-benefits could be quantified in monetary terms. The study shows that it may be very profitable to build green buildings if one accounts for green co-benefits. Furthermore, it may be easier to find it profitable in non-residential buildings.

However, more research should be done in order to further develop these methods and to gain more knowledge regarding reduced employee turnover, reduced sick absence, increased productivity, etc. in green buildings.

7 A model for evaluation

This chapter presents an overview of multi-criteria decision analysis followed by a proposed model which could be used by stakeholders in the construction and real estate industry to evaluate different options for their buildings, enabling informed decisions regarding their buildings for the entire life cycle. The model for evaluation was introduced in the licentiate thesis published in 2013 (Berggren, 2013).

7.1 Introduction

As shown in Chapters 3, 4 and 6, there are many different indicators that may be used to quantify a building or a building element, evaluating energy performance, moisture performance and green co-benefits. The indicators are expressed in different units, hence, creating a multi-criteria decision problem.

Multi-criteria decision analysis, MCDA—also known as multiple attribute decision-making (MADM) or multi-criteria decision-making (MCDM)—is often referred to as a quantitative approach assisting decision-making where there are multiple conflicting goals expressed in dissimilar units. This approach involves applying mathematics to support the decision-making; hereafter, in this thesis, referred to as MCDA.

Numerous studies have been conducted where different methods are evaluated and described. Examples may be found, including the Weighted Sum Method (WSM), the Weighted Product Method (WPM), the Analytic Hierarchy Process (AHP), the Complex Proportional Assessment (CO-PRAS), the Technique for Order of Preference by Similarity to Ideal Solution, (TOPSIS), etc. (Belton & Stewart, 2002; Huang, Chen, & Chang, 2015; Medineckiene, 2017; Mulliner, Malys, & Maliene, 2016; Schade, Olofsson, & Schreyer, 2011; Triantaphyllou, 2000), More examples and guidelines may be found, which also may help stakeholders to choose from the wide range of methods (ASTM International, 2016; Guitouni & Martel, 1998; Pohekar & Ramachandran, 2004; Roy & Słowiński, 2013).

It is important to highlight that there is no such thing as a “right answer” or an optimum within the concept of MCDA. It should, rather, be perceived as a working method which enables stakeholders to manage subjectivity and to integrate objective/quantitative and value judgement—thus, the many different methods and the need for guidelines. However, the benefit of MCDA is that it may increase the transparency of decision-making, enabling stakeholders to better understand the decision from their own and from others’ perspectives (Belton & Stewart, 2002).

Many environmental indicator systems use a form of MCDA, as this often enables stakeholders to find technical solutions that provide “the highest ranking”. This may seem contradictory to the statement above that there is no “right answer” or optimum. This is due to that many subjective decisions are already made within the environmental indicators systems, i.e. criteria and importance of these are defined and static.

The process of MCDA may be described differently and at different levels of detail. Overall, the MCDA process includes three phases (Mulliner et al., 2016; Triantaphyllou, 2000):

1. Determine alternatives and criteria
2. Preferences and aggregation
3. Process numerical values to determine a ranking

The first phase includes defining which alternatives are to be evaluated and which criteria the evaluation should be based on; e.g. different wall assemblies may be evaluated based on time, cost, etc.

Preferences refer to how criteria are valued; i.e. what indicator or indicators is/are used and how different levels of performance for each indicator is relatively valued. Aggregation refers to how the model allows all the criteria to be weighted into an overall rating or value. One criterion may have more than one indicator; e.g. time can be evaluated based on two indicators—production time at construction site and delivery time—which affects the long-term planning. This is illustrated as a “value tree”, presented in Figure 7.1.

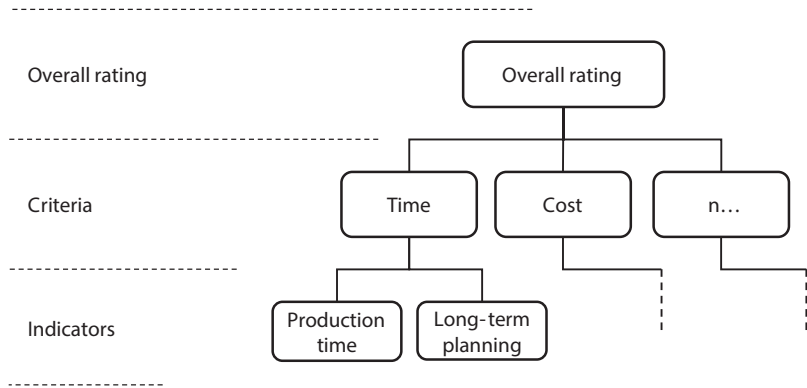


Figure 7.1 Schematic presentation of value tree

A rule-of-thumb may be that the indicators are stated in a way that enables an almost unambiguous assessment of the indicator. If this is not possible, the sub criterion should be broken down into a new set of more detailed sub criteria before broken down to indicators.

When a set of criteria are broken down to indicators, the relative value of the indicator needs to be defined; e.g. if wall assembly *a* takes three days to complete and wall assembly *b* takes six days to complete, how are these two alternatives valued relative to each other? Below, three basic methods are described.

The first method involves the fact that stakeholders define a best- and worst-accepted indicator. Based on these, it is assumed that indicators outperforming the best value have the same value as best value. Indicators below worst-accepted value are equal to zero. Values in between are assumed to have a linear distribution, this is presented graphically as Method 1 in Figure 7.2.

The second method involves defining one or several values in-between the accepted best and worst values. A possible effect of the two methods is graphically described in Figure 7.2.

Using the first method, the value decreases from 100% to 50% when the duration is increased by three days—from three days to six days. Using the second method, the duration only needs to be increased by roughly two days—from three to five days—to decrease the value to 50%. Examining the example, the second method, in this case, enables the stakeholder to

value time saving relatively low when the duration is long. Consequently, time savings when the duration is short are valued higher.

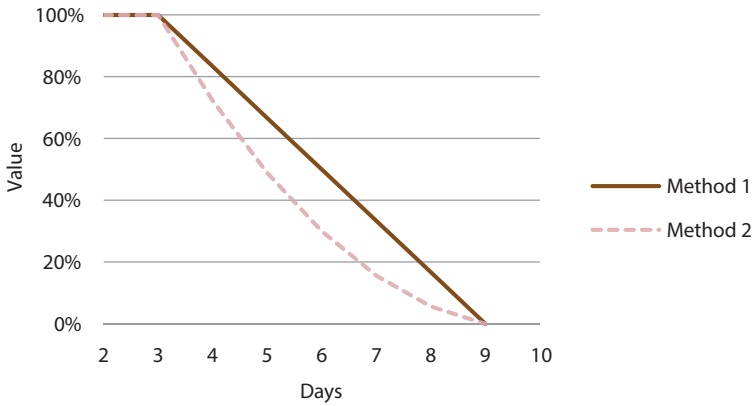


Figure 7.2 Value as a function of days to complete a wall assembly

The third method, based on the Analytic Hierarchy Process (AHP) and the standard ASTM E1765-16 (ASTM International, 2016), uses a matrix to enable pair wise comparisons. An explanation of the evaluation matrix based on the example described above is presented in Table 7.1.

Table 7.1 Matrix for pairwise comparison

		Indicator (days)		
		3	6	9
Indicator (days)	3	Excellent 1	Good Desirability of 3 over 6	Acceptable Desirability of 3 over 9
	6	Desirability of 6 over 3	1	Desirability of 6 over 9
	9	Desirability of 9 over 3	Desirability of 9 over 6	1

The desirability of three days over six days is defined by $3/6=0.5$, the desirability of three days over nine days is defined by $3/9=0.33$ and so on. If

decreasing values are preferred, all desirability indicators are inverted. The result of the calculations of desirability is presented in Table 7.2. Based on the matrix, three days are 3.00 times more desirable compared to nine days, six days is 1.50 times more desirable compared to nine days, etc. Using this method, no indicator will get a relative value of zero.

Table 7.2 Matrix with results from pairwise comparison

		Indicator (days)		
		3	6	9
Indicator (days)		Verbal expression		
		Excellent	Good	Acceptable
	3	1	2.00	3.00
	6	0.50	1	1.50
9	0.33	0.67	1	

In the case described above, the indicator is already given in a quantified value—days. However, the method may be used when comparing verbal expressions or different classes, such as A, B, C, D, etc.

In principle, there is no limitation to the size of the matrix system described above. However, ten levels may be considered as a practical maximum (Öberg, 2005).

Comparing the three methods, three days are valued twice as high compared to six days using the first method, almost three times as high using the second method and twice as high using the third method.

When all indicators are transferred into values, the overall value is aggregated. In its simplest form, this is done by summarising all values. However, a weighting factor may be preferred. Using weighting factors, the overall value may be calculated according to the WSM, as shown in Equation 7.1.

$$V(a) = \sum_1^i w_i v_i(a) \tag{Equation 7.1}$$

where

- $V(a)$ Total value of alternative a
- w_i Weighting factor for criterion i , for all alternatives
- v_i Relative value for criterion i , for alternative a

The weighting factors may be set subjectively or by using more structured methods. Two methods are described below.

One example of a method, sometimes referred to as the “swing weight method” (Belton & Stewart, 2002), is based on, firstly, identifying the indicator considered to be of greatest importance. Secondly, all other indicators are valued relative to the most important indicator. To translate the evaluation into numerical value, a predefined scale may be used as below:

- Equally important/The most important = 5
- Less important = 3
- Not so important = 1

Often, larger scales are used. Examples may be found in (Hastings & Wall, 2006; Schade et al., 2011; Öberg, 2005).

When all indicators are relatively valued towards the most important indicator, the weighting factor is defined by dividing the value by the sum of all indicators’ values; e.g. to define the weighting between indicator i_1 , i_2 , i_3 and i_4 , the indicator i_2 is identified as the most important indicator. The result of the relative evaluation and weighting factors are presented in Table 7.3.

Table 7.3 Relative evaluation of importance of indicators

Indicator	Numerical value	Normalised weighting factor
i_1	1	0.08
i_2	5	0.42
i_3	3	0.25
i_4	3	0.25

Using a scale with more steps may differentiate the values more than the result in Table 7.3. However, one shortcoming in using the swing weight method, is that indicators that are valued equally in relation to the most important indicator (in this case, i_3 and i_4) are not relatively valued towards each other.

Another example of a method uses an evaluation matrix, as presented in Table 7.1. Using the evaluation matrix, it is possible to evaluate all indicators relative towards each other. Based on the same example as above, an evaluation is presented in Table 7.4. In this case, i_3 is valued as less important than i_4 . The normalized eigenvector of the matrix calculates the priority, i.e. the weighting factor. As can be seen, there is now a relative difference between the indicators i_3 and i_4 .

Table 7.4 Relative evaluation of importance of indicators using pairwise comparison

	i_1	i_2	i_3	i_4	Priority (eigenvector)
i_1	1	1/5	1/3	1/3	0.08
i_2	5	1	3	3	0.51
i_3	3	1/3	1	1/3	0.15
i_4	3	1/3	3	1	0.27

This method is often referred to as the Analytic Hierarchy Process (AHP), presented in (Saaty, 1980). Within the EU-project InPro (InPro, 2010), the method was adopted and tested in a case study (Schade et al., 2011). The authors conclude that the method increases the transparency of decision making, and the client may become more involved in the decision-making in the design process.

7.2 The proposed model

7.2.1 Aggregation of indicators

The overall goal is to evaluate moisture and energy performance. Since there may be a large set of indicators to express one of these, an overall main criteria classification is used for which the indicators are sorted under, as presented in Figure 7.3. The setup of criteria and indicators is not static;

i.e. it is possible to vary the number of indicators used. Furthermore, it is possible to add more main criteria; e.g. co-benefits.

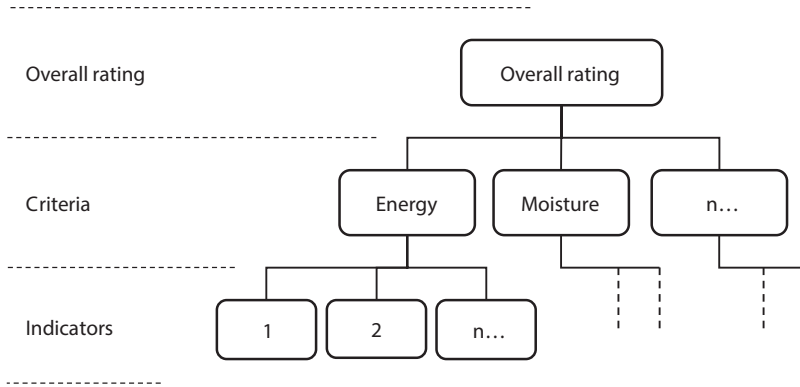


Figure 7.3 General value tree describing the proposed model

The aggregation of the indicators follows the WSM, and the weighting factors are set based on the AHP method, as described above.

Indicators are first sorted under each main criterion. Within each criterion, the indicators are pairwise-compared according to the scale presented in Table 7.5. The scale above is based on the “Saaty scale” (Saaty, 1980). The stakeholders may be shown the verbal scale or both the verbal and numerical scale. If the stakeholders hesitate between two alternatives, intermediate values may be used.

The relative importance between the different main criteria are defined in the same way. Finally, the weighting factor for each criterion is defined as the product of the relative importance of the criterion and the relative importance of the indicator.

Table 7.5 Grades used for weighting

Relative importance compared to second indicator	Grade
Equally important	1
More important	3
Much more important	5
Very much more important	7
Extremely more important	9
Less important	3 ⁻¹
Much less important	5 ⁻¹
Very much less important	7 ⁻¹
Extremely less important	9 ⁻¹

7.2.2 Valuation of indicators

To support the translation of the indicators into relative values, one of the two methods described below may be used, depending on the type of indicator and the preferences of the stakeholder.

Using the first method, stakeholders are asked to define levels that are consistent with the value judgements expressed in Table 7.6. The judgements are translated into the relative values presented in the table.

For the value judgement “excellent”, the value is set to 120%. This is done to indicate that excellent is outperforming what is actually required; i.e. a good or very good technical solution, fulfilling the requirements of the stakeholder, does not have to be the best possible solution.

Table 7.6 Values for indicators based on value judgement

Value judgement	Value
Excellent	120%
Very good	90%
Good	60%
Fair	30%
Not acceptable	0%

If stakeholders find the first method challenging to apply, the second method may be more suitable. First, a design target is set, which should not be equal to a best possible outcome; it should, rather, reflect the stakeholders' level of satisfaction. Secondly, the best possible outcome is defined, followed by the lowest accepted level. Finally, the threshold for "Not acceptable" is set. The judgements are translated into relative values, as presented in Table 7.7.

Table 7.7 Values for indicators based on design target approach

Value judgement	Value
Best possible outcome	120%
Design target	100%
Lowest accepted level	1%
Not acceptable	0%

Two possible outcomes, using the different methods, are presented in Figure 7.4. In this case, the indicator is energy performance based on load/generation balance; low/decreasing values are preferred.

Scenario 1, using Method 1:

- 1) "Poorer energy performance compared to the building regulations, 85 kWh/m²a, is *not acceptable*." Value = 0%
- 2) "Fulfilment of the energy performance set in the building regulations is *fair*." Value = 30%
- 3) "Reaching the energy performance similar to a passive house, 50 kWh/m²a, is *good*." Value = 60%
- 4) "Energy performance of 40 kWh/m²a is *very good*." Value = 90%
- 5) "Energy performance of 35 kWh/m²a is *excellent*." Value = 120%

Scenario 2, using Method 2:

- 1) "The *design target* is 40 kWh/m²a." Value = 100%
- 2) "However, *best possible outcome* is a Net ZEB." Value = 120%
- 3) "*Lowest accepted level* is 60 kWh/m²a." Value 1%
- 4) "Using more energy than allowed in the building regulations is *not acceptable*." Value = 0%

The effect of the different methods and scenarios is graphically presented in Figure 7.4.

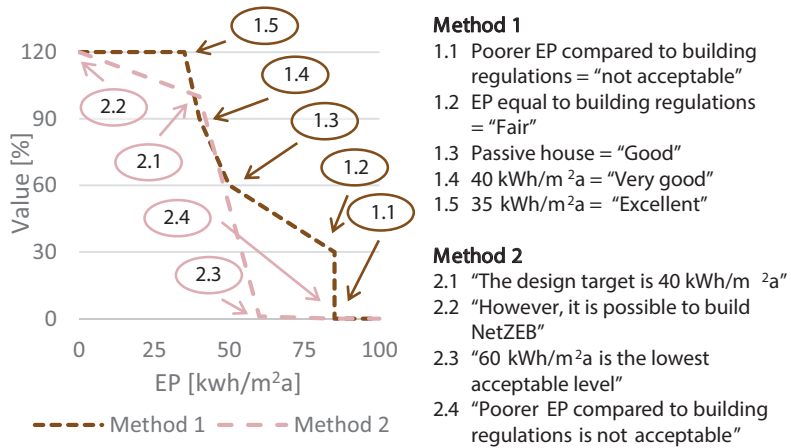


Figure 7.4 Relative values for indicator; energy performance, using two different methods

The result from using the first method indicates that the stakeholder is aware of the increased effort needed to improve the energy performance nearer the judgment of “Excellent”. Taking the step from the requirement in the building regulation, 85 kWh/m²a, to compliance with the energy performance requirement similar of a passive house, 50 kWh/m²a, is seen as good. The stakeholder assumes that it is possible to reach this level with a reasonable effort. Taking the step to improve the energy performance by 10 and 5 kWh/m²a, respectively, is seen as increasingly difficult. Hence the first step is 10 kWh/m²a, and the second only 5 kWh/m²a.

The second method indicates that the design target is to achieve an EP valued as very good in Scenario 1. However, since it is possible to build Net ZEBs, it is possible to outperform the design target and achieve a value of 120%. The lowest acceptable level is 60 kWh/m²a, which is given the value 1%.

Before the model is tested, it is difficult to assess whether any of the methods are better than the other one. Both could be used, and the resulting graphs should be used as a basis for discussion.

7.2.3 Aggregating overall value

Before the overall value is aggregated, the value of each indicator is calculated.

When the overall value is aggregated, based on the WSM, a performance failure indicator, k , based on the product of all relative values of the indicators, is included (see Equation 7.2).

$$\begin{aligned}
 k(a)=1 & \quad \text{for } v_1(a) \cdot \dots \cdot v_n(a) > 0 \\
 k(a)=0 & \quad \text{for } v_i(a) \cdot \dots \cdot v_n(a) = 0
 \end{aligned}
 \tag{Equation 7.2}$$

where

- $k(a)$ The performance failure indicator for alternative a
- $v_i(a)$ Relative value for criterion i , for alternative a

The value, V , is calculated as shown in Equation 7.3.

$$V(a) = k(a) \cdot \sum_1^i w_i v_i(a)
 \tag{Equation 7.3}$$

The performance failure indicator, intended to prevent sub-optimization, was not found in any of the studied methods presented in Section 7.1. By using the performance failure indicator, alternatives where one or more indicators are at a non-acceptable level receive an overall value of zero, regardless of the value of the other indicators.

Using the example with indicators weighted as presented in Table 7.4, a hypothetical input comparing three different alternatives is presented in Table 7.8.

Table 7.8 Relative evaluation of importance of indicators using pairwise comparison

	Priority	$v_i(a)$	$v_i(b)$	$v_i(c)$
i_1	0.08	5%	75%	0%
i_2	0.51	100%	5%	100%
i_3	0.15	5%	75%	100%
i_4	0.27	5%	75%	100%

The use of weighting factors and a performance failure indicator has a large impact on the final calculated value. If the relative values for the different indicators were simply summarised, alternative c would be the highest valued alternative, with a summarized value of 300%, followed by alternative b and, lastly, alternative a .

If weighting factors are used but not the performance failure indicator (Equation 7.2), alternative c would still receive the highest value. However, alternative a now receives a higher calculated value compared to alternative b .

The calculated weighted value is presented below, not using the performance failure indicator.

$$V(a)=0.08\cdot 0.05+0.51\cdot 1.00+0.15\cdot 0.05+0.27\cdot 0.05=53\%$$

$$V(b)=0.08\cdot 0.75+0.51\cdot 0.05+0.15\cdot 0.75+0.27\cdot 0.75=39\%$$

$$V(c)=0.08\cdot 0.00+0.51\cdot 1.00+0.15\cdot 1.00+0.27\cdot 1.00=92\%$$

When the performance failure indicator is used, alternative c receives the value of zero, and alternative a is now the alternative which receives the highest value, V .

The calculated weighted value is presented below, using the performance failure indicator.

$$V(a)=1\cdot (0.08\cdot 0.05+0.51\cdot 1.00+0.15\cdot 0.05+0.27\cdot 0.05)=53\%$$

$$V(b)=1\cdot (0.08\cdot 0.75+0.51\cdot 0.05+0.15\cdot 0.75+0.27\cdot 0.75)=39\%$$

$$V(c)=0\cdot (0.08\cdot 0.00+0.51\cdot 1.00+0.15\cdot 1.00+0.27\cdot 1.00)=0\%$$

7.3 Test of proposed model

7.3.1 Analysis of limited part of building envelope

In this case, a fictional subcontractor who manufactures prefabricated exterior wooden frame walls is approached by a potential client to deliver exterior walls suitable for a detached single-family house.

The client has already made a preliminary analysis, indicating that the wall must meet the requirement $U_c < 0.10 \text{ W/m}^2\text{K}$. Historically, the subcontractor has always delivered exterior walls with a higher U_c of $0.17 \text{ W/m}^2\text{K}$. Therefore, there is a need to investigate an improved construction.

The subcontractor asks the potential client regarding specific requirements on thermal bridges and moisture safety design. It turns out that the potential client has not considered these parameters. Together, the potential

client and the subcontractor define three indicators for the energy performance criteria and two indicators for the moisture performance criteria:

- Energy; thermal transmittance - U_c
The initial requirement set by the potential client
- Energy; thermal bridge - exterior corner
The final design for the building is not set. However, the junction for the exterior corner needs to be defined as a part of the new exterior wall
- Energy; thermal bridge - exterior wall-window
The final design for the building is not set. However, the architect has specific requirements regarding the aesthetics of the junction between the exterior wall and the window
- Moisture; general risk of mould growth
Hygrothermal simulations for a standard section of the construction are evaluated using the m-model. The investigated point is the exterior part of the wooden frame construction
- Moisture; analysis of exterior corner
The exterior corner is evaluated using the Hagentoft-model

The subcontractor decides to investigate three different alternatives (see Figure 7.5; these are the same wall assemblies as investigated in Chapters 4 and 5).

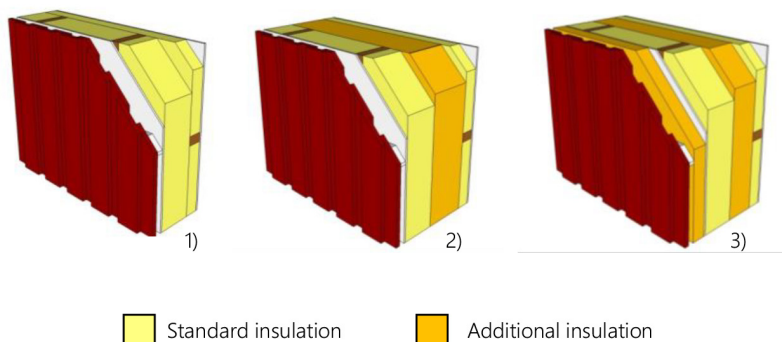


Figure 7.5 *Alternative 1 - Standard wall constructions. Alternative 2 – Additional insulation on the interior side of the wood frame construction. Alternative 3 – Additional insulation on the exterior and interior side of wood frame construction*

The main criteria and different indicators are pairwise prioritized. The prioritization and the resulting weighting factors are presented in Tables 7.9-7.11. The product of the prioritization of main criteria and indicators, the specific weighting factors, are presented in Table 7.12.

Table 7.9a Prioritization of main criteria

This criterion	is more/less	than this criterion
Energy performance	more important	Moisture performance

Table 7.9b Evaluation matrix and calculated priority of main criteria

	Energy	Moisture	Weighting factor, w
Energy	1	3	0.75
Moisture	3^{-1}	1	0.25

Table 7.10a Prioritization of energy indicators

This indicator	is more/less	than this indicator
Thermal transmittance - U_c	very much more important	Thermal bridge; wall-window
Thermal transmittance - U_c	very much more important	Thermal bridge; exterior corner
Thermal bridge; wall-window	more important	Thermal bridge; exterior corner

Table 7.10b Evaluation matrix and calculated weighting of energy indicators

	Thermal transmittance	Thermal bridge; wall-window	Thermal bridge; exterior corner	Weighting factor, w
Thermal transmittance	1	7	7	0.77
Thermal bridge; wall-window	7^{-1}	1	3	0.16
Thermal bridge; exterior corner	7^{-1}	3^{-1}	1	0.08

Table 7.11a Prioritization of moisture indicators

This indicator	is more/less	than this indicator
General risk of mould growth	more important	Analysis of exterior corner

Table 7.11b Evaluation matrix and calculated weighting of moisture indicators

	General risk of mould growth	Analysis of exterior corner	Weighting factor, w
General risk of mould growth	1	3	0.75
Analysis of exterior corner	3^{-1}	1	0.25

Table 7.12 Specific weighting factors for indicators

Indicator	Weighting factor, w
Thermal transmittance	0.58
Thermal bridge; wall-window	0.12
Thermal bridge; exterior corner	0.06
General risk of mould growth	0.19
Analysis of exterior corner	0.06

The relative values for moisture indicators and thermal transmittance of building envelope are determined by using the method of stating a design target followed by defining the best possible outcome, the lowest accepted level and the threshold for “Not acceptable”. The relative values for the thermal bridges are defined by defining excellent, very good, good, fair and not acceptable. Relative values for energy and moisture indicators are presented in Figure 7.6 and Figure 7.7, respectively.

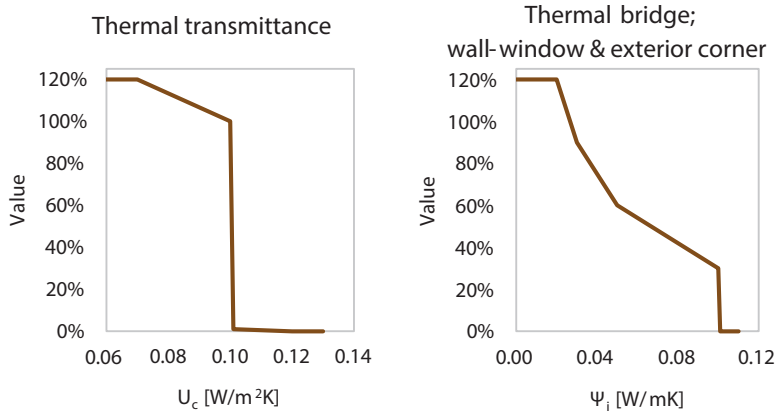


Figure 7.6 Relative values for energy indicators

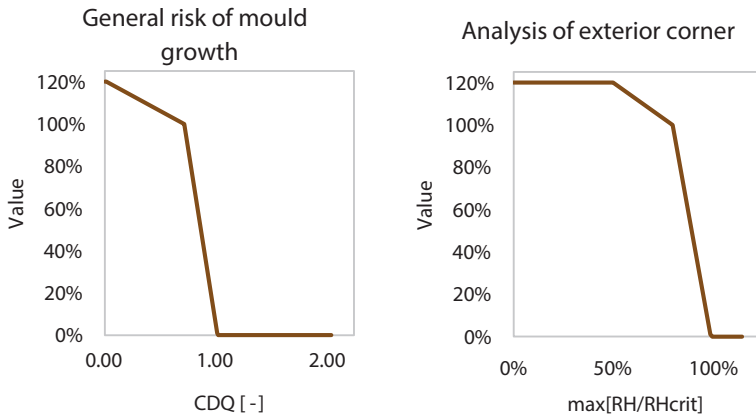


Figure 7.7 Relative values for moisture indicators

The quantified results, the relative value of the indicators, the resulting performance failure indicator and the final weighted value are presented in Table 7.13. Relative values larger than 100% means that the design target is outperformed. The weighted value is the sum of the value of each indicator multiplied by the specific weighting and the performance failure indicator.

The first alternative receives the highest relative value when the risk of mould growth is analysed (the risk of mould growth is low). However, since failing to fulfil the most important indicator, thermal transmittance, the weighted value is 0. The second alternative fulfils the requirement regarding thermal transmittance but fails to fulfil the requirement regarding risk of mould growth; as such, the weighted value is 0. The third alternative is the only construction that receives a weighted value. Hence, it is the only construction that does not get a relative value equal to 0% for any indicator.

Table 7.13 Quantified results, relative values, performance failure indicator and weighted value for the investigated alternatives

		Value of alternatives		
		1	2	3
Thermal transmittance (priority, w: 0.58)	Quantified result	0.170	0.085	0.085
	Relative value	0%	106%	106%
Thermal bridge; wall- window (priority, w: 0.12)	Quantified result	0.026	0.043	0.030
	Relative value	102%	71%	90%
Thermal bridge; exterior corner (priority, w: 0.06)	Quantified result	0.058	0.027	0.028
	Relative value	55%	100%	96%
General risk of mould growth (priority, w: 0.19)	Quantified result	0.29	1.34	0.37
	Relative value	85%	0%	76%
Analysis of exterior corner (priority, w: 0.06)	Quantified result	98%	98%	94%
	Relative value	2%	2%	7%
Performance failure indicator		0	0	1
Weighted value		0%	0%	93%

7.3.2 Analysis of a multi-dwelling building

In this fictional case, a client wishes to investigate differences between concrete walls with external insulation and infill walls—insulated wooden frame walls. Furthermore, the client wishes to investigate two options: a standard building and a low-energy building. U-values for the building envelope are presented in Table 7.14. For all cases, balanced ventilation with heat recovery $\eta=80\%$ is installed. General descriptions of the building systems are presented in Figure 7.8.

Table 7.14 Different levels of U-values used

Construction	U-values for different building categories (W/m^2K)	
	Standard building	Low-energy building
Floor slab on ground	0.17	0.09
Roof	0.12	0.08
External walls	0.20	0.09
Windows/ doors	1.50	0.90

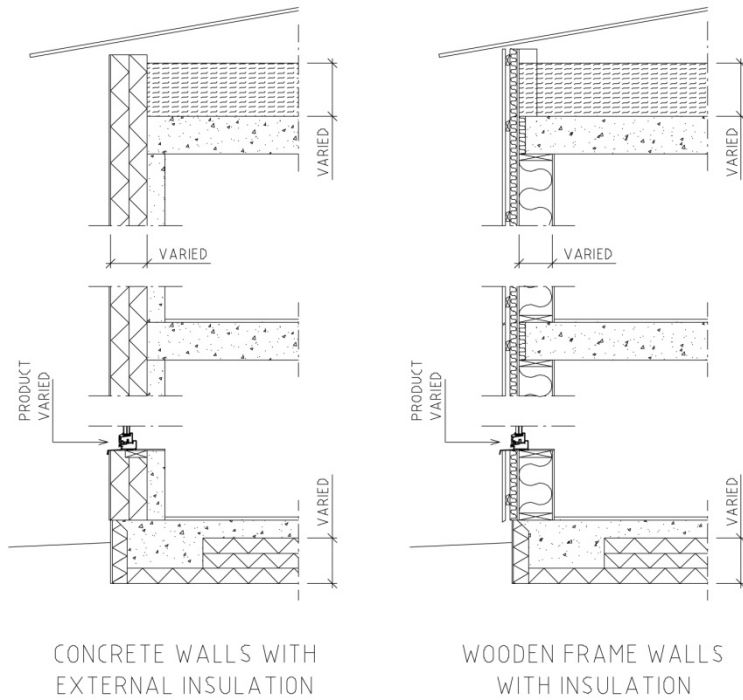


Figure 7.8 Generic descriptions of investigated building systems

In the evaluation, the indicators below are included. To facilitate the large number of indicators, abbreviations in brackets are used in the evaluation matrices:

- Energy (E1): average U-value of the building envelope, including thermal bridges
- Energy (E2): annual energy needs for space heating
- Energy (E3): peak load for space heating
- Energy (E4): embodied energy for superstructure and building envelope
- Moisture (M1): Mould index for exterior wall, using WUFI Bio
- Moisture; Analysis of junctions using the Hagentoft-model
 - (M2) Floor slab on ground – exterior wall
 - (M3) Intermediate floor – external wall
 - (M4) Attic slab – exterior wall

The main criteria and different indicators are pairwise prioritized. The prioritization and the resulting weighting factors are presented in Tables 7.15-7.17. The product of the prioritization of main criteria and indicators, the specific weighting factors, are presented in Table 7.18.

Table 7.15a Prioritization of main criteria

This criterion	is more/less	than this criterion
Energy performance	equally important	Moisture performance

Table 7.15b Evaluation matrix and calculated priority of main criteria

	Energy	Moisture	Weighting factor, w
Energy	1	1	0.50
Moisture	1	1	0.50

Table 7.16a Prioritization of energy indicators

This indicator	is more/less	than this indicator
Average U-value	more important	Energy performance
Average U-value	less important	Peak load for space heating
Average U-value	equal important	Embodied energy
Energy performance	less important	Peak load for space heating
Energy performance	more important	Embodied energy
Peak load for space heating	less important	Embodied energy

Table 7.16b Evaluation matrix and calculated weighting of energy indicators

	E1	E2	E3	E4	Weighting factor, w
E1	1	3	3^{-1}	1	0.22
E2	3^{-1}	1	3^{-1}	3	0.21
E3	3	3	1	3^{-1}	0.30
E4	1	3^{-1}	3	1	0.26

Table 7.17a Prioritization of moisture indicators

This indicator	is more/less	than this indicator
Mould index	more important	Analysis of ground floor junction
Mould index	more important	Analysis of intermediate floor junction
Mould index	more important	Analysis of attic floor junction
Analysis of ground floor junction	equal important	Analysis of intermediate floor junction
Analysis of ground floor junction	equal important	Analysis of attic floor junction
Analysis of intermediate floor junction	equal important	Analysis of attic floor junction

Table 7.17b Evaluation matrix and calculated weighting of moisture indicators

	M1	M2	M3	M4	Weighting factor, w
M1	1	3	3	3	0.50
M2	3-1	1	1	1	0.17
M3	3-1	1	1	1	0.17
M4	3-1	1	1	1	0.17

Table 7.18 Specific weighting factors for indicators

Indicator	Weighting factor, w
Average U-value	0.11
Energy performance	0.11
Peak load for space heating	0.15
Embodied energy	0.13
Mould index	0.25
Analysis of ground floor junction	0.08
Analysis of intermediate floor junction	0.08
Analysis of attic floor junction	0.08

All relative values are defined with reference to a chosen design target followed by the best possible outcome and lowest accepted level. The result is presented in Figure 7.9 and Figure 7.10.

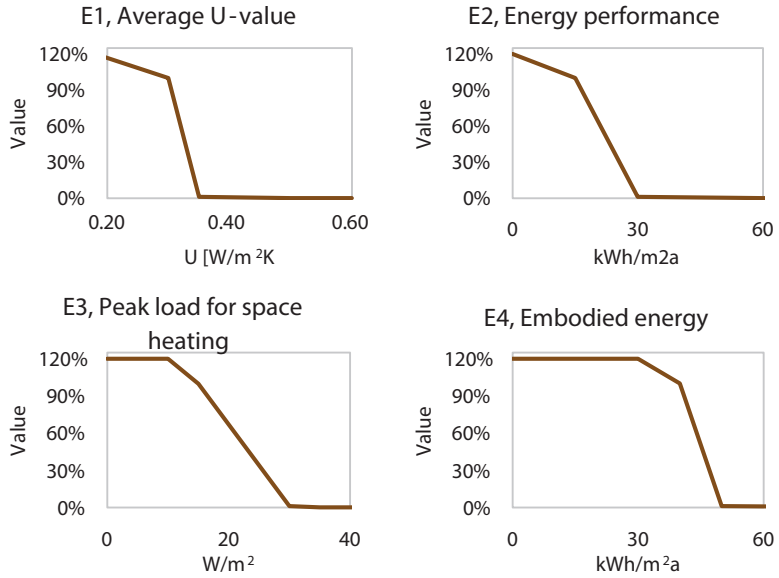


Figure 7.9 Relative values for energy indicators

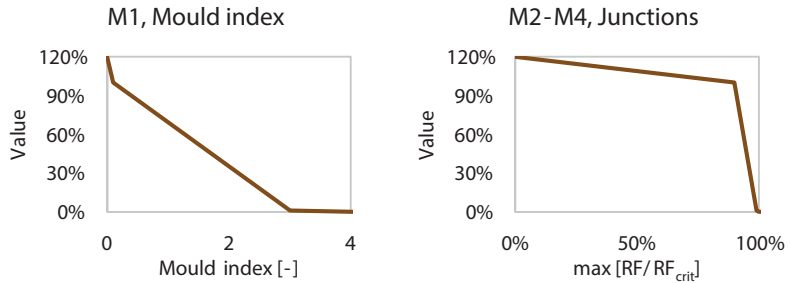


Figure 7.10 Relative values for moisture indicators

The quantified results, the relative value of the indicators, the resulting performance failure indicator and the final weighted value are presented in Table 7.19. No indicator was below the lowest accepted level. Hence, the performance failure indicator is equal to 1 for all alternatives. The low energy building with concrete construction receives the highest weighted value considering all indicators.

If only energy indicators are evaluated, the low-energy building with wooden construction would be given the highest value even though the concrete building has higher relative values for E1-E3. The weighting/importance of embodied energy gives the wooden construction a higher value.

If only moisture indicators are evaluated, the standard building with concrete construction would be given the highest value.

Table 7.19 Quantified results, relative values, performance failure indicator and weighted value for the investigated alternatives

		Standard building		Low-energy building	
		Concrete	Wood	Concrete	Wood
E1 (w: 0.11)	Quantified result	0.31	0.33	0.19	0.21
	Relative value	80%	41%	118%	115%
E2 (w: 0.11)	Quantified result	29	30	14	15
	Relative value	8%	1%	101%	100%
E3 (w: 0.15)	Quantified result	19	20	13	14
	Relative value	77%	66%	109%	104%
E4 (w: 0.13)	Quantified result	37	35	43	41
	Relative value	106%	110%	66%	89%
M1					
(w: 0.06)	Quantified result	0.9	1.8	1.5	2.3
	Relative value	70%	41%	51%	24%
M2 (w: 0.06)	Quantified result	90%	92%	93%	95%
	Relative value	100%	78%	67%	45%
M3 (w: 0.06)	Quantified result	92%	95%	91%	99%
	Relative value	78%	45%	89%	1%
M4 (w: 0.06)	Quantified result	91%	94%	92%	97%
	Relative value	89%	62%	78%	23%
Performance failure indicator		1	1	1	1
Weighted value		74%	54%	81%	62%

7.4 Discussion and conclusions

MCDA may help stakeholders to increase the transparency of a decision-making and to better understand the effect of subjective judgements. The test of the model shows that it is possible to evaluate and quantify both energy and moisture performance in a concise way. It should be possible to use MCDA more in the construction industry to assist with decision-making. However, it is important to keep in mind that this method, as other MCDA methods, does not deliver a “right answer” or an optimum.

To further increase the transparency and the basis for decision-making, different MCDA methods could be combined. This has also been suggested by other researchers (Huang et al., 2015; Medineckiene, 2017; Mulliner et al., 2016). However, as this will result in different rankings, it may result in too much information for the stakeholder, increasing the challenges in decision-making.

As mentioned, the performance failure indicator was not found in any of the studied methods presented in Section 7.1. As WPM uses multiplication, the WPM method would also give alternatives where one or more indicators are given an overall value of 0. However, the WPM method may be perceived as less transparent, as the weighting by multiplication is more complex.

The MCDA calculations in this chapter were, to a large extent, done manually, which is rather time-consuming. However, there is a large selection of software available, helping stakeholders to manage their decision-making (International Society on MCDM, 2019).

8 Conclusions

This chapter presents the main conclusions from the research in relation to the five research questions presented in the introduction. After the conclusions related to the research questions, additional conclusions are presented, which were made during the PhD studies.

8.1 The Swedish residential building stock

The first research question was as follows:

- Is it possible to distinguish different typical buildings and/or building techniques in the existing residential building stock?

The majority of the existing Swedish residential buildings built before 1991 are covered by the compiled data from SCB, which cover 1960-1993. The data show that the most common multi-dwelling building from this period may be described as a three- or four-storey slab block building with a clay brick facade built in a non-metropolitan region. The most common one- or two-dwelling building may be described as a one-storey, one-dwelling building with wooden facade built in a non-metropolitan region. However, if one delimits a description of the existing building stock to using one description, a large part of the existing building stock is excluded. It is important to underline that it is not a single construction type or building that has been predominant. Furthermore, regional differences exist for multi-dwelling buildings.

Based on the available data, it is possible to draw some conclusions regarding construction types, which should be prioritised in further research regarding the Swedish building stock.

Regarding multi-dwelling buildings, exterior walls (including windows and doors) play an important role, as they may form roughly 50-75% of the building envelope. Insulated wood infill walls with clay brick facades are common throughout Sweden. Furthermore, rendered facades applied on lightweight concrete are common in the Stockholm region and

non-metropolitan regions, and concrete sandwich walls are common in metropolitan regions.

Regarding one- or two-dwelling buildings, both exterior wall and roof constructions are a major part of the building envelope. Insulated wood walls with facades of clay bricks or wood are common and represent more than 80% of the dwellings from the studied period. Roof constructions both with an insulated tie beam and where the tie beam is part of the interior floor slab (in 1.5-storey buildings) are common in dwellings from the studied period.

The conclusions above show that it is possible to distinguish typical buildings and building techniques. However, it underlines the importance of not using a single reference building to describe a building from the studied period. The compiled data from statistical reports will hopefully contribute to improve future definitions of typical buildings in the Swedish residential building stock, which may be used as a basis for further analysis of renovation measures and possible impacts of climate change.

8.2 Importance of thermal bridges

The second research question was as follows:

- Will the importance of thermal bridges in building envelopes increase?

The studied examples show that if the design of junctions in a building envelope is kept the same while the heat resistance is increased by adding more insulation, the relative share of transmission heat transfer losses due to thermal bridges increases. Furthermore, the relative share varies based on different types of external walls.

The surveys show that there is still a significant spread among Swedish consultants related to how they choose to quantify a building envelope and a trend towards simplifications. As several consultants are usually involved in the design phase, there is a risk for misunderstandings, which may, in severe cases, result in calculation errors over 30%, resulting in under/oversized heating systems and energy use in the user stage that is far from expected.

As the relative impact of thermal bridges increases, their importance also increases. At the same time, the studied Net ZEBs show that it is possible to design and construct buildings where the relative impact of thermal bridges is low. Hence, wisely designed junctions play an important role in the design of Net ZEBs and nZEBs.

There is a need to increase knowledge in relation to calculations of thermal bridges and to design and implement junctions with low impact

on the transmission heat transfer losses of building envelopes in the construction industry.

8.3 Energy and moisture performance, including co-benefits

The third research question was as follows:

- How may energy and moisture performance and green co-benefits be evaluated?

The term “energy performance” of buildings is often used today, and it is generally alleged that it refers to the annual energy use per conditioned living area. However, differences exist in building regulations in different countries and in definitions of Net ZEBs. The most common differences are which energy uses are included (space heating, hot water, plug loads, lighting, etc.) and the metrics used (delivered energy, primary energy, carbon emissions, etc.). To enhance knowledge transfer and to increase exchange of experiences and new ideas between countries, more harmonised requirements in building regulations could be one measure taken. As this may be a difficult and time-consuming task, a first step may be to present definitions using the definition framework presented by the research task: IEA SHC Task 40/ECBS Annex 52.

Energy performance may also be referred to as “peak load for space heating”, “average thermal transmittance transfer through building envelope”, etc. However, as mentioned above, annual energy use per conditioned living area is generally presumed when this term is used.

Within this study, no international or European standard or framework for assessing and presenting moisture performance has been found. Critical levels for onset of mould growth, corrosion, rot, cementation reactions, etc. were found. Furthermore, different models for assessment of the risk of mould growth were found. The critical levels and assessment models could serve as a basis for further work, which could focus on developing moisture performance indicators, presenting a performance, rather than a risk, for performance failure.

Studies which may be used as a basis for quantifying green co-benefits do exist. However, many of the co-benefits (higher work productivity, reduced employee turnover, etc.) may be difficult to quantify. In this study, examples were shown of how green co-benefits could be quantified in monetary terms. The study shows that it may be very profitable to build

green buildings if one accounts for green co-benefits. Furthermore, it may be easier to find it is profitable in non-residential buildings.

Comparing energy and moisture performance and green co-benefits, there are two important differences to consider:

1. The energy performances of buildings and building elements are, almost without exception, expressed in quantitative terms. Also, the examples of quantification of green co-benefits are expressed in quantitative, monetary terms. However, moisture performance and/or moisture safety design of buildings and/or building elements are often based on experience. The experiences are often expressed qualitatively and not specified in quantitative terms. Therefore, it is difficult to compare and analyse different building techniques, materials, etc. based on quantitative terms
2. Related to energy performance, a poorly designed junction, creating a relatively large thermal bridge, may be compensated for by improving other parts of the building, installing better windows and/or a more energy-efficient HVAC system, etc. However, a poorly designed junction, resulting in damaging amounts of water or moisture entering the building envelope, may affect the entire building regardless of how well-designed the rest of the building is and can, thus, not be compensated

Common for all calculations and investigations presented—regardless if it is energy performance of building envelopes, buildings' energy performance, hygrothermal simulations, quantification of green co-benefits or a life cycle assessment—is the need to clearly state the boundary conditions when the results are presented, as they may have a major impact on the results.

8.4 New boundary conditions and increased risk for mould growth

The fourth research question was as follows:

- Will increased thermal resistance and new boundary conditions increase the risk for mould growth?

There is a warming of the global climate system: the conducted hygrothermal simulations and the evaluations using the different models for assess-

ment of the risk of mould growth show that the ongoing climate change will most likely increase the risk of mould. However, it is important to highlight that only one climate scenario was used and that the focus was wooden constructions.

It does, however, show that, by applying simple measures, it is possible to substantially reduce the risks of mould growth:

- Construction materials based on biodegradable materials, e.g. wooden studs, should always be given exterior insulation to decrease the risk of mould growth. However poor assembly—i.e. enabling driving rain to penetrate exterior walls, most likely at junctions—may actually increase the risk for mould growth
- Within the construction phase of buildings, there is a need to implement all reasonable measures to decrease the amount of moisture added in this phase

Buildings are expected to have a long lifespan. Therefore, the effects of climate change must be considered in the design of new buildings and when buildings are to be renovated. There is, therefore, a need for weather data, taking future climate change into account, which may be used in the design phase. The climate data should not only be based on mean or typical outdoor climates, as both typical and extreme weather data are needed.

8.5 A model for evaluation

The fifth research question was as follows:

- How could a method which may combine the different performance indicators expressed in different units be used in the evaluation?

Energy and moisture performance and green co-benefits may be expressed in many different ways. A model was proposed and tested. The model does not specify specific indicators which should be used.

The tests of the model showed that it is possible to handle a large set of criteria and to weight them into one value. Hence, it should be possible to use the model to assist with decision-making. However, it is important to keep in mind that this method, as with other MCDA methods, does not deliver a “right answer” or an optimum.

Testing the model, some major conclusions have been made.

- When the pairwise priority had been made for the main criteria and the indicators, the specific weighting factors were calculated and ranked. Presentation of the ranking may be useful, as it enables stakeholders to reflect on the effect of their priorities
- When many indicators are valued and presented at the same time, it will be cluttered, which may make it difficult to interpret the result. This may be managed by dividing the main criteria into different sub criteria. The presentation of the results could then be filtered by the different criteria and indicators. E.g., one stakeholder may initially only be interested in the weighted value; however, realising that a certain alternative receives a low value for the moisture criterion, the stakeholder may wish to investigate and compare the values of each indicator within that specific criterion
- Within this study, most of the work was done manually and was time consuming. There are plenty of types of software available to support these kinds of MCDA; however, these software are general and not tailored for the construction industry

8.6 Other conclusions

Other conclusions, not directly linked to the defined research questions, are presented below:

- In Sweden, boundary conditions for simulations related to energy performance of buildings are rather well defined in industry standards and building regulations, which increases transparency and predictability. The same does not apply to hygrothermal simulations and assessments of risk of performance failure related to moisture. Standards do exist but are limited to defining reporting of hygrothermal calculations
- The embodied energy of buildings increases slightly when taking the step towards Net ZEB balance, and the embodied energy expressed as the relative share of the total energy use increases significantly. However, the energy savings achieved related to building operation exceed, with great margin, the increased embodied energy
- Monitoring energy use is important to ensure that predicted energy use is achieved in the actual use of buildings. It is important to normalise the measured energy use in order to determine an accurate energy performance. The normalisation of measured energy use

may, to a large extent, close performance gaps and explain deviations between simulations and measurements and, thus, between predictions and reality. It is important that the normalisation considers deviation in both interior and exterior climates

- As more buildings are designed and built as Net ZEBs, the interaction with the energy grid becomes more important. Grids with a large number of Net ZEBs may require reinforced grids or other solutions to grid management that come with a cost for the grid operator and/or the customers. As buildings often are designed individually, without knowledge and consideration of other buildings, it could be useful to implement load match and grid indicators in the design process, which could reduce the stress on the grid, making buildings an asset to the grid instead of a burden

9 Future research

The compiled data related to the existing building stock could be used to improve future definitions of typical buildings in the Swedish residential building stock. As there is a need for renovation for many existing residential buildings in Sweden, there is an opportunity to make them more energy efficient. The compiled data enable strategic development of more cost-effective and robust methods or prefabricated building elements that substantially can increase the thermal resistance of building envelopes in existing buildings. All the compiled data are available for other researchers for further studies.

Standardized boundary conditions for hygrothermal simulations and methods to express the moisture performance in quantitative terms should be developed. As a first step, a common industry standard in Sweden could be developed.

In relation to standardized boundary conditions for hygrothermal conditions, there is a general demand for weather data, taking future climate change into account, which may be used in the design phase. This data could be used for various simulations, investigating indoor climate, energy demand, hygrothermal conditions in building components, etc. Furthermore, more research is needed in relation to how climate change may affect buildings.

Normalisation of measured energy use is a complex task and standardized methods are needed to help stakeholders to verify the energy performance of buildings. Future research should focus on how to normalise for deviating occupancy presence, ventilation (both mechanical and airing), indoor temperature and internal heat gains from plug loads and lighting. Furthermore, there is a need to normalise energy generation from renewables (e.g. PV panels, wind mills, etc.).

There is also a need to investigate and define quantitative design parameters, LMGI indicators, which could be used to minimize the stress on the grid already in the design phase.

Finally, there is a need for an MCDA software tailored for the construction industry to facilitate more use of MCDA. The software could be based on the method presented in this thesis.

Summary

One of the greatest challenges the world is facing is climate change. Failure to fight climate change will likely result in severe, irreversible and pervasive impacts for people and ecosystems. As more than 30% of the globally consumed primary energy is used in commercial and residential buildings in operation and roughly 18% of the GHG emissions can be related to buildings, reduction of energy use and the use of renewable energy in buildings constitutes important climate change mitigation measures.

Improving the energy performance of buildings by means of increased thermal resistance is frequently introduced in order to achieve a lower energy-demand for buildings, both for renovation and new buildings. However, increased thermal resistance of the building envelope will result in a different microclimate within it. As buildings and their components are traditionally designed based on a mix of experience, rules-of-thumb and implicit rules, there is a need to evaluate buildings and building envelopes where moisture safety is valued as an important factor, which also can meet future demands for energy performance, considering future climate change.

The objective of this research is to investigate methodologies and performance indicators for evaluation of energy and moisture performance in buildings, including co-benefits which may occur in “green buildings”. Furthermore, the objective is to identify a methodology for evaluation of energy and moisture performance of buildings, including co-benefits.

The following research questions were formulated.

1. Is it possible to distinguish between different typical buildings and/or building techniques in the existing building stock?
2. Will the importance of thermal bridges in building envelopes increase?
3. How may energy and moisture performance and green co-benefits be evaluated?
4. Will increased thermal resistance and new boundary conditions increase the risk for mould growth?
5. How could a method which may combine the different performance indicators expressed in different units be used in the evaluation?

The work was set out with a historical review of building envelopes for residential buildings. Followed by literature review and case studies to investigate how energy performance, moisture conditions and green co-benefits may be calculated. A method for evaluation based on MCDM was developed and tested.

Residential buildings in Sweden

The review of the existing residential buildings in Sweden from the 1960s to the 1990s is based on data from reports from 1967 to 1994 and has not been publicly available in a database for other researchers for further studies until now. The study found that there is a rather large homogeneity in the existing residential building stock. However, it is not possible to use a single reference building that would cover a majority of the existing buildings. A set of different reference buildings and constructions are needed to enable further studies, which may investigate different possibilities related to renovation. In Sweden, common constructions for exterior walls in multi-dwelling buildings, which should be used for further studies, are insulated wood infill walls with clay brick facades, lightweight concrete walls with rendered facades and concrete sandwich walls. The most common constructions for one- or two-dwelling buildings are insulated wooden walls with clay brick facades or wooden facades. Furthermore, roof constructions both with an insulated tie beam and where the tie beam is a part of the interior floor slab are frequent and should be included in further studies for one- and two-dwelling buildings.

Energy performance

Regarding energy performance of building envelopes, the relative share of transmission heat transfer due to thermal bridges increases when the heat resistance is increased. The conducted investigations show that the state of knowledge related to thermal bridges is not satisfying. More guidelines and education/training are needed.

Regarding the energy performance of buildings, the case studies show that it is possible to build Net ZEBs with technologies available on the market today. Furthermore, the case studies show the complexity of load match and grid interaction. In a Nordic climate, it is difficult to achieve a high load match and/or low stress on the grid unless energy storage is used. Further, measurement and verification of energy performance in the user stage is important, and measured values should be normalised in order to clarify whether energy use in the user stage is due to different conditions

or actual performance failures. Detailed measurements and follow-ups of buildings in the user stage may not only gain experiences related to energy performance, but it may also give important knowledge related to how specific products behave under certain temperatures, user patterns, etc. Normalisation due to changes in the actual use of the building shows greater impact compared to normalisation due to deviating exterior climate.

Regarding embodied energy and environmental impact, it becomes growingly important to not only consider the user stage when Net ZEBs or similar buildings are designed. In conventional buildings, the environmental impact from the user stage dominates the environmental impact. However, in Net ZEBs, the impact from the user stage is very low, and, consequently, the relative impact from the product and construction stages is dominant. Taking the step from a conventional building to a Net ZEB shows a small increased impact in the product and user stages. However, the increased impact is very small compared to the reduced impact in the user stage.

Moisture performance

The hygrothermal simulations show that it is possible to increase the amounts of insulation in a wooden construction without increasing the risk for mould growth.

It is not only wood that may suffer from performance failure due to moisture. However, wood, in general, is affected by mould growth before other common building materials, such as insulation, gypsum boards, etc. Furthermore, performance failure may not only appear in the form of mould growth. Problems with swelling and shrinking, carbonation, corrosion, etc. may also occur for different materials. In general, these problems usually occur after mould growth is initiated. Consequently, evaluation of the risk of mould growth is important, as it is likely to be the first performance failure that may appear.

Possible effects of mould growth due to climate change in Sweden

The hygrothermal simulations show an increased risk of mould growth considering the ongoing climate change for wooden constructions according to the climate scenario used. Furthermore, poor assembly—i.e. enabling driving rain to penetrate exterior walls, most likely at junctions—will also increase the risk for mould growth.

Construction materials based on biodegradable materials, e.g. wooden studs, should always be given exterior insulation to decrease the risk of

mould growth. Reducing built-in moisture has a positive effect, decreasing the risk for mould growth. Hence, measures to decrease the amount of moisture added in the construction stage should always be considered.

Exterior insulation, reduced built-in moisture and care for junctions, resulting in decreased penetration of driving rain, have a greater positive effect than the effects of climate change and increased amounts of insulation. Hence, it is possible to increase the amounts of insulation in a wooden construction without increasing the risk for mould growth.

Added values in green buildings

The case studies show that it may be very profitable to build green buildings if one accounts for green co-benefits. Furthermore, it may be easier to find it profitable in non-residential buildings. The investigated case studies show that, even if the value of green co-benefits are assumed to be low, it still has a great impact on the profitability of green buildings. Furthermore, it would be possible to quantify more green co-benefits, which are not included in these case studies, e.g. increased value of building.

A model for evaluation

Multi criteria decision analysis (MCDA) may help stakeholders to increase the transparency of decision-making and to better understand the effect of subjective judgements. The test of the model, based on MCDA, shows that it is possible to evaluate and quantify both energy and moisture performance in a summarising way. It should be possible to use MCDA more in the construction industry to assist with decision-making. However, it is important to keep in mind that this method, as other MCDA methods, does not deliver a “right answer” or an optimum.

Common for all calculations and investigations presented—regardless if it is energy performance, moisture performance or green co-benefits—is the need to clearly state the boundary conditions when the results are presented, as they may have a major impact on the results.

Conclusions from the research in relation to the five research questions

- Is it possible to distinguish different typical buildings and/or building techniques in the existing residential building stock?

Based on the available data, it is possible to draw some conclusions regarding the Swedish building stock.

Regarding multi-dwelling buildings, exterior walls (including windows and doors) play an important role, as they may form roughly 50-75% of the building envelope. Insulated wood infill walls with clay brick facades are common throughout Sweden. Furthermore, rendered facades applied on lightweight concrete are common in the Stockholm region and non-metropolitan regions and concrete sandwich walls are common in metropolitan regions.

Regarding one- or two-dwelling buildings, both exterior walls and roof constructions are a major part of the building envelope. Insulated wood walls with facades of clay bricks or wood are common and represent more than 80% of the dwellings from the studied period. Roof constructions both with an insulated tie beam and where the tie beam is part of the interior floor slab (in 1.5-storey buildings) are common in dwellings from the studied period.

The conclusions above show that it is possible to distinguish typical buildings and building techniques. However, it underlines the importance of not using a single reference building to describe a building from the studied period.

- Will the importance of thermal bridges in building envelopes increase?

The studied examples show that if the design of junctions in a building envelope is kept the same while the heat resistance is increased by adding more insulation, the relative share of transmission heat transfer losses due to thermal bridges increase. Furthermore, the relative share varies based on different types of external walls.

As the relative impact of thermal bridges increases, the importance of thermal bridges increases. At the same time, the studied Net ZEBs show that it is possible to design and construct buildings where the relative impact of thermal bridges is low. Hence, wisely designed junctions play an important role in the design of Net ZEBs and nZEBs.

There is a need to increase knowledge in relation to calculations of thermal bridges and to design and implement junctions with low impact on the transmission heat transfer losses of building envelopes in the construction industry.

- How may energy and moisture performance and green co-benefits be evaluated?

The term “energy performance” of buildings is often used today, and it is generally alleged that it refers to annual energy use per conditioned

living area. However, differences exist in building regulations in different countries and in definitions of Net ZEBs. The most common differences are which energy uses are included (space heating, hot water, plug loads, lighting etc.) and the metrics used (delivered energy, primary energy, carbon emissions, etc.). To enhance knowledge transfer and to increase exchange of experiences and new ideas, a first step may be to present definitions using the definition framework presented by the research task: IEA SHC Task 40/ECBS Annex 52.

Within this study, no international or European standard or framework for assessing and presenting moisture performance has been found. Critical levels for onset of mould growth, corrosion, rot, cementation reactions, etc. were found. Furthermore, different models for assessment of the risk of mould growth were found. The critical levels and assessment models could serve as a basis for further work, which could focus on developing moisture performance indicators, presenting a performance rather than a risk for performance failure.

Studies which may be used as a basis for quantifying green co-benefits do exist. However, many of the co-benefits (higher work productivity, reduced employee turnover, etc.) may be difficult to quantify. In this study, examples were shown of how green co-benefits could be quantified in monetary terms. The study shows that it may be very profitable to build green buildings if one accounts for green co-benefits. Furthermore, it may be easier to find it profitable in non-residential buildings.

Common for all calculations and investigations presented—regardless if it is energy performance of building envelopes, buildings' energy performance, hygrothermal simulations, quantification of green co-benefits or a life cycle assessment—is the need to clearly state the boundary conditions when the results are presented, as they may have a major impact on the results.

- How could a method which may combine the different performance indicators expressed in different units be used in the evaluation?

Energy and moisture performance and green co-benefits may be expressed in many different ways. A model was proposed and tested. The model does not specify specific indicators which should be used.

The tests of the model showed that it is possible to handle a large set of criteria and to weight them into one value. Hence, it should be possible to use the model to assist with decision-making. However, it is important to keep in mind that this method, as other MCDA methods, does not deliver a “right answer” or an optimum.

Future research

The compiled data related to the existing building stock could be used to improve future definitions of typical buildings in the Swedish residential building stock. As there is a need for renovation for many existing residential buildings in Sweden, there is an opportunity to make them more energy efficient.

Standardized boundary conditions for hygrothermal simulations and methods to express the moisture performance in quantitative terms should be developed. As a first step, a common industry standard in Sweden could be developed.

Future research should also focus on improving how to normalise measured energy performance and to further investigate and define quantitative design parameters which could be used to minimize the stress on the grid already in the design phase.

Finally, there is a need for a MCDA software tailored for the construction industry to facilitate more use of MCDA. The software could be based on the method presented in this thesis.

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Article 1



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Original Article

Net ZEB office in Sweden – A case study, testing the Swedish Net ZEB definition

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Abstract

An important measure for climate change mitigation is reduction of energy use in buildings worldwide.

In 2010 Skanska Sverige AB began designing an office building in the southern parts of Sweden, aiming towards a Net zero energy building (Net ZEB) balance. The construction work started in the middle of 2011.

In the beginning of 2012 Sveriges Centrum för Nollenergihus/the Swedish Centre for Zero-energy buildings (SCNH) published a Swedish definition for a zero-energy building in the Swedish climate. In short; the Swedish definition of a zero-energy building demands fulfilment of the passive house criteria, and that a zero energy balance must be reached over a year based on import/exported balance.

This study summarises the overall design ideas, constructions, installations, energy balance of the office building and investigates whether the building reaches the zero energy-building definition according to SCNH. The simulations show that a Net ZEB balance may be reached. However, the passive house criterion is not reached. The study discusses pros and cons in the Swedish definition of "zero-energy building"/Net ZEB and suggests clarifications needed and possible amendment that may be implemented in an updated version of the definition.

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Keywords: Net zero energy building; Zero energy building; Office building; Net ZEB definition

1. Introduction

Reduction of energy use constitutes an important measure for climate change mitigation. Buildings today

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account for 40% of the world's primary energy use and 24% of the greenhouse gas emissions (International Energy Agency (IEA), 2011). The population and need for residential and non-residential buildings increases worldwide. Therefore, reduction of energy consumption and increased use of energy from renewable sources in the buildings sector constitute important measures required to reduce energy dependency and greenhouse gas emissions.

Today, the concept of Net zero energy buildings (Net ZEBs) is no longer perceived as a concept that can only be reached in a very distant future. A growing number of projects in the world, in different climates, show that it is possible to reach Net ZEB balance with technologies avail-

able today on the market. Examples may be found in (Fachinformationszentrum, 2011; Lenoir et al., 2011; Musall et al., 2010; SHC Task40/ECBCS Annex52 IEA, 2011; Voss and Musall, 2011).

In contradiction to autonomous Zero energy buildings (ZEBs), the Net ZEBs interacts with the energy infrastructure. Renewable energy generation covers the annual energy load. At a first glance, the “zero energy concept” seems simple and intuitive. However, there may be significant differences between definitions that seem similar. Relevant studies that investigate differences and try, to clarify the definitions may be found in (BPIE, 2011; Kurnitski et al., 2011; Marszal et al., 2010, 2011; Sartori et al., 2010; Sartori et al., 2012). In the most recent of the studies (Sartori et al., 2012) a comprehensible framework is presented. The framework considers relevant aspects characterising Net ZEBs and may be used to define consistent (and comparable with others) Net ZEB definitions in accordance with country specific conditions. The presented framework was largely developed in the context of the joint IEA SHC Task40/ECBCS Annex52: Towards Net Zero Energy Solar Buildings (International Energy Agency (IEA) Solar Heating and Cooling programme (SHC) & (ECBCS), 2008).

In 2010, Skanska Sverige AB began designing an office building in the southern parts of Sweden, aiming towards Net ZEB balance, called “Våla Gärd”. The construction work started in the middle of 2011. The building was taken into use in the autumn of 2012. In the beginning of 2012 the Swedish Centre for Zero Energy Buildings (SCNH) published a revised definition of “mini energy house”, passive house and zero-energy building (Sveriges Centrum för Nollenergihus, 2012) for the Swedish climate. In short; the Swedish definition of a zero-energy building demands the fulfilment of the Swedish passive house criteria, and that a weighted zero energy balance must be reached over a year based on import/export balance. Hence, it is a Net ZEB.

This study summarises the framework presented within the IEA SHC Task40/ECBCS Annex52 and the

Swedish Net ZEB definition. Furthermore overall design ideas, constructions, installations and energy balance of the Net ZEB office are presented. The studied case investigates whether the building reaches the Net ZEB definition according to SCNH, discusses pros and cons in the Swedish definition of Net ZEB and proposes small clarifications and additions suggested for an updated version of the definition. The studied building is an office building. Hence, only the Swedish Net ZEB definition for non-residential buildings is addressed in this study.

1.1. Terminology and the balance concept of Net ZEB

In Fig. 1(left), the terminology used and the link between them are presented. The Net ZEB balance is reached when the weighted supply meets or exceeds the weighted demand. The general strategy to reach a Net ZEB balance may be described as a two-step procedure: first, apply energy efficiency measures to reduce energy demand (e.g., passive house design principle). Secondly, generate energy to achieve the balance, Fig. 1(right). The passive house design principle may be described as (Janson, 2010):

- Reducing thermal losses through the building and install/use a balanced ventilation system with a high system heat recovery efficiency.
- Minimise the need of electricity by installing energy efficient fans, pumps, appliances and lighting systems.
- Utilise solar energy, both for passive solar gains and as a source for domestic hot water production and local production of electricity.
- Measure and visualise the energy use in a user friendly and transparent way.

Different aspects, recommended to be addressed within the Net ZEB framework (Sartori et al., 2012) are summarised below:

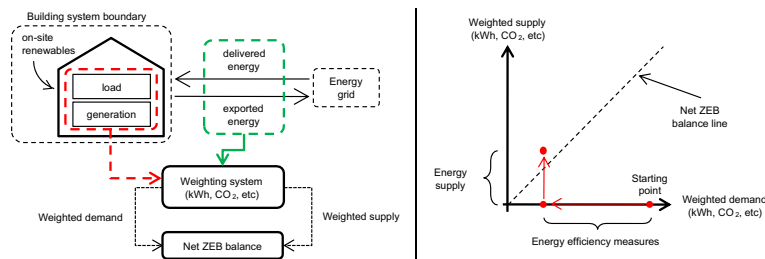


Figure 1. Based on (Sartori et al., 2012). Left; sketch of connection between buildings and energy grids showing relevant terminology. Right; graph representing the Net ZEB balance concept and strategy.

1. *Building system boundary*
 - 1.1. *Physical boundary* – needed to know where to compare/measure energy flows in and out the system and to identify energy generated from renewable sources “on-site”.
 - 1.2. *Balance boundary* – defines which energy uses that are included in the Net ZEB balance. The terminology described in EN 15603 [SIS 2008] may be used.
 - 1.3. *Boundary conditions* – represent definitions of reference climate, comfort standard and type of building use.
2. *Weighting system*
 - 2.1. *Metrics* – refers to the specific metric chosen for the Net ZEB balance. Common metrics are: primary energy (total or non renewable), site energy, carbon emissions, exergy, costs etc.
 - 2.2. *Symmetry* – demand and supply may be weighted symmetrically or asymmetrically. For example if costs are balanced, the tariffs may differ for export and import.
 - 2.3. *Time dependent accounting* – commonly static weighting factors are used. However quasi-static or dynamic weighting factors would most likely help the design of Net ZEBs towards more optimal interaction to the grid.
3. *Net ZEB balance*
 - 3.1. *Balancing period* – May differ, usually one year.
 - 3.2. *Type of balance* – refers to whether the balance is based on load/generation; the building’s energy demand compared to energy generation, no self-consumption evaluated, or import/export; energy flows to and from the building, passing the physical boundary. It shall be noted that the graphical presentation (Fig. 1 right) of the two different balances will differ due to on-site energy self consumed and possible storage losses within the building if energy storage is used.
 - 3.3. *Energy efficiency* – in addition to the Net ZEB balance, requirements may be set on energy efficiency, such as U-values of windows, air tightness etc.
 - 3.4. *Energy supply* – there may be requirements on minimum share of the building’s energy demand covered by renewable sources. Furthermore it may not be allowed to offset delivered electricity with exported heat, etc.
4. *Temporal energy match characteristics*
 - 4.1. *Load matching* – evaluations/requirements of/on – load matching may be set according to Eq. (1).
 - 4.2. *Grid interaction* – evaluations/requirements of/on – grid matching may be set according to Eq. (2) and Eq (3).
5. *Measurement and verification*

In order to check that a building is in compliance with the definition, a procedure for calculations and/or measurements needs to be defined in order to verify the building.

$$f_{load,i,T} = \min[1, g_i/l_i] \quad (1)$$

$$f_{grid,i,T} = (e_i - d_i)/\max[e_i - d_i] \quad (2)$$

$$f_{grid,i,year,T} = STD(f_{grid,i,T}) \quad (3)$$

Where g is generation, l is load, e is exported energy, d is delivered energy, i is the energy carrier and T is the evaluation period, year, month, week, etc.

1.2. The Swedish Net ZEB definition

The Swedish Net ZEB definition (Sveriges Centrum för Nollenergihus, 2012) is presented below according to the framework presented above:

1. *Building system boundary*
 - 1.1. The *Physical boundary* is defined in accordance to the Swedish building regulations (Boverket, 2011). Hence, in general, the physical boundary is the building itself. However, the physical boundary is enhanced to the building site for solar thermal (ST) collectors, PV panels and equipment that generate heating or cooling (e.g., usually different types of heat pumps or biomass boilers). The Swedish building regulations are not clear regarding how to account for wind mills and micro CHP plants on-site. However, the Swedish Net ZEB definition states that wind mills may be placed anywhere on the building site.
 - 1.2. *Balance boundary* is also defined in accordance to the Swedish building regulations. Hence, energy used for heating, cooling and dehumidification, ventilation and humidification, hot water and permanently installed lighting of common spaces and utility rooms are included in the balance. Other services are not included in the balance (e.g., computers, copiers, TVs etc.).
 - 1.3. *Boundary conditions* – The Swedish Net ZEB definition defines set point temperature for heating. Furthermore, it defines internal heat gains from occupancy presence and electricity use. Also energy use for heating of water is defined. Set point for cooling is not defined. No requirements or definitions are set for outdoor climate.
2. *Weighting system*
 - 2.1. The chosen *Metric* to calculate the Net ZEB balance is referred to as weighted energy.
 - 2.2. Symmetric weighting is applied.
 - 2.3. Static weighting factors are used. Hence, no *Time dependent accounting*. The following factors are used; $w_{electricity}$: 2.5, $w_{district\ heating}$: 0.8, $w_{district\ cooling}$: 0.4. All other energy carriers are multiplied by one, w_{ther} : 0.4. (bio fuel, natural gas, oil etc.)
3. *Net ZEB balance*
 - 3.1. The *Balancing period* is one year.
 - 3.2. The *Type of balance* is import/export.

- 3.3. Energy efficiency – in addition to the Net ZEB balance, the building must fulfil the Swedish passive house requirements, in short:
 - 3.3.1 Peak load for heating (VFT) $\leq 7.7 + 0.233(21 - DVUT)$ W/m². The maximum value may be increased for buildings with conditioned area (A_{temp}) < 400 m² by 2 W/m² (DVUT is the design outdoor temperature).
 - 3.3.2 Air permeability, $q_{50} \leq 0.30$ l/s, m².
 - 3.3.3 Average U-value for all windows and glazed areas ≤ 0.80 W/m²K.
- 3.4. Energy supply – no requirements.
 - 4. Temporal energy match characteristics
 - 4.1. Load matching – no requirements.
 - 4.2. Grid interaction – no requirements.
 - 5. Measurement and verification. To enable verification of the energy performance, energy metering must be separated into heat and electricity. Electricity should also be separated into energy use included and excluded in the Balance boundary. Furthermore, consumption of hot water must be measured and operating hours for the building should be documented.

In addition to the requirements presented above, the Swedish Net ZEB definition requires:

- 1. Noise from ventilation system should not exceed sound class B, SS 025268 (Swedish Standards Institute, 2007).
- 2. Indoor temperature must be investigated through simulations.
- 3. If the ventilation system is designed for intermittent operation, the design should ensure that air filters are dry before shut down.
- 4. Specific fan power and energy consumption for ventilation, pumps, lighting, motors, control, monitoring equipment etc. This must be reported together with the presentation of the energy simulation.
- 5. Electricity consumption and internal heat gains from these should be calculated, documented and compared with reference values, defined in the Net ZEB definition (the defined boundary conditions).

- 6. Material used for the construction should not have microbiological growth of abnormal quantity or have divergent odour. Isolated, visible, onset of mould growth on wood must be grounded or planed away. Wood is not allowed to have moisture content above 0.20 kg/kg when delivered on-site. Furthermore, it is not allowed to have moisture content above 0.16 kg/kg when interior and exterior cladding is mounted. Critical moisture conditions for carpets, adhesives and fillers shall not be exceeded. Measurements shall be made by an authorised controller or equivalent.

2. Case study – Office Building; Väla Gård

2.1. Calculations and simulations

Calculations of U-values and thermal bridges are according to EN ISO 6946:2007 (Swedish Standards Institute, 2007a), EN ISO 13370:2007 (Swedish Standards Institute, 2007c) and EN ISO10211:2007 (Swedish Standards Institute, 2007b). All calculations are based on internal areas. To enable quick evaluation of different options, static calculations for maximum heat transfer losses and peak load for cooling is calculated. The calculation of maximum heat transfer losses is carried out according to the equation defined in the SCNH definition of Net ZEB. A simplified method for calculation of peak load for cooling (P_{cool}), presented in Eq. (4), was developed and used in this case study.

$$P_{cool} = Q_{i,light} + Q_{i,eq} + Q_{solar} \tag{4}$$

Where $Q_{i,light}$ is internal heat gains due to electric light (W/m²), $Q_{i,eq}$ is internal heat gains due to electric equipment (W/m²) and Q_{solar} is heat gains due to solar radiation calculated according to Eq. (5) (W/m²).

$$Q_{solar} = (\sum A_g \cdot g_g \cdot Q_{solar,g}) / A_{temp} \tag{5}$$

Where A_g is the area of glazing (m²), g_g is g-value of glazing (%), $Q_{solar,g}$ is intensity of solar radiation on window surface according to Eq. (6) (W) and A_{temp} is conditioned area (m²).

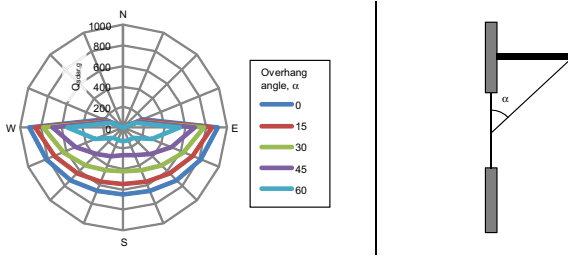


Figure 2. Left $Q_{solar,g}$ in different directions, sorted on different overhang angles. Right; sketch describing the overhang angle.

By using the solar height, S_h , at July 15th, the intensity of the solar radiation is calculated for different directions according to Eq. (6) and presented in Fig. 2 for different overhang angles.

$$Q_{solar.g} = F_{dir} \cdot R_{dir} + F_{dif} \cdot R_{dif.sky} + R_{dif.ground} \quad (6)$$

Where F_{dir} is shading correction factor for direct radiation (–), R_{dir} is direct radiation from the sun (W) (assumed to be $800 \cos(S_h)$), F_{dif} is shading correction factor for diffuse radiation (–), $R_{dif.sky}$ is diffuse radiation from the sky (W) (assumed to be 100) and $R_{dif.ground}$ is diffuse radiation due to ground reflectance (W) (assumed to be 100).

If external screens are used, shading correction factors may be given by the manufactures or the suppliers. If fixed overhangs are used, shading correction factors may be calculated according to Eqs. (7) and (8). Maximum solar radiation is calculated by checking different azimuths/directions of the sun, perpendicular to the different facades.

$$F_{dir} = \max[0, 1 - (0.5 \tan \alpha) / (\tan(90 - S_h))] \quad (7)$$

$$F_{dif} = 1 - (\alpha/90) \quad (8)$$

Where α is the overhang angle as defined in Fig. 2 (°) and S_h is solar height (°).

In addition to static calculations, simulations are carried out using IDA ICA 4.5 Beta (EQUA, 2012). Time-step for evaluation of import and export of energy was 15 min.

2.2. Description of case study

The studied building is a two-storey office building situated in the south of Sweden. The overall design concept may be described as two main buildings with double pitched roofs, connected by a smaller building with a flat roof. The smaller building serves as an entrance and reception. On the first floor, the facade facing south west is shaded by a fixed overhang, $\alpha = 60^\circ$. The gable walls on the “main buildings have fixed screens as solar shading, shading factor $F_{All} = 0.5$. The smaller “entrance building” has glass facades. The glazing on the upper floor has a fixed

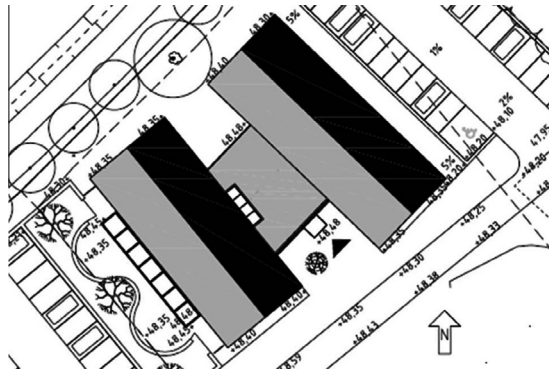


Figure 3. Orientation of building.



Figure 4. Facade facing south east.

overhang shading, $\alpha = 75^\circ$. The building has a geothermal heat pump system, with four heat pumps located at the building site. The heat pumps have variable speed compressors, enabling the system to adjust the speeds (and heat production) depending on the varying heating loads. Hence, the system eliminates energy losses caused by stopping and starting. Furthermore this enables the heat pumps to manage more than 100% of the estimated peak load. Free cooling is extracted from the bore holes during summer. Roof sides facing south west are equipped with PV panels. During summer, the PV panels are expected to export electricity to the grid. Input data for simulations and characteristics are presented in Figs. 3–5, and Tables 1 and 2.



Figure 5. Photograph of the building, as built, taken from west facing towards east.

Table 1
Input data for simulations – constructions.

Constructions	
Slab on ground, 350 mm EPS	$U = 0.08 \text{ W/m}^2\text{K}$
Exterior walls, 200 mm Graphite EPS + 95 mm min. wool	$U_c = 0.11 \text{ W/m}^2\text{K}$
Double pitched roof, 520 mm min. wool	$U_c = 0.08 \text{ W/m}^2\text{K}$
Flat roof, 350 mm EPS + 20 mm min. wool	$U_c = 0.10 \text{ W/m}^2\text{K}$
Windows	$U_w = 0.90 \text{ W/m}^2\text{K}$
Glazed entrance	$U_w = 1.00 \text{ W/m}^2\text{K}$
Thermal bridges	To be identified
Air permeability (q_{50}/n_{50})	0.3 l/s, m^2 1.0 h^{-1}

Table 2
Input data for simulations – HVAC, equipment, solar energy.

HVAC, equipment, solar energy	
Heating and cooling	Set point for temperature; 21–23 °C
Ventilation	VAV ventilation 1–8 l/s, m^2 heat exchange efficiency; 82% ventilation operating weekdays 6–18 (ventilation off; July and Christmas)
Lighting and equipment	Lighting (on/off); 6.7/0.1 W/m^2 operating weekdays 7–17, off; July and Christmas Equipment (on/off); 6.7/0.1 W/m^2 operating weekdays 7–17, off; July and Christmas
Occupancy	Occupancy load; 0.05 occ/m^2 weekdays 7–17
Heat pump	COP ^{heating} ; 3COP ^{cooling} ; 20
Solar energy	PV _{Area} ; 450 m^2 , kW _{pv} ; 67.5

Table 3
Different options as basis for calculations and simulations.

Name	Description
Base case	As described in Fig. 3
Opt. 1	Windows and glazing, U_w ; 0.80 $\text{W/m}^2\text{K}$
Opt. 2	Solar shading all windows and glazing, fixed overhang; $\alpha = 30^\circ$
Opt. 3	Solar shading all windows and glazing, fixed overhang; $\alpha = 45^\circ$
Opt. 4	Solar shading all windows and glazing, fixed overhang; $\alpha = 60^\circ$
Opt. 5	Air permeability (q_{50}/n_{50}); 0.15 l/s, $\text{m}^2/0.5 \text{ h}^{-1}$
Opt. 6	Heat exchange efficiency; 90%
Opt. 7	All building elements, excluding windows and glazing; 0.11 $\text{W/m}^2\text{K}$ including thermal bridges
Opt. 8	Opt. 1, 4, 5, 6 and 7

In addition to the base case, calculations and simulations for other options, described in Table 3, are investigated

3. Results

Examining the construction design, sixteen potential thermal bridges were identified and calculated. All specific values for thermal bridges were increased by 10%, as input data for simulation, to account for any additional thermal bridges not identified (safety margin). The thermal bridges are presented in Fig. 6. The thermal bridges increase the transmission heat transfer losses by 29%. In Fig. 7, the relative impact of each identified thermal bridge is presented. The relative impact is calculated by multiplying the specific value of each thermal bridge with the specific quantity. As can be seen, roughly 50% of the transmission heat transfer losses through thermal bridges occur in junctions to the floor slab. A rather large share of the transmission heat transfer losses through thermal bridges also occur in junctions to windows.

To enable comparison of the static calculations and the dynamic simulations, the results from the calculations and simulations of peak loads for heating and cooling are presented together in Fig. 8 (left). Also, the Net ZEB balances for the different options are presented (right).

Examining peak loads for heating and cooling, there are differences between the calculated and simulated results. Regarding peak load for heating, the simulations show a slightly higher peak load compared to the calculated value.

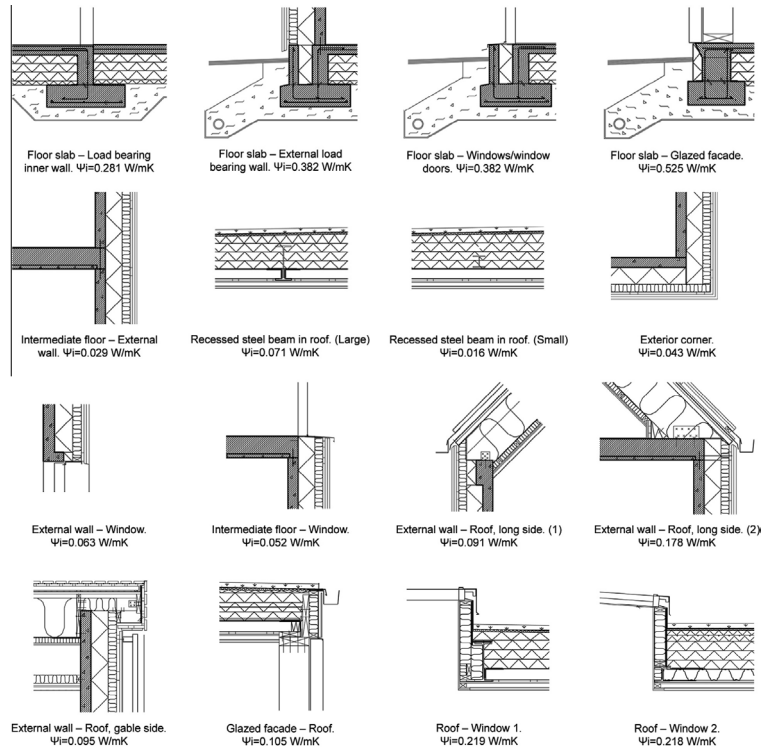


Figure 6. Identified thermal bridges. Presented values do not include any safety margin.

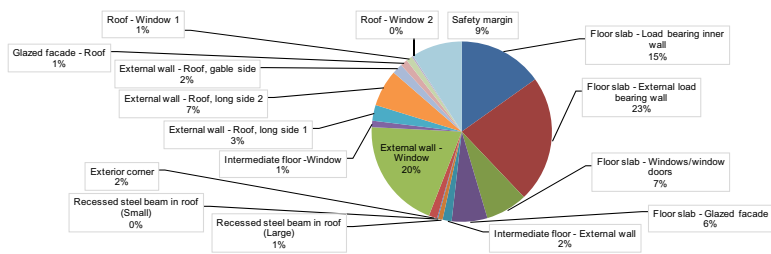


Figure 7. Relative impact of identified thermal bridges.

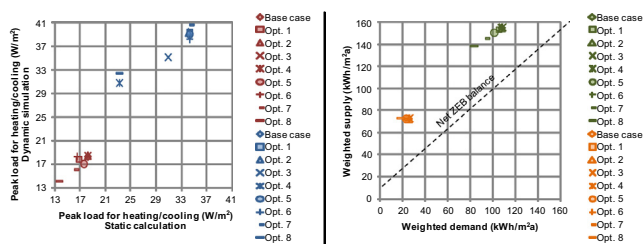


Figure 8. Left: peak load for heating (red, lower left in figure) and cooling (blue, upper right in figure), static calculations vs. dynamic simulations. Right: weighted supply and weighted demand. Import/export balance (orange, lower left) and load/generation balance (green, upper right) are presented.

This is likely due to that the lowest outdoor temperature in the simulation ($-11.1\text{ }^{\circ}\text{C}$) is lower compared to the calculated design temperature for heating ($-9.2\text{ }^{\circ}\text{C}$). The largest percentage difference within peak load for heating is within option six, where the heat exchange efficiency is increased. This could be due to that the peak loads appear at night when the ventilation is off, which affects the simulation but not the static calculation. Over all, comparing static calculations and simulations regarding peak load for heating, show rather small percentage differences; 1–11%.

There are bigger differences comparing peak loads for cooling; 11–34%. The biggest differences are in options where large external overhangs are considered, option four and option eight. The percentage differences are 29% and 34%, respectively. In all other options, percentage differences vary between 11% and 17%. A better convergence may be reached by adjusting the simplified model, choosing a later day of the year to calculate the solar height and adjusting assumed intensity of the solar radiation.

The building as built, and all investigated options, outperforms the Net ZEB balance (Fig. 8 right). Examining the import export/balance for the different options in Fig. 8, it is hard to distinguish differences between the different options. This is due to the geothermal heat pumps which reduce the effects of the different investigated options. The effects of the different options are somewhat larger when investigating load/generation balance in the same figure.

There are no disparities in the difference between load-generation and import-export for each investigated option. This is due to that the simulations did not include modeling of hot water storage tanks. It is assumed that the consumption of electric energy for heat pumps simply is the heat-and cooling loads divided by the specific COPs assumed for the system. More detailed modelling of the heat pumps and the hot water storage tanks would result in disparities.

4. Discussion and conclusions

Since this office was designed before there was a Swedish definition of Net ZEB; it is not surprising that all require-

ments within the Swedish Net ZEB definition are not fulfilled. However, this study shows that it is possible to reach the most important requirement in the Swedish Net ZEB definition, i.e. the Net ZEB balance, using existing technologies. The office building, as built, theoretically reaches the Net ZEB balance but does not fulfil the energy efficiency requirement regarding peak load for heating and U-values for windows set in the Swedish Net ZEB definition. To reach the requirement regarding peak load for heating all investigated options would have been needed to include.

A large share of the transmission heat transfer losses occur through thermal bridges (29%). This may be perceived as if the building has large thermal bridges. This is not the case. The thermal bridges account for a relatively large share primarily due to that all building elements have a high heat resistance. However, thermal bridges occurring in junctions related to the floor slab and windows could have been better designed. The footings around the floor slab perimeter and underneath the interior load bearing walls could have been fitted with insulation underneath and on the exterior side. The reason for not mounting insulation around the footings is most likely due to structural design; the risk of settling is low when no insulation is used. However, there are insulation products on the market that may handle/carry large loads, e.g., Foamglas® (Foamglas, 2013) and XPS, extruded polystyrene boards, (Sundolitt, 2013). The specific value of the thermal bridge due to window embrasures is relatively low. The high relative impact is due to the large quantity. So even if the specific value is low some extra attention should have been given to the junction between external wall and window. The thickening of the interior concrete construction could probably be reduced in order to further reduce the thermal bridge.

Examining the impact of the different options; three options have a slightly larger impact on the energy demand of building. Hence, the following recommendations could be given if the building still was in the design phase, or was to be redesigned:

- Investigate whether it is feasible to further improve the heat resistance of building elements, i.e., investigated option seven; all building elements, excluding windows and glazing; $0.11 \text{ W/m}^2\text{K}$ including thermal bridges, reduced the energy demand by 13%.
- Try to improve the air tightness. Make sure to carry out early air tightness tests, to identify potential improvements, and to test the building as built, i.e. investigated option five; air permeability ($q_{50/n_{50}}$) $0.15 \text{ l/s, m}^2/0.5 \text{ h}^{-1}$, reduced the energy demand by 6%.
- Investigate if it is possible to install windows with lower U-value, i.e., investigated option one; windows and glazed entrance, Uw; $0.80 \text{ W/m}^2\text{K}$, reduced the energy demand by 2%.

It shall be noted that the Swedish Net ZEB definition excludes energy used for plug loads. To ensure low costs related to energy use during operation; all measures that may reduce the use of electricity should be investigated.

After testing the Swedish Net ZEB definitions some points may be made. The *physical boundary* is rather clear. To further enhance the clearness, the definition could refer to the building site as the physical boundary, if that is what is intended, instead of referring to the Swedish building regulations.

The *Balance boundary* is also rather clear. A complementary reference to the Swedish building regulations could be the reports published by SVEBY (SVEBY, 2011), which clarify and interpret the Swedish building regulations. E.g. the Swedish building regulations do not specifically give guidance regarding whether energy for elevators are included in the balance boundary, but SVEBY does.

Regarding *Boundary conditions*; the design temperatures which shall be used to calculate the peak load for heating are well defined. Input data for simulations could be further clarified, both regarding interior and exterior boundary conditions. However, there are many factors affecting the result of an energy simulation. It may be more suitable to specify a report template or to develop a simple tool to verify the energy performance. Preferably it could be an upgrade of the existing tool; Energihuskalkyl (Aton Teknikkonsult AB, 2009).

The Net ZEB definition uses the terms import and export on a yearly basis. Hence there is no actual need to clarify the *Type of balance*. However, since there are no defined input data in short time steps, it may be more suitable to use load/generation balance, i.e., the annual energy needed and the annual energy generated.

If load/generation balance is introduced there may be a need to specify how to calculate/consider on-site generation that does not have the ability to export excess energy, e.g., solar thermal collectors producing heat for domestic hot water.

There are today no requirements regarding *Temporal energy match characteristics*. A future update of the Swedish Net ZEB definition may include these. If these should

be included, further studies should be made in collaboration with stakeholders representing the Nordic energy infrastructure. As an alternative to *Temporal energy match characteristics* quasi-static or dynamic weighting factors could be used.

This study also presents a simplified method for calculations of peak loads for cooling. The method could be improved and used as a method to estimate peak loads for cooling in early design phases.

The Swedish Net ZEB definition was not available when this building was designed and constructed. All investigated options would have been able to implement except for the requirement on U-values for windows and glazing. To be able to meet that specific requirement, changes in the architectural design would have been required. From a design perspective it is always important to consider measures for energy efficiency before aiming at a Net ZEB Balance. Net ZEB office buildings may not need the same requirements on energy efficiency as residential buildings due to the rather high internal heat gains. The energy efficiency is likely to be optimised anyway due to market principles: it is very costly to construct a Net ZEB that is not first of all an energy efficient building.

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The building will be assessed during the operational phase, 2012–2014, in order to verify simulations and to assess the indoor environment. The measurements are to a large extent financed by LÅGAN (2013).

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Article 2



LCE analysis of buildings – Taking the step towards Net Zero Energy Buildings



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ABSTRACT

The basic concept of a Net Zero Energy Building (Net ZEB) is that on-site renewable energy generation covers the annual energy load.

The main objective of this study is to analyse the increase of embodied energy compared to the decrease of the energy use related to building operation; partly by a literature review, partly by detailed analysis of eleven case studies; taking the step from a low energy building to a Net ZEB. The literature review shows that the metric of evaluation, assumed life-span, boundary conditions, age of database and the origin of database differ in different studies and influence the result of embodied energy. The relationship between embodied energy and life cycle energy use is almost linear for all cases studied herein. During the last two decades, embodied energy in new buildings has decreased slightly. However, the relative share of embodied energy related to life cycle energy use has increased. The detailed life cycle energy analysis show that taking the step from a low energy building to a Net ZEB results in a small increase of the embodied energy. However, the energy savings achieved in the annual operating energy balance clearly exceed the increase in embodied energy.

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1. Introduction

Today a number of buildings exist for which the design principle has been to achieve a Zero Energy Building (ZEB) or Net Zero Energy Building (Net ZEB) [1–6].

There are many different approaches and definitions of the two concepts. In general, the ZEB concept may be described as an autonomous building which does not interact with any external energy supply system (grid) such as district heating network, gas pipe network, electricity grid or likewise. The Net ZEB concept is a building where the weighted supply of energy from the building meets or exceeds the weighted demand and interacts with an energy supply system (grid). Such a building can export energy when the building's system generates a surplus and import energy when the building's system is insufficient to generate the energy required. The scope of the energy balance for the Net ZEB may vary for different concepts but is usually based on an annual balance of primary energy [7]. It is not always clear, however, whether this refers to total primary energy or non-renewable primary energy. Within this paper, the term; "primary energy use" is used when it

is not clear whether the source refers to total primary energy use or non-renewable primary energy use.

This paper focuses on Net ZEBs. In Net ZEB definitions, there may or may not be a maximum limit on energy demand. The requirements are generally that the demand is covered by renewable energy sources and that the building is in compliance with the national standards and regulations. However, to meet the goal, a low demand gives an advantage. The general approach to reach Net ZEB could be described as a two-step concept. The first step is to reduce the energy demand by applying energy efficiency measures. The second step is to supply energy, generated by renewable sources, which may be supplied into an external grid when favourable [8–11]. This is illustrated in Fig. 1.

Reduction of energy demand has been promoted worldwide for some time and the techniques used have been applied in Passive Houses and low energy houses for many years and are adapted in the most known Net ZEBs [12]. The basic principle in heating dominated climates may be summarized as design and construction of a well insulated and airtight building envelope in combination with balanced ventilation with high heat recovery efficiency [13–15].

When the energy use of a building is discussed from a lifecycle perspective, it is today generally alleged that energy use in the operational phase of buildings accounts for 70–90% of energy used during its life cycle. There are a number of substantiated and extensive studies with results supporting that allegation [16–20]. Those

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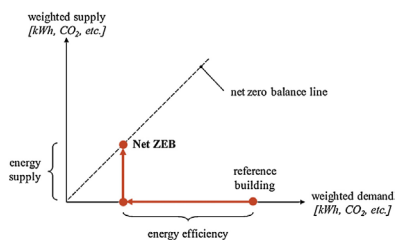


Fig. 1. Schematic presentation of demand/supply balance of a Net ZEB [11].

studies differ in regard to calculation methodology used to account for the total energy use, Life Cycle Energy (LCE), but they reach similar conclusions which support the statement above. However, the consequence is that for Net ZEBs the relative share of energy use related to building operation will decrease.

Earlier studies have mainly focused on embodied energy in buildings with energy performance more or less equal to national building regulations or low energy buildings. An Italian study [21] compared a standard house and a low energy house, clearly showing the changing role of embodied energy in relative terms. The non-renewable primary energy use for construction and maintenance increased by 20% when taking the step from the standard house to a low energy house. However, the relative share of embodied energy of the total life cycle energy use increased from 17% to roughly 50%.

Sceptics to the Net ZEB concept might even argue that the energy savings achieved related to building operation of a Net ZEB is lower compared to the increased energy use for production, maintenance and demolition. A German study [22] compared different concepts for a building; built according to building regulations, low-energy house, Passive House and ZEB for a lifespan of 80 years. In general, the life cycle energy use decreased for each step taken towards the Passive House standard. Taking the step to the ZEB, the life cycle energy use increased. The life cycle energy use of a ZEB consists of embodied energy only. Due to the very high technical level of the ZEB, mainly due to the need of large energy storage system, the life cycle energy use of a ZEB is higher compared to a Passive House.

It may be argued that the German study is inconsistent since the life cycle energy use for the ZEB includes all embodied energy for the building's on-site generation and energy storage systems, whereas the embodied energy of the grid supplying the Passive House with energy is not included in the life cycle energy balance comparison.

The main purpose of the study presented in this paper is to analyse the embodied energy where the focus is on the impact on the total life cycle energy use when the step is taken from a low energy building to Net ZEB instead of ZEB and to highlight important parameters that the authors believe should be addressed in the context of a life cycle energy analysis.

Life cycle energy analysis is one way of conducting Life Cycle Assessment (LCA). Other ways to assess the environmental impact of buildings may be to calculate the carbon footprint or Life Cycle CO₂ (LC CO₂). Some studies combine the evaluation of life cycle energy use with calculation of global warming potential, ozone emissions, carbon foot print, etc. [21,23,24]. The relative impact of different measures will change when applying different methodologies. Especially, this can be seen in [23,24], where the energy analysis is not based on primary energy. Analysing conversion factors for CO₂-equivalents and primary energy, presented

in [11], the ratios are more alike when comparing factors for non-renewable primary energy and CO₂-equivalents than compared to ratios between factors for total primary energy and CO₂-equivalents. However, differences still occur; comparing ratios for non-renewable primary energy and CO₂-equivalents. For example, non-renewable primary energy factors for oil and natural gas are roughly the same, whereas the factors for CO₂-equivalents for oil are roughly 20% higher compared to natural gas. In this study, the metric; non-renewable primary energy is in focus. This is due to that data from previous studies generally were given as primary energy. Specifically, non-renewable primary energy was chosen to better reflect the environmental impact in form of CO₂-equivalents.

Table 1 shows a list of nomenclature used in this paper.

2. Methodology

2.1. Literature review

The literature review was conducted by reviewing peer-reviewed papers and through a survey among participating researchers of the IEA SHC Task40/ECBCS Annex52 "Towards Net Zero Energy Solar Buildings", asking for case studies where LCE analyses were conducted and for information on country specific strategies for LCE analysis.

The purpose of the literature review was threefold;

- Identifying parameters which were handled differently in the studies
- Studying different databases, tools and rating systems used today
- Gathering LCE analysis data to enable analysis of the embodied energy as a relative share of life cycle energy use and the changing role of embodied energy.

All data were normalized into kWh/(m² a). Only data based on primary energy were used, and where all energy use related to building operation was included in the operating energy (OE). However, primary energy factors used were not always presented and it was not always clear whether the data were in total primary energy or non-renewable primary energy. Furthermore, it was not always clearly stated what parts of the energy use were included in operating energy.

2.2. Detailed analysis of Minergie-A buildings

The Minergie® concept was developed in 1994 and since 1998 the Minergie® association has worked continuously to define and promote energy efficient buildings [26]. The Minergie institute has defined three different labels/definitions of energy efficient buildings where Minergie-A [27] is the latest standard for residential buildings, implemented in 2011. A Minergie-A building has a heating demand ≤ 90% of the allowed heating demand according to the Swiss building regulations [28]. Also, a net zero energy balance for space heating, domestic hot water and ventilation is required, based on weighted energy carriers defined in [27]. If the energy carrier for heating is wood and more than 50% of the space heating and domestic hot water is covered by solar thermal collectors, a credit of 15 kWh/(m² a), weighted energy, is given. It is required to calculate embodied energy, which must not exceed 50 kWh/(m² a), non-renewable primary energy. Energy efficient white goods are required.

Minergie-A buildings are appropriate examples to evaluate the step towards Net ZEBs. They are Net ZEBs; balanced, e.g. energy for plug loads and lighting is not included in the requirements.

In this study, the embodied energy of Minergie-A buildings includes the superstructure, building envelope and the HVAC

Table 1
Nomenclature used in this paper.

ZEB	Zero energy building, autonomous building
Net ZEB	Net zero energy building, all energy as defined in EN 15603 [25] included
Net ZEB _L	Net zero energy building, limited balance; energy for lighting and other services are excluded
LCE	Life cycle energy
LCA	Life cycle analysis
EE	Embodied energy (EE = EE _i + EE _r + DE)
EE _i	Initial embodied energy
EE _r	Recurring embodied energy
DE	Demolition energy
OE	Operating energy, Net energy use related to building operation
HP	Heat pump
PV	Photovoltaic
ST	Solar thermal
EPR	Energy payback ratio
EPT	Energy payback time
NER	Net energy ratio

system. The calculation of embodied energy was carried out based on data from the Bauteilkatalog [29]. Embodied energy data within Bauteilkatalog includes energy for replacement when the expected service life time expires and energy for demolition is included (cradle to grave analysis). Hence, the total life cycle energy use is analysed.

Further analysis focused on studying the effect on embodied energy and operating energy due to photovoltaic panels (PV panels), and solar thermal collectors. All buildings were redesigned and recalculated to examine the effect of taking the step towards Net ZEB, using a three-step approach:

- Buildings' redesigned and recalculated without PV panels (low energy standard).
- Buildings' redesigned and recalculated with enough PV panels to meet a Net ZEB_L balance.
- Buildings' redesigned and recalculated with enough PV panels to meet a Net ZEB balance.

When data was extracted from the data base (July 2011) [30], a total of 11 buildings had applied for Minergie-A certification. For this study, all data for the Minergie-A buildings were recalculated with Swiss weighting factors for non-renewable primary from SIA 2031 [31] (Table 2).

Operating energy use for plug loads and lighting are not included in the Minergie® calculations. To enable analysis including the total operating energy, energy for lighting and plug loads was included in the energy demand. This results in an additional OE of 51.7 kWh/(m² a), non-renewable primary energy. This estimation is based on a mean value of 20.5 kWh/(m² a) of delivered electricity, measured for plug loads and lighting in 16 Passive House dwellings in Sweden [15].

3. Results and discussion

3.1. Literature review

Within the literature review, a total of 143 case studies were collected [19,20,32–45]. Out of these cases studies, 73 cases were

Table 2
Swiss weighting factors for non-renewable primary energy [31].

Energy carrier	Weighting factor, non-renewable primary energy [–]
Electricity	2.52
Wood	0.05
Pellets	0.21
District heating	0.79
Oil	1.23
Natural gas	1.14

summarized in tabular form in [20]; clearly showing the embodied energy, operating energy and life cycle energy use. A summary of the data for the additional 70 cases is presented in Appendix A, following the same principle to enable comparison. Furthermore 11 case studies were gathered from the Minergie-A database [30], making a total of 154 cases available for analysis.

The basic framework for calculation of life cycle energy (LCE) use was defined differently in different studies. The overall goal, however, was to calculate the sum of all energies incurred in the life cycle of the studied project and/or building. The life cycle energy use may be defined as in Equation 1 according to Ramesh et al. [20] or as graphically described by Dixit et al. [46]. Comparing the two, one can see that the overall framework is the same.

$$LCE = EE_i + OE + EE_r + DE \quad (1)$$

where LCE is the total life cycle energy use, EE_i is the initial embodied energy, OE is the operating energy, EE_r is the recurring embodied energy and DE is the demolition energy.

3.1.1. Country strategies for embodied energy

Today, no country has requirements regarding embodied energy requirement for buildings. Some countries have developed non-mandatory standards [47–49] that could be incorporated as a baseline in a building rating system. Many rating systems enable a possibility to include the environmental impact of building materials in the assessment of a building's environmental impact [26,50–58]. However, only two of twelve Net ZEB definitions reviewed in [7] consider including embodied energy in the Net ZEB balance.

A common barrier for all countries is the lack of a national matured and agreed database for building materials. Within Europe, there are two commonly used, extensive databases; Ecoinvent [59] and GEMIS [60]. However, other databases exist, e.g. [61–65], and a lot of different tools are available to calculate embodied energy, global warming potential, impact of the environment and other parameters for construction materials and assemblies, e.g. [29,66–68].

On a European transnational level, an European Ecolabel and Green Public Procurement (GPP) criteria for buildings is being developed [69]. Within the European Commission, the Joint Research Centre, a web based platform has been developed where guidelines, tools and life cycle data are published [70].

3.1.2. Metrics used in the LCE-analysis

To ensure transparency and consistency, the applied metric for LCE analysis should be primary energy. Dixit et al. [46] concludes that inclusion of delivered energy in LCE analysis creates complications.

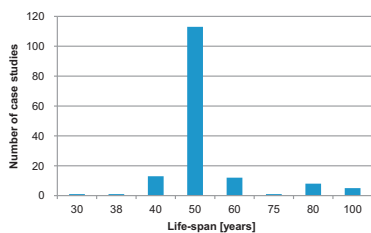


Fig. 2. Allocation of different case studies based on the applied life-span in the 154 different case studies.

Delivered energy may also be referred to as final, end-use or un-weighted energy [7].

Within [19] 45 of 60 cases are presenting operating in primary energy. It is however not always clear whether the term primary energy refers to total primary energy or non-renewable primary energy.

As mentioned in the introduction, some studies combine the evaluation of life cycle energy use with calculation of global warming potential, ozone emissions etc. These types of analyses together with LCE analysis are different types of Life Cycle Assessments (LCAs). The difference between LCA and LCE analysis is that within LCA many different indicators may be used in the evaluation. In LCE, the indicator is always energy. The calculated life cycle energy use is usually divided by an assumed life-span of the building and the conditioned area. Hence the indicator is given in kWh/(m² a).

3.1.3. Life span in LCE-analysis

When the result from the LCE analysis is presented in kWh/(m² a), the expected life-span has no impact on the analysis of operating energy, in absolute terms, if the analysis is based on a simulation of the annual energy use and assumes that the energy supply system, extraction of raw materials for energy generation etc. do not change over time. However, it may have a significant impact on initial embodied energy and demolition energy as this is based on activities that occur once (energy for replacement, recurring embodied energy, may occur more or less than one time) and the energy use is divided by the assumed life-span.

The life-span used in the different studies varies between 30 and 100 years. Out of the 154 different cases, the average life-span is 53 years and the median is 50 years. In Fig. 2, the allocation of the different case studies is shown; the most used life-span is 50 years.

3.1.4. Boundary conditions for the LCE-analysis

A common problem in LCE analysis is to acquire all data coupled to the life cycle. The system boundary may be set where the data collection is getting too difficult and may therefore be strongly related to availability of research resources.

Differences may be found whether demolition, recycling, feed-stock energy and renovation are included. Furthermore, no analysis in the studied material seems to include furnishings. Adalberth [16] and Blengini and Di Carlo [21] include white goods and sanitary ceramics in addition to materials included in the structural elements, building envelope and HVAC-system. Suzuki and Oka [71] and Cole and Kernan [72] are two examples of studies with focus on the materials included in the structural elements, building envelope and HVAC-system.

Studies sometimes refer to life cycle energy use as the sum of embodied energy and operating energy. This may indicate that demolition energy is excluded in the analysis or included in the embodied energy, e.g. in [73] a LCE analysis is presented, excluding demolition energy. In [74] life cycle energy use refers to the sum of embodied energy and operating energy, including demolition energy in the embodied energy. However, the effect of energy use during demolition is often small. In [16] the relative share of energy use due to demolition was <1% of the total life cycle energy use. In [17,21,75] the energy use during demolition was negative, i.e. the energy extracted from the materials through recycling and combustion exceeded energy needed for disassembly. Hence, differences between different studies due to including or excluding demolition energy may be expected to be small.

Based on differences in the reviewed studies it is possible to divide the boundary conditions into two main categories:

- Boundary conditions regarding downstream and upstream processes.
- Boundary conditions regarding material included in the analysis.

To address the second category and to enhance transparency in the LCE-analysis, one may separately analyse the embodied energy of a measure taken to improve the operating energy use of a building. This approach is based on a marginal utility approach and assumes that the building or buildings that are analysed is/are to be built anyway. It is therefore sufficient to analyse the specific effect of different measures in relation to a reference case in order to find good measures from a LCE perspective. This may be implemented in different ways.

Leckner and Zmeureanu [45] use two different indices in LCE-analysis; Energy Payback Ratio, EPR, and Energy Payback Time, EPT. The indices are described in Eqs. (2) and (3).

Hernandez and Kenny [76] suggest the use of a similar index as EPR called Net Energy Ratio, NER. The difference between the two indices is that EPR is based on the total changes over the life cycle and NER is based on the annual change (Eq. (4)). If the operating energy use is based on a simulation of the energy demand and assumes that the energy supply system, extraction of raw materials for production of energy etc. do not change over time, EPR and NER will have the same quota. The NER may also be referred to as Energy Yield Ratio or Energy Return of Investment.

$$EPR = \frac{\Delta OE_T}{\Delta EE_T} \quad (2)$$

where EPR is the energy payback ratio for a specific measure, ΔOE_T is the total life cycle difference of operating energy due to the specific measure and ΔEE_T is the total difference of embodied energy due to the specific measure.

$$EPT = \frac{\Delta EE_T}{\Delta OE} \quad (3)$$

where EPT is energy payback time for a specific measure and ΔOE is the annual difference of operating energy due to the specific measure.

$$NER = \frac{\Delta OE}{\Delta EE} \quad (4)$$

where NER is the net energy ratio for a specific measure and ΔEE is the annual difference of embodied energy due to the specific measure.

3.1.5. Age of data

Energy use means capital expenditures. Therefore, in the production and distribution of materials and components the industry is always looking for cost-efficient ways to streamline and decrease the energy use. As a natural consequence, age of data has a large

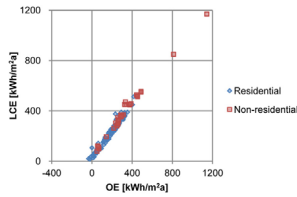


Fig. 3. Relationship between operating energy (OE) and life cycle energy (LCE), primary energy. All 154 case studies are included.

impact on the result of an analysis. A good example of where the market has decreased costs and decreased energy use is the production of Crystalline Silicon PV modules. In [77] the overlap between price and energy pay-back time of Crystalline Silicon PV modules were presented. The study showed that the EPT of PV modules decreased from 20 years, in the 1970s, to below five years, in 2005.

3.1.6. Different data bases

As mentioned in Section 3.1.1, a number of tools and databases that can be used to compile and analyse embodied energy for buildings are available today. Dixit et al. [46] highlight and discuss the source of data as an important parameter that influences the result in embodied energy analysis.

Villa et al. [44] present five case studies in which three different databases have been used (case studies 43–58 in Appendix A, Table A.2). A comparison of the results of calculated embodied energy show a percentage difference of 15–87% for the different case studies due to use of different databases. The authors conclude that an important contributing factor to the differences is different methods used to quantify embodied energy for wooden products in databases used in their analysis.

The differences in the data bases are in general due to the above-named parameters and due to specific conditions regarding energy-mix, fabrication methods and transportation.

3.2. Analysis of case studies

Results given in this section are based on all 154 case studies. In Fig. 3 the relationship between operating energy and life cycle energy is presented for all cases from the literature review together with data from Minergie-A buildings [20,30,32–45]. In Fig. 4, case studies with operating energy > 100 kWh/(m² a) are

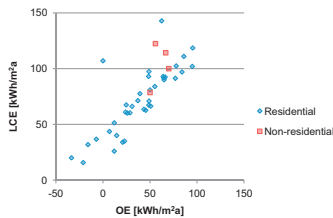


Fig. 4. Relationship between operating energy (OE) and life cycle energy (LCE), primary energy. Case studies with OE < 100 kWh/(m² a).

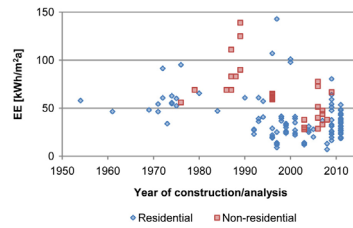


Fig. 5. Embodied energy (primary energy) by year of construction.

excluded. The relationship between operating energy and life cycle energy is almost linear. This data correspond well with the earlier, highlighted, linear relationship in [19,20]. The negative values of operating energy occur if the energy supply exceeds the energy demand.

Low energy buildings and Net ZEBs usually requires more material in form of insulation and installations (PV panels, solar thermal collectors, heat pumps etc.). Hence it could be logical to assume that the linear relationship between operating energy and life cycle energy would flatten out. However the tendency is that the linear relationship is constant. This may be due to that design and construction often has a focus on sustainable material management. Furthermore, PV panels and solar thermal collectors generate more energy during building operation, compared to the embodied energy. It may also be partly due to that newer buildings show a tendency of a lower embodied energy compared to older buildings, see Fig. 5. The decrease could be due to more efficient use of materials and more efficient manufacturing.

In Figs. 6 and 7 the relationship between the operating energy and the embodied energy as percentage share of life cycle energy use is presented together with an exponential regression for residential buildings and non-residential buildings. As there are no case studies for non-residential buildings where operating energy ≤ 0 kWh/(m² a), data for a fictitious building have been incorporated.

Using the exponential regression formulas, the embodied energy exceeds 50% of life cycle energy use when the annual operating energy use is ≥ 33 kWh/(m² a) and ≥ 45 kWh/(m² a) for residential and non-residential buildings respectively. It may occur as strange that embodied energy as a share of life cycle energy exceeds 100% when the operating energy < 0 kWh/(m² a). The effect is due to buildings that annually supply more energy than the

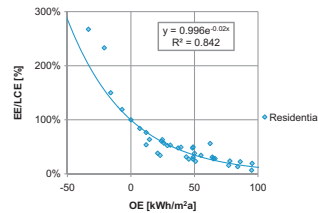


Fig. 6. Relationship between OE and EE/LCE (primary energy) for residential case studies with OE < 100 kWh/(m² a).

Table 3
Summary of characteristics for Minergie-A buildings [30].

Case study	Gross area [m ²]	Life span	EE [kWh/(m ² a)]	OE [kWh/(m ² a)]	LCE [kWh/(m ² a)]
71	374	60	53	-33	20
72	227	60	32	29	60
73	440	60	49	49	98
74	290	60	48	-16	32
75	221	60	43	25	67
76	306	60	38	39	78
77	249	60	37	-21	16
78	314	60	34	26	60
79	1206	60	37	7	44
80	1087	60	34	37	71
81	1056	60	44	49	93

annual energy demand, every year generating a surplus and thus reducing the total life cycle energy use.

3.3. Detailed analysis of Minergie-A buildings

3.3.1. Characteristics of Minergie-A buildings

A summary of the gathered data from the Minergie-A database is presented in Table 3. All cases are residential buildings. Three stakeholders outperform the Minergie-A requirement of Net ZEB_L balance, with the goal to reach Net ZEB balance (case studies 71, 74 and 77).

All case studies have installed PV panels. Except no. 76, all buildings have applied energy efficiency measures similar to a Passive House design with advanced thermal insulation and ventilation with heat recovery. Buildings without heat pump (HP), have installed pellet-/wood boiler. None of the Net ZEB buildings have installed heat pump.

The deviation and mean values of photovoltaic peak power and area of solar thermal collectors (STC) per heated areas based on Table 3 and sorted by the Net ZEB balance concept are shown in Fig. 8. Generally, buildings without a heat pump (HP) have larger solar thermal collectors and PV panels than buildings with heat pump. Also, buildings with Net ZEB balance have larger solar thermal collectors and higher installed nominal power (kWp) for PV panels than buildings with Net ZEB_L balance.

In case studies with Net ZEB_L balance, installation of a heat pump enables a mean reduction of solar thermal collectors by 50%. Installed nominal power (kWp) for PV panels are roughly the same. None of the Net ZEB balance buildings have heat pump.

Assuming that the buildings are equal to low energy/Passive House standard, taking the step from a low energy house/Passive House to a Net ZEB_L acquires instalment of 0.019 kWp PV panels and 0.030 m² of solar thermal collectors per gross heated floor area. Alternatively; 0.020 kWp for PV panels, 0.015 m² of solar thermal collectors and a heat pump.

Comparing cases without heat pump; taking the step from Net ZEB_L to Net ZEB acquires a mean increase of PV panels by 0.018 kWp and solar thermal collectors by 0.050 m² per gross heated floor area. This roughly corresponds to, taking the step from Net ZEB_L to Net ZEB, a doubled kWp installed for PV panels. The ratio of solar thermal collector area, comparing Net ZEB and Net ZEB_L, are eight to three.

The average installed PV power, kWp/m², for Net ZEBs corresponds well with [12], which provides more in-depth analysis of Net ZEB characteristics. More detailed analyses of the characteristics of Net ZEBs may also be found in [3,4].

3.3.2. Energy Payback Time and Net Energy Ratio

Energy payback time (EPT) and net energy ratio (NER) were calculated according to Eqs. (3) and (4). In order to calculate EPT and NER, ΔOE needs to be calculated. The calculations are based on non-renewable primary energy.

The results differ depending on the energy source replaced. e.g. if solar thermal collectors are replacing 1 kWh of electricity; ΔOE = 2.52 kWh, replacing 1 kWh of district heating; ΔOE = 0.79 kWh etc.

To compare the different energy supply strategies: district heating, electricity, oil or natural gas was compared with the photovoltaic, solar thermal or heat pump systems. The deviation and mean value of EPT and NER for all cases are presented in Table 4. Basis for the calculations is presented in Appendix B.

Heat pumps show by far the lowest EPT, often less than one year. The EPT for PV panels are often ten times higher, and for solar thermal collectors often three times higher. Hence, installing a heat pump is a recommended solution from a LCE perspective.

PV panels have the highest EPT and should therefore be the last option to consider. If, for any reason, the option of installing a heat pump is not chosen; the appropriate design strategy

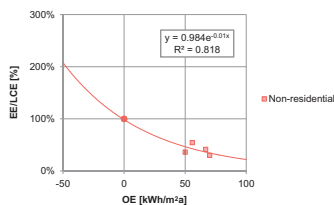


Fig. 7. Relationship between OE and EE/LCE (primary energy) for non-residential case studies with OE < 100 kWh/(m² a).

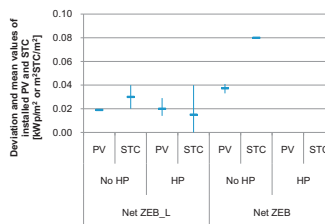


Fig. 8. PV and ST, sorted by type of Zero-balance concept and with/without installed HP. Distribution of PV and ST per heated floor area.

Table 4
Results from calculations of EPT and NER.

Renewable energy supply option	Replacing energy source	Energy payback time [years]			Net energy ratio [-]		
		Max	Min	Mean	Max	Min	Mean
Photovoltaic	District heating	13.1	10.4	11.5	2.9	2.3	2.6
	Electricity	4.1	3.2	3.6	9.2	7.3	8.3
	Oil	7.7	6.1	6.8	5.0	3.9	4.5
Solar thermal	Natural gas	8.6	6.8	7.6	4.4	3.5	4.0
	District heating	4.7	2.6	3.8	7.6	4.3	5.4
	Electricity for heating	1.3	0.7	1.1	27.0	15.2	19.3
	Oil	2.7	1.5	2.2	13.0	7.3	9.3
Heat pump	Natural gas	3.1	1.7	2.5	11.6	6.5	8.3
	District heating	1.3	1.0	1.1	30.1	22.2	27.6
	Electricity for heating	0.4	0.3	0.3	106.6	78.8	92.8
	Oil	0.8	0.3	0.5	94.0	38.0	68.8
	Natural gas	0.9	0.3	0.5	94.0	33.8	66.3

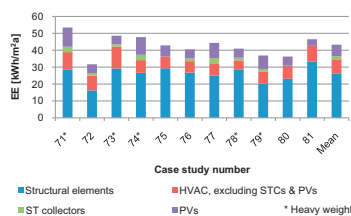


Fig. 9. Embodied energy (EE) within Minergie-A cases (non-renewable primary energy). Cases marked with * indicates heavy weight superstructure.

would be to first size and install a solar thermal collector system with respect to the energy needed for heating before considering PV. Furthermore, electricity generated from PV should not be used within the building to replace district heating; instead it should be exported to the grid, in order to replace electricity. However, this design strategy assumes that there is always an energy load in the grid. Furthermore it does not consider possible increased stress on the grid if an export strategy is chosen.

Examining the NER calculations, where high NER is preferable, confirms the recommendations above. However, some differences may be noted. Within the EPT comparison, there was roughly a factor three difference between PV panels and solar thermal collectors. Comparing NER, the difference is reduced; roughly to two. Comparing the heat pumps and solar thermal collectors, the mean factor difference of EPT is 3.8. The mean factor difference of NER is 5.8. The differences occur due to that the NER methodology includes the effect of the expected service life time of a measure. In this case

the service life times are 30 years for PV panels and heat pumps, and 20 years for solar thermal collectors.

3.3.3. Distribution of embodied energy in Minergie-A projects

The distribution of embodied energy within the different Minergie-A cases are presented here. The results should be studied in the context that they are based on mid-European climate and primary energy factors for Swiss non-renewable primary energy factors [31].

The deviation of embodied energy in Minergie-A cases is shown in Fig. 9. Roughly 60% of the embodied energy is due to the structural elements, 20% for HVAC and 20% for solar thermal collectors and PV panels. Heavy weight buildings do not necessarily have a higher embodied energy for structural elements. This could be a result of differences in expected life span for light and heavy weight constructions. Light weight walls have an expected life span of 40 years, heavy walls 60 years [29].

The detailed distribution of embodied energy and operating energy use is presented in Fig. 10. For each project, demand and supply related to operating energy and embodied energy is presented. e.g. there is an energy demand to produce PV panels, presented as embodied energy on the demand side in Fig. 10 (EE PVs). However, the PV panels also supply energy during building operation, presented as operating energy on the supply side (OE PVs).

Examining the demand for the different cases, the following rough division may be done: 35% is embodied energy, 45% is demand for plug loads and lighting and 20% is demand for heating, hot water and mechanical systems. The deviation of loads are roughly the same for buildings with Net ZEB, balance and Net ZEB balance.

Fig. 11 shows mean values of operating energy use and embodied energy for the three different building standards based on the

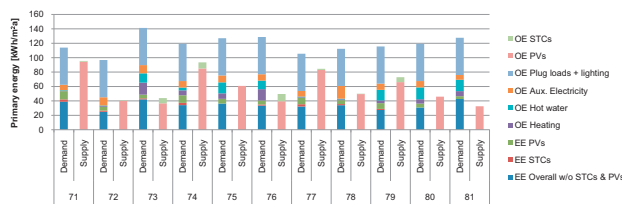


Fig. 10. Distribution of operating energy (OE) and embodied energy (EE) by demand and supply in Minergie-A projects (non-renewable primary energy).

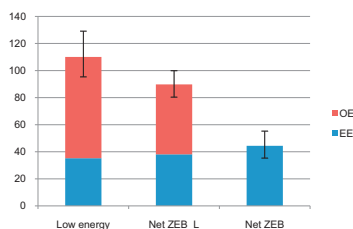


Fig. 11. Mean values of embodied energy (EE), operating energy (OE) and the variation of life cycle energy use (non-renewable primary energy), comparing three different building standards.

11 Minergie-A cases, recalculated as stated in Section 2.2. Also the variation of the total life cycle energy use is presented.

The results show that the increase of embodied energy does not negatively affect the step from a low energy building towards a Net ZEB. When taking the step from a low energy building to a Net ZEB, the increase of embodied energy is about 25%. However, the operating energy use drops down to zero. The life cycle energy use of a Net ZEB is calculated to be about 40% of the life cycle energy use of a low energy building. The life cycle energy use of a Net ZEB is much lower compared to a low energy building.

4. Conclusions

Since the oil crisis in the 1970s, efforts have been made to reduce energy use in buildings to reduce the oil dependency. Today, reduction of energy use in buildings is also seen as an important strategy for climate mitigation. As the operational energy (OE) is reduced, the relative share of embodied energy (EE) increases.

Worldwide, extensive work has been carried out or is in progress to identify and calculate the environmental impact from construction materials or assemblies. However, a mandatory national requirement for buildings is unlikely to be seen within the next few years. This is largely due to that it requires a large effort to collect, calculate and analyse the environmental impact of different materials. Furthermore, there is no standardized approach for data collection.

In the review of previous studies, five parameters have been identified which vary between the different studies and thus may influence the outcome; metric of evaluation, assumed life-span, boundary conditions, age of data and the origin of database. In order to increase transparency and allow for comparison between different studies, these parameters should always be clearly stated. In the review, it is possible to distinguish favoured choices within two of the parameters; life-span and metric of evaluation. The most used life span is 50 years and most studies choose consistently to apply primary energy for the LCE analysis.

The literature review shows that methods for calculating life cycle energy use are far from standardized. Today, it is therefore not suitable to try to include EE in a Net ZEB balance. However, it may be suitable to have as an additional/complementing requirement as defined within the Minergie-A requirements. To further facilitate the interpretation, clarification of results and increased transparency of analysis, the guidelines given in EN ISO 14040 [78] and EN ISO 14044 [79] may be followed.

Despite differences in different studies, the compilation shows that the previously found linear relationship between OE and LCE

[19,20] remains when the step is taken towards the Net ZEB balance.

Taking the step from Net ZEB_i to Net ZEB by increasing the use of solar energy roughly doubles the needed kWp of PV panels and more than doubles the area of solar thermal collectors. It is therefore imperative that all possible and cost efficient energy efficiency measures are applied in order to enable reaching the Net ZEB balance, especially in larger building where the relative areas suitable for PV panels and solar thermal collectors in relation to the heated area decreases. The analysis of EPT and NER for solar energy options shows that electricity from PV panels should primarily be used to replace electricity, not transformed and used for space heating or hot water heating.

The detailed analysis of the 11 Minergie-A buildings show that roughly 45% of energy demand is due to plug loads and lighting and 35% is embodied energy. The remaining energy loads are energy for heating, hot water and HVAC systems. The embodied energy is roughly to 60% due to structural elements, 20% due to HVAC systems and 20% due to ST collectors and PV.

The embodied energy increases slightly when taking the step from a low-energy building towards Net ZEB balance. However, the energy savings achieved related to building operation OE exceeds, with great margin, the increased embodied energy. The overall assessment shows that the life cycle energy use of a Net ZEB is about 60% lower compared with the life cycle energy use of a low energy building/Passive House. From a life cycle energy perspective, the Net ZEB is preferable over a low energy building.

Today, structural elements hold the largest share of embodied energy in buildings. Therefore, a first step of implementing analysis of embodied energy could focus on structural elements. Technical systems that reduce the operating energy use, e.g. solar thermal collectors, PV panels and heat pumps, if properly designed; always reduce the operating energy use more than the increase of the embodied energy incorporated in the technical system.

The embodied energy has decreased slightly over time, indicating that the construction of buildings and technical systems in general has become more efficient over time. However, the relative share of embodied energy of the total life cycle energy is increasing. Increased use and acceptance of LCE analysis as an important parameter in the design of buildings may in a near future lead to design decisions not only based on energy savings related to operating energy. Thus, in new construction, choosing insulation material with low EE instead of increasing the amount of insulation in an already well-insulated construction may be a decision in a not so distant future.

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Appendix A.

See Tables A.1 and A.2.

Table A.1
Summary of gathered non-residential case studies with LCE-analysis (primary energy).

Case study	Size [m ²]	Lifespan	EE [kWh/m ² a]	OE [kWh/m ² a]	LCE [kWh/m ² a]	Reference
1	4400	50	38	258	296	[32]
2	4400	50	78	376	453	[32]
3	2151	80	30	70	100	[33]
4	4719	80	51	143	194	[34]
5	1700	50	67	56	123	[35]
6	1516	50	48	67	114	[4,36]
7	11,170	38	29	50	79	[37]
8	7300	75	28	1142	1170	[38]

Table A.2
Summary of gathered residential case studies with LCE-analysis (primary energy).

Case study	Size [m ²]	Lifespan	EE [kWh/m ² a]	OE [kWh/m ² a]	LCE [kWh/m ² a]	Reference
9	236	50	34	206	240	[39]
10	91	50	57	208	265	[39]
11	135	50	39	317	356	[39]
12	155	50	52	310	362	[39]
13	132	50	58	236	294	[39]
14	163	50	46	172	218	[39]
15	120	50	55	255	309	[39]
16	140	50	46	403	449	[39]
17	239	50	54	195	250	[39]
18	211	50	66	187	252	[39]
19	140	50	36	185	221	[39]
20	130	50	61	192	253	[39]
21	154	50	41	211	252	[39]
22	120	50	55	322	377	[39]
23	147	50	63	168	231	[39]
24	170	50	56	188	244	[39]
25	120	50	91	241	332	[39]
26	320	50	47	200	247	[39]
27	121	50	48	305	353	[39]
28	164	50	61	327	388	[39]
29	122	50	61	189	250	[39]
30	305	50	40	111	151	[39]
31	168	50	52	202	254	[39]
32	192	50	60	166	227	[39]
33	124	50	95	417	512	[39]
34	200	50	20	44	64	[40]
35	200	50	17	46	63	[40]
36	200	50	16	51	66	[40]
37	200	50	19	49	67	[40]
38	200	50	14	77	91	[40]
39	108	50	61	163	223	[41]
40	45	60	26	15	40	[42]
41	228	50	37	353	390	[43]
42	228	50	41	115	157	[43]
43	1404	50	23	217	240	[44]
44	1404	50	54	217	271	[44]
45	1404	50	64	217	281	[44]
46	1404	50	16	228	245	[44]
47	1404	50	20	228	248	[44]
48	1404	50	26	228	255	[44]
49	1404	50	20	227	246	[44]
50	1404	50	23	227	250	[44]
51	1404	50	23	227	250	[44]
52	1453	50	31	131	163	[44]
53	1453	50	59	131	190	[44]
54	1453	50	51	131	182	[44]
55	1484	50	33	125	158	[44]
56	1484	50	48	125	172	[44]
57	1484	50	38	125	163	[44]
58	982	50	80	62	143	[44]
59	96	50	18	239	258	[45]
60	96	50	19	184	203	[45]
61	96	50	20	155	175	[45]
62	96	50	23	95	119	[45]
63	96	50	25	78	102	[45]
64	96	50	26	66	93	[45]
65	96	50	27	65	92	[45]
66	96	50	29	55	84	[45]
67	96	50	31	50	81	[45]
68	96	50	35	31	66	[45]
43	96	50	39	12	51	[45]
70	96	50	44	-7	37	[45]

Table B.1
Effect on ΔEE_r and ΔEE in Minergie-A case studies due to PV and ST collectors.

Case study	ΔEE_r^a [kWh/m ² heated area]			ΔEE^b [kWh/a, m ² heated area]			$-\Delta OE^b$ [kWh/a, m ² heated area]		
	PV	STC	HP	PV	STC	HP	PV	STC	HP
71	341	64		11.4	3.2		37.5	18.3	
72	153	33		5.1	1.6		15.9	10.2	
73	151	28	29	5.0	1.4	1.0	14.6	7.8	26.8
74	313	63		10.4	3.2		33.7	30.6	
75	198			6.6			24.1		
76	162	32	29	5.4	1.6	1.0	15.7	11.7	36.3
77	270	62		9.0	3.1		32.9	25.5	
78	161	32		5.4	1.6		19.6	8.7	
79	241	28		8.0	1.4		26.2	9.7	
80	160		29	5.3		1.0	18.2		34.7
81	118		29	3.9		1.0	12.9		35.5

^a Non-renewable primary energy.

^b Un-weighted energy. Differences in primary energy are calculated using factors presented in Table 2.

Appendix B.

See Table B.1.

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Article 3



Calculation of thermal bridges in (Nordic) building envelopes – Risk of performance failure due to inconsistent use of methodology



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ABSTRACT

Reduction of energy use in buildings is an important measure to achieve climate change mitigation. It is essential to minimize heat losses when designing and building energy efficient buildings. For an energy-efficient building in a cold climate, a large part of the space heating demand is caused by transmission losses through the building envelope. Therefore, calculations of these must be carried out in a correct way to ensure a properly sized heating system and a good indoor climate. There is today a risk of misunderstanding and inconsistent use of methodology when transmission heat transfer is calculated. To investigate the state of knowledge among Swedish consultants a survey was conducted regarding thermal bridges and calculations of transmission heat transfer. Furthermore, the impact of thermal bridges was studied by comparative calculations for a case study building with different building systems and different amounts of insulation. The study shows that the relevant standards and the building code in Sweden are interpreted in many different ways regarding calculation of transmission heat transfer and energy performance. There is a lack of understanding regarding the impact of different measuring methods on thermal bridges. When more insulation is used the relative impact of thermal bridges increases. It is therefore not suitable to use a single predefined percentage factor, increasing the transmission heat transfer through building elements, to account for the effect of thermal bridges. If values for normalized thermal bridges are to be used, they need to be differentiated by building system and different amounts of insulation

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1. Introduction

Buildings account for 40% of the primary energy use and 24% of the generation of green house gases worldwide [1]. The population of the world, and consequently also the building sector, is expanding. Therefore, a reduction of the specific energy demand of buildings and increased use of renewable energy are important measures of climate change mitigation.

To promote improvement of energy performance within the European Union, the members of the European Parliament approved the directive 2002/91/EC on Energy Performance of Buildings, EPBD [2], in December 2002. On the 18th of May 2010 a recast of the EPBD was approved [3] which further clarifies the intention that buildings shall have a low energy demand. The recast of the EPBD specifies that by the end of 2020 all new buildings shall be “nearly zero-energy buildings”. A nearly zero-energy building is defined as a building with a very high energy performance and

the low amount of energy required should be covered to a very significant extent by energy from renewable sources.

Several stakeholders are already today making efforts to design and build buildings that outperform the Swedish building code on energy performance requirements. The share of new dwellings designed as passive houses or low energy buildings has increased noticeably in Sweden. The share in the residential sector has increased from 0.7% in 2008 to 7.2% in 2010. For multi dwelling buildings, the share is even higher, 11.2% in 2010 [4].

To design and build energy efficient buildings, different design strategies may be applied such as the Energy triangle, The Kyoto Pyramid Passive energy design process, The IBC Energy Design Pyramid [5] or the Passive house design principle [6]. They differ slightly from each other, but the common first fundamental step is to reduce the energy demand, which in a Nordic climate is achieved by constructing a well insulated and air tight building envelope in combination with balanced ventilation with high system heat recovery efficiency.

When a building is designed according to such principles, most of the energy demand for space heating is caused by transmission heat transfer through building elements and thermal bridges. It is therefore vital to calculate the transmission heat transfer in a correct way and not exclude or misjudge what may be a potential

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thermal bridge. Poor calculations may lead to undersized heating systems, poor indoor climate and energy costs that exceed expectations. By extension, it is likely that this could lead to economical consequences for the builder, the client and/or the consultants.

This article consistently uses the term; transmission heat transfer, in order to distinguish transmission heat transfer from ventilation heat transfer. These terms are derived from EN ISO 13789 [7].

The EPBD states that the energy performance of buildings should be calculated on the basis of a methodology, which takes into account existing European standards. A commonly used standard to calculate the transmission heat transfer coefficient is EN ISO 13789, which is referred to in most Nordic countries directly or indirectly, e.g. in Denmark [8], Finland [9], Norway [10] and Sweden [11]. To calculate the transmission heat transfer coefficients, the building envelope needs to be clearly defined and divided into different building elements.

The dimension of the building elements can be measured according to three different methods which differ in the way of whether the junctions between different elements are included or excluded in the areas of these elements. Different stakeholders may apply the standard differently; thus there is a risk of misunderstanding.

An additional risk of misunderstanding is that different, usually simplified, methods may be used in order to account for thermal transmittance through thermal bridges [12]. E.g. in the Norwegian standard for calculation of energy performance of buildings, NS 3031 [13], three different normalized thermal bridges values relative to the heated floor area are specified. These values are differentiated based on whether the building has a wooden construction or not and the amount of insulation used to decrease the thermal bridges in the exterior parts of the wall constructions. In Sweden, the impact of thermal bridges may be accounted for by increasing calculated transmission heat transfer through building elements by 20%, regardless of building system used [14]. In Denmark, typical solutions are covered by tabulated values [15]. In Finland, a simplified method is used where the effect of thermal bridges usually are included in the calculated transmission heat transfer through building elements by weighting thermal conductivity of different materials [16]. Calculations and realization of details are not controlled by any authorities [12]. In Germany, thermal bridges are taken into account by increasing the calculated transmission heat transfer by 0.10 W/m²K. However, this increase may be reduced by 50% if junctions between different building elements are designed according to best practice examples, given by the national standard [17].

Simplified methods, not taking into account effects of different construction methods or quantities of insulation, may be incorrect. A previous investigation has indicated that the transmission heat transfer losses due to thermal bridges may increase when more insulation is used in exterior walls [18]. Furthermore, it indicates that the relative increase of the transmission heat transfer through building elements that is needed to account for thermal bridges increases with increased insulation thickness. The increasing importance of thermal bridges are probably the highest in the North European countries since the standard amounts of insulation applied in buildings today are high compared to other European countries [19–24].

The subject, thermal bridges; is not new. There are several studies that have investigated transmission heat transfer losses, through building envelopes including thermal bridges [25–42]. Most of the studies investigate the effect of different calculation and simulation methodologies, such as static/dynamic and 1D/2D/3D [25–31]. Many studies investigate the impact thermal bridges may have on the overall transmission heat transfer losses, through building envelopes [32–37]. Some studies mainly

focus on cost-efficient or cost-optimal quantities of insulation [39–42]. As mentioned earlier, different measuring methods may be used to quantify building elements. Of the previous studies mentioned above; only two studies clearly defines how they quantify building elements [37,41]. Furthermore, all studies on cost-optimal/cost-efficient quantities handle thermal bridges using simplified methods i.e. the results of optimal quantities may be incorrect.

This article presents the state of knowledge regarding thermal bridges among Swedish engineers and architects in order to see if there is a risk of misunderstanding and therefore, need for guidelines. Furthermore, it shows the relative impact of thermal bridges in different building systems using different amounts of insulation. A survey among Swedish engineers and architects was carried out in combination with comparative calculations of thermal transmittance through building envelopes with different external wall constructions and insulation thickness.

2. Methodology

2.1. Calculation of transmission heat transfer through building elements and thermal bridges

To calculate heat transmission through a building envelope, the transmission heat transfer coefficient H_T is calculated as in Eq. (1):

$$H_T = \sum_i A_i U_i + \sum_k l_k \psi_k + \sum_j \chi_j + A_g U_g + P \psi_g \quad (1)$$

where A_i is the area of the building element i adjacent to outdoor air, U_i is the thermal transmittance of the element i , l_k is the length of the thermal bridge k , ψ_k is the linear thermal transmittance of the thermal bridge k , χ_j is the point thermal bridge j , A_g is the area of the ground construction, U_g is the thermal transmittance of the ground construction, P is the perimeter of the ground construction and ψ_g is the linear thermal transmittance associated with wall-floor junction. Calculations of U-values follow EN ISO 6946 [43] and EN ISO 13370 [44].

Thermal bridges may be defined as a part of the building envelope penetrated by materials with different thermal conductivity and/or with changed thickness/amount of materials used and/or with difference between internal and external areas, according to EN ISO 10211 [45].

The linear thermal transmittance of the thermal bridges (ψ) is calculated as in Eq. (2):

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \quad (2)$$

where L_{2D} is the thermal coupling coefficient obtained from a 2-D calculation, U_j is the thermal transmittance of the 1-D element j and l_j is the length of the 1-D element j .

The point thermal transmittance of the thermal bridges (χ) is calculated as in Eq. (3):

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{j=1}^{N_j} \psi_j \cdot l_j \quad (3)$$

Where L_{3D} is the thermal coupling coefficient obtained from a 3-D calculation, ψ_j is the linear thermal transmittance calculated according to Eq. (2) and l_j is the length of the thermal linear thermal bridge.

Measuring of lengths and areas may be done according to three different ways; internal, overall internal or external dimensions. The differences are shown in Fig. 1.

Any of the measurement methods in Fig. 1 may be used. Specific values for linear thermal bridges and point thermal bridges vary depending on the measuring system used. To avoid misunderstandings and to enable comparisons, subscripts shown in Table 1 will be used in this study.

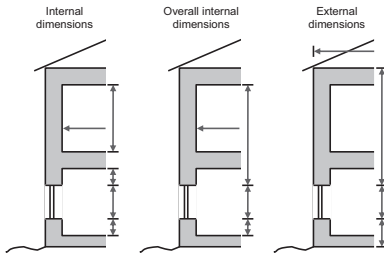


Fig. 1. Three different methods of measurement according to EN ISO 13789.

Table 1
Subscripts to clarify used system of measuring.

Subscript	Definition
<i>i</i>	Internal dimensions
<i>oi</i>	Overall internal dimensions
<i>e</i>	External dimensions

2.2. The survey

Recipients for the survey were gathered by contacting the major building engineering, architect and construction firms in Sweden, explaining that a short survey was to be conducted regarding handling of thermal bridges and energy calculations. If the company had employees who worked with assignments related to these questions, contact information in the form of was collected. Through this method 100 engineers and architects were identified, who received an electronic questionnaire. Two reminders were sent out; in total 73 answers were received from 33 different firms/workplaces. The survey was conducted during September and October, 2010.

The questionnaire was based on three different sections. Initially, the questions addressed measuring methods used for quantification of areas. Subsequently the respondents were asked to review junctions, as shown in Fig. 2, and they were asked whether the junction increases transmission heat transfer in addition to the losses included in building elements or not. Finally, general questions were asked regarding professional background, work experience, approach used to assess thermal bridges, etc.

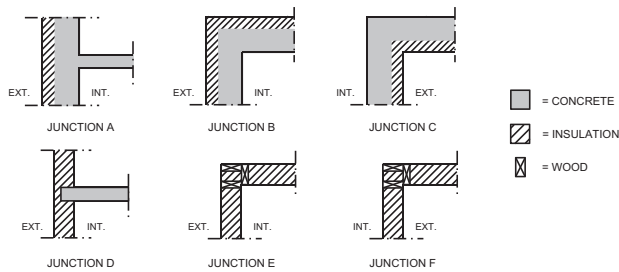


Fig. 2. Presentation of schematic/simplified junctions, included in the questionnaire. Internal environment is marked INT. External environment is marked EXT.

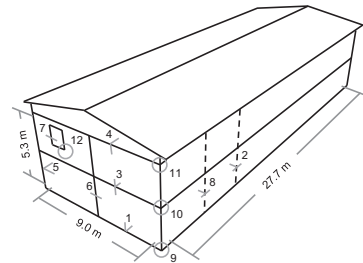


Fig. 3. Case study building.

2.3. Quantification of thermal bridges

To investigate the effect of thermal bridges, a small multi dwelling building with eight apartments was chosen as a case study. The building is a two floor residential building with four apartments on each floor. Different building envelopes and junctions were modelled with HEAT 2.8 [46] and HEAT 3.6 [47]. Key features of the building and the investigated potential thermal bridges are shown in Fig. 3 and Table 2.

Common building systems for exterior walls in Sweden were chosen; concrete walls with external insulation and cladding, precast concrete sandwich walls and insulated wooden frame wall constructions with cladding. The transmission heat transfer coefficient, H_T , was investigated for the three different building categories as shown in Table 3 for all three exterior wall systems. To investigate the differences between the measuring methods, Ψ_i , Ψ_{oi} , Ψ_e , have been calculated for each case and with areas for building elements quantified according to the three different measuring methods.

The U-values for the old building stock and for new buildings were collected from an extensive field study conducted by the Swedish National Board of Housing, Building and Planning, called BETSI [48], and the current energy performance requirements in the Swedish building code [11]. The U-values for best practice were taken from [6]. U-values specified for the old building stock are equivalent to buildings constructed before 1976. To achieve the required U-values, the amount of insulation was varied and different windows were modelled as shown in Fig. 4. In all combinations,

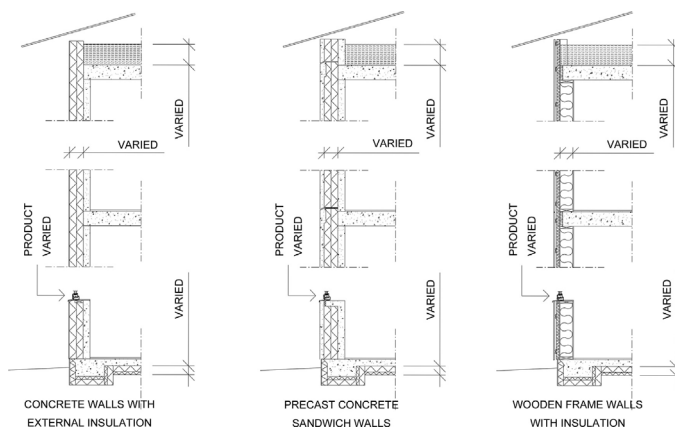


Fig. 4. Description of varied building systems and insulation thicknesses.

accompanying structures as floor slab on ground, intermediate floor and roof construction, were concrete constructions.

3. Results

3.1. The survey

The respondents had good knowledge of energy calculations; 84% (54 respondents) had work experience of energy calculations. Out of these 54 respondents, 63% had more than five years of work experience. This reflects the intention to find experienced professionals.

Table 2
Characteristics of reference building (measuring is based on internal dimensions). Junction number refers to Fig. 3.

Characteristic	Data	Unit	Clarification
Heated area	498.0	m ²	As defined in the Swedish building regulations [11]
Windows/doors	72.5	m ²	
Junction 1	73.3	m	Ground floor slab–exterior wall
Junction 2	30.2	m	Interior load bearing wall–exterior wall
Junction 3	73.3	m	Interior floor slab–exterior wall
Junction 4	73.3	m	Attic floor slab–exterior wall
Junction 5	20.2	m	External wall corner
Junction 6	20.2	m	Connection of prefabricated wall elements
Junction 7	210.4	m	Exterior wall–window-/door frame
Junction 8	70.6	m	Exterior wall–internal non load bearing wall
Junction 9	4	pcs	External corner; floor slab–exterior wall
Junction 10	4	pcs	External corner; interior floor slab–exterior wall
Junction 11	4	pcs	External corner; attic floor slab–exterior wall
Junction 12	144	pcs	External corner; exterior wall–window-/door frame

Internal measuring was most frequently used by the respondents to define building elements, and external measuring was mostly used to define a building's envelope area. However, the deviation of answers shows that there are no specific measuring method that can be assumed to be the norm in Sweden. The other predefined measuring methods were also used to an extent which exceeded 20% for each measuring method.

The results were slightly more uniform when the respondents were asked how they interpret the Swedish definition of building element area, A_i , and enclosing area, A_{om} . The area A_{om} is defined as "Total surface area of the enclosing parts of the building in contact with the heated indoor air (m²)" according to the Swedish building regulations, BBR [11]. The result shows that internal measuring is the most common interpretation of the Swedish building regulations. Around half of the respondents replied that they interpreted the building regulations as that internal measuring should be applied. Roughly one third replied that overall internal measuring should be applied. A breakdown of the answers regarding the method of measurement is given in Table 4.

The specific values for thermal bridges will vary depending on the chosen measuring method for the quantification of building elements, A_i , as stated in Section 2.1. The result from the assessment of junctions has therefore been sorted based on the chosen measuring method to quantify A_i , see Fig. 5. For example: If a respondent answered that A_i is defined by internal measuring and afterwards answered that junction A, which is a thermal bridge only due to the

Table 3
Different levels of U-values used.

U-value for different building categories (W/m ² K)			
Construction	Old building stock	New construction	Best practice
Floor slab on ground	0.31	0.17	0.09
Roof	0.20	0.12	0.08
External walls	0.35	0.20	0.09
Windows/doors	2.30	1.50	0.90

Table 4
Distribution of answers to questions 1–4.

Question	Method of measurement				
	Internal	Overall internal	External	Other	No answer
Q1: Method of measurement used for quantification of building elements in energy calculations	42%	22%	29%	7%	0%
Q2: Method of measurement used to define a building's enclosing area	29%	22%	44%	1%	4%
Q3: Method of measurement used for quantities of A_i according to the Swedish definition in BBR	57%	29%	4%	0%	10%
Q4: Method of measurement used to define a building's A_{en} according to the Swedish definition in BBR	48%	36%	7%	0%	9%

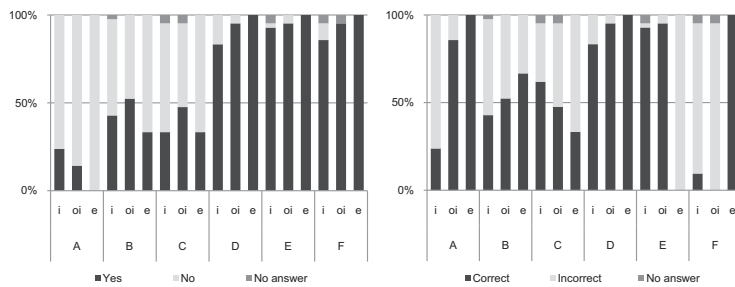


Fig. 5. Answers to the assessment of junctions sorted by chosen measuring method. Left: Answers given by the respondents to the question: will this junction increase the transmission heat transfer losses in addition to the losses included in building elements? Right: Correct and incorrect answers.

difference between internal and external areas, is not a thermal bridge; The answer is incorrect and therefore listed as incorrect.

In the assessment of the first two junctions (A & B), which had a smaller internal area compared to the external areas, 53% and 52% of the respondents gave an incorrect answer to each question respectively. The third junction (C), which had a larger internal area compared to the external area, had a slightly lower percentage of incorrect answers; 39%. Junctions D & E were thermal bridges both due to the effect of partial penetration of the building envelope by materials with different thermal conductivity and differences between internal and external areas. The assessments from the respondents here showed a significantly lower incorrectness; 12% (D) and 8% (E) of the respondents made an incorrect assessment. The last junction, F, was a junction where the insulation was penetrated by wood which resulted in an increased thermal transmittance. However, the effect of the difference between internal and external area was larger. This junction had the largest amount of incorrect answers; 85%.

The respondents who interpreted quantification of A_i as internal measuring had a slightly higher share of incorrect answers (45%) compared to respondents who interpreted that A_i should be based on the overall internal (36%) or external (33%) measuring. The breakdown is presented in Table 5.

Table 5
Number of answers in the assessment of junctions based on correct, incorrect and N/A.

Method of measurement	Allocation of answers			N/A
	Correct answers	Incorrect answers		
Internal	132	113		7
Overall internal	79	45		2
External	12	6		0
Total	223	164		9

The most common method used by the respondents to account for thermal bridges was to quantify the amount of thermal bridges and multiply the quantities with default values from literature or energy calculation software (44%). The second most common method (22%) was to increase the thermal transmittance of building elements (including all elements; walls, roof, windows, etc.) by a certain percentage. The used percentage factor varied between 5% and 20%, median; 15%.

3.2. Influence of thermal bridges on the case study building

The calculated transmission heat transfer coefficient, H_T , for the case study building (Fig. 3), based on different measuring methods, different building systems for exterior walls and different building categories is presented in Fig. 6. The total transmission heat transfer coefficient is the same, regardless of measuring method used, within each specific wall constructions in each building category e.g. a building designed with exterior concrete walls according to best practice has the same H_T regardless of measuring method. However, the share of transmission heat transfer due to thermal bridges varies. The share of transmission heat transfer due to thermal bridges is the highest in the best practice building category for all three building systems. The share of thermal bridges is always the highest if internal measuring is used, regardless of exterior wall construction and building category.

The share of transmission heat transfer losses due to the thermal bridges is presented in Table 6. In the cases where external walls are concrete walls with external insulation, the share varies between 2% and 17%. The share varies between 7% and 27% in wooden frame walls with insulation. The highest shares, between 14% and 39%, are found in cases with precast concrete sandwich walls. The corresponding increase in percentage factor, which should be used if one is only increasing the transmission heat transfer coefficient

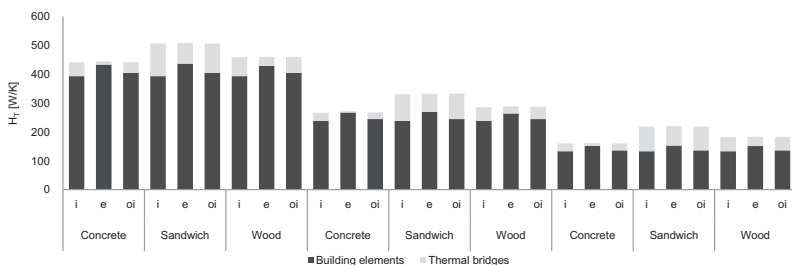


Fig. 6. Calculated transmission heat transfer coefficient, H_t , by different measuring method, exterior wall constructions and building categories.

Table 6

The share of the transmission heat transfer coefficient, H_t , due to thermal bridges by different measuring methods, building system and building category.

Measuring method	Exterior wall constructions	Building categories		
		Old building stock	New Construction	Best practice
Internal	Concrete walls with external insulation	11%	11%	17%
	Precast concrete sandwich walls	22%	28%	39%
	Wood stud walls with insulation	14%	17%	27%
Overall internal	Concrete walls with external insulation	8%	9%	15%
	Precast concrete sandwich walls	20%	26%	38%
	Wood stud walls with insulation	12%	15%	26%
External	Concrete walls with external insulation	3%	2%	6%
	Precast concrete sandwich walls	14%	19%	31%
	Wood stud walls with insulation	7%	9%	18%

by a certain percentage instead of analysing thermal bridges, is consequently even higher. In the worst case, the corresponding increase is 64%. This applies to precast sandwich walls and insulation thickness equivalent to best practice.

The transmission heat transfer losses due to thermal bridges have been summarized by multiplying the specific values for each thermal bridge with the corresponding quantity for the case study building (Fig. 3). The summation has been done based on the three different measuring methods and the various U-values as defined in Table 3. The distribution of transmission heat transfer losses due to thermal bridges is shown in Fig. 7.

The precast concrete wall system shows a decrease of transmission heat transfer losses due to thermal bridges when more insulation is added, regardless of measuring method applied. However, the transmission heat transfer losses are very high in all cases.

Comparing the old building stock and new construction, the transmission heat transfer through thermal bridges is lower in new constructions. This is true regardless of exterior wall construction.

However, almost no change or a small increase of the transmission heat transfer losses due to thermal bridges can be seen when the step is taken from the building category of new construction to the best practice. This is due to that the specific

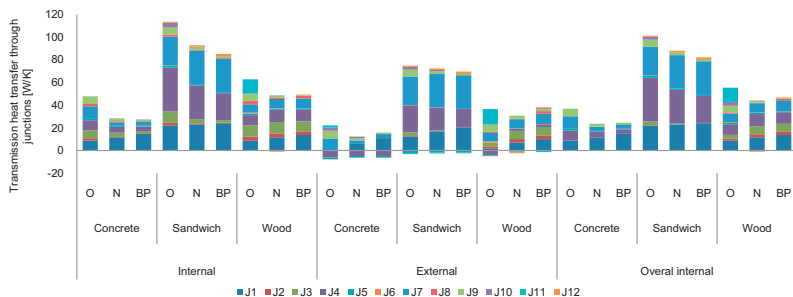


Fig. 7. The sum of transmission heat transfer losses in the investigated junctions, J1–J12, by different measuring method, exterior wall constructions and building categories. Building category abbreviations: O, Old building stock; N, New construction and BP, Best practice.

value of some thermal bridges increases when more insulation is used.

In many junctions, the specific value of thermal bridges decreases or barely changes when more insulation is used. However, some junctions show a significant increase in transmission heat transfer. Regardless of the building system for the external walls, the specific value for the junction between the floor slab and external wall (J1) is increasing. Within the building system with precast concrete sandwich walls, the specific value of the thermal bridge between external wall and window-/door frame is also increasing (J7) when more insulation is used. Within the building system with wooden framework, more junctions may be found where the specific values of the thermal bridges are increasing when more insulation is added. In addition to the junction between floor slab and external wall (J1), the specific value of the thermal bridges increases in the junction between the external wall and the internal load bearing constructions (J2 & J3), roof construction (J4) and windows (J7).

4. Discussion

4.1. The survey

The survey showed that there is no widespread and established view among engineers and architects regarding how to quantify building elements as input for calculation of transmission heat transfer losses. Today, several consultants usually are involved in the design and construction phase of a building. It is possible to imagine a scenario in which the architect will be asked to provide quantities of building components and junctions, the construction engineer calculates U-values and specific values for thermal bridges based on these and the building services consultant or energy coordinator carries out the actual energy calculation. In this scenario, misunderstandings and therefore inaccurate calculations of transmission heat transfer losses may occur. An increased use of Building Information Modelling, BIM, in the design and construction of buildings may also be seen as a potential source of calculation errors if geometry and quantity take offs (data export from the model e.g. floor-, roof-, wall areas etc. to text data) are used from the BIM model without a critical review of the data and geometry provided from the model. On the other hand, a standardized and automatic way to use correct data as input could minimize such errors.

Roughly a fifth of the respondents used the method of leaving out the calculation of thermal bridges and instead increased the transmission heat transfer through building elements by a certain percentage. However, the used percentage factor is generally lower than the factor which should be used according to the Swedish National Board of Housing, Building and Planning, in connection to this method.

The survey indicated that engineers and architects do not know or think about that a thermal bridge also, by definition, occurs when there is a difference between internal and external area. This was shown when the respondents were asked to assess whether different junctions increased the transmission heat transfer losses in addition to the losses included in building elements. This is alarming. If one does not think that a junction is a potential thermal bridge, one is not likely to carry out any analysis or calculation to investigate the effect on thermal transmission by the specific junction.

The survey was conducted among Swedish engineers and architects and the results should therefore be interpreted on the basis of that. If a more standardized method would have been defined, mandatory to use and described in guidelines, the results would hopefully have been different.

4.2. Influence of thermal bridges

In the relevant standards for energy calculations, used as a basis for this study, there is no defined "correct" measuring method. As shown, the specific values of the thermal bridges may vary depending on chosen measurement method. It is therefore important to strictly follow one measuring method in combination with relevant calculation method.

Many of the previous studies, mentioned in the introduction, highlights the need for dynamic calculations in order to correctly assess the impact of thermal bridges. However, this study investigates the effect of thermal bridges based on steady state calculations. Nevertheless, this study clearly shows the increased need of considering thermal bridges when calculating the transmission heat transfer through building elements and thermal bridges.

Heat losses from a building also occur due to ventilation heat transfer. In addition to the air flow rate due to mechanical ventilation, an additional air flow must be considered, due to infiltration. The infiltration is depending on the air permeability of the building envelope, which may be determined as defined in EN 13829 [49]. This standard clearly states that the reference area used to define air permeability, q_{50} , is based on overall internal dimensions. Based on these conditions, overall internal measurement may possibly be more suitable for calculating transmission heat transfer. Especially if an energy calculation software is used that calculates both the transmission heat transfer coefficient and the infiltration air flow based on the same area.

In all cases where the specific value of the thermal bridge increases when more insulation is used, it is due to a geometrical effect; the transmitting area increases e.g. when more insulation is added to the exterior wall, the increased amount of insulation increases the window bays, thus increasing the transmitting area. The same effect is seen when more insulation is mounted towards interior load bearing constructions in concrete (floor slabs and walls). Since concrete has a high thermal conductivity, this means that the concrete slab, in general, has the same temperature as the indoor air. The increased amount of insulation therefore results in an increased interface area between the wall and the interior concrete construction. Consequently this also means an increase of transmitting area and a higher specific value of the thermal bridge. Also, the specific value of the thermal bridge towards the concrete floor slab increases due to the same effect.

The effect of increased specific values of thermal bridges occurs in this case study due to the assumption that the decreased transmission heat transfer is achieved by increasing the insulation thickness inwards, which is a common approach in Nordic countries. However, there are other technical solutions, available today, for exterior wall constructions where the increased thickness of insulation is increased outwards. By using the alternative technical solution this effect would not occur.

In design of new passive houses, low energy buildings or Net Zero Energy Buildings it is possible that junctions are given extra attention in order to decrease the effect of thermal bridges. Consequently, this would decrease the effect of the thermal bridges. However, today examples of newly built passive houses may be found both with innovative junctions and standard junctions [6].

The largest transmission heat transfer due to thermal bridges may be found in junctions between external wall and floor slab constructions, windows and attic floors. These junctions should therefore be in focus of future development of building systems and in the architectural and construction design of new buildings.

In general, building projects are unique projects where the specific conditions imply unique building elements and more or less unique solutions for the junctions between the elements. This study has tried to be consistent regarding junctions. This means that more

or less the same technical solution has been used to connect the building elements, regardless of the amount of insulation.

5. Conclusions

5.1. The survey

The result from the survey shows that the state of knowledge is not satisfying among Swedish engineers and architects regarding different measuring methods and the effect on thermal bridges. Furthermore, no clear practice/norm can be identified regarding which measuring method that usually is applied. A need for clearer building regulations, development of guidelines regarding how to use available international standards and need of education/training of engineers and architects has been identified.

A well defined measuring system with the subscripts presented in Table 1 or clarification in text should always be applied in order to minimize the risk of misunderstandings when information regarding building element areas and thermal bridges are exchanged between engineers and architects or communicated in publications.

5.2. Influence of thermal bridges

The study clearly shows the increasing role of thermal bridges in transmission heat transfer calculations when improving the building's energy performance. This is true even though the specific value of thermal bridges may decrease when more insulation is added. The relative (percentage) effect of thermal bridges increases when more insulation is used. If values for normalized thermal bridges are to be used, they need to be differentiated by building system and different amounts of insulation.

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Article 4

Article

Two Methods for Normalisation of Measured Energy Performance—Testing of a Net-Zero Energy Building in Sweden

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Abstract: An increasing demand for energy-efficient buildings has led to an increasing focus on predicted energy performance once a building is in use. Many studies have identified a performance gap between predicted energy use and actual measured energy use once buildings are in the user phase. However, none of the identified studies normalise measured energy use for both internal and external deviating boundary conditions. This study uses a Net-zero energy building (Net ZEB) building in Sweden to test two different approaches to the normalisation of measured energy use—static and dynamic methods. The normalisation of energy use for a ground source heat pump reduces the performance gap from 12% to 1–5%, depending on the method of normalisation. The normalisation of energy from photovoltaic (PV) panels reduces the performance gap from 17% to 5%, regardless of the method used. The results show that normalisation is important in order to accurately determine the energy performance of buildings. The most important parameters are the indoor temperature and internal loads, which have the largest effect on normalisation in this case study. Furthermore, the case study shows that it is possible to build Net ZEB buildings with existing technologies in a Northern European climate.

Keywords: net-zero energy building; normalisation; energy performance; energy monitoring; performance gap

1. Introduction

Buildings account for over 40% of primary energy use worldwide and 24% of greenhouse gas emissions [1]. The world's population is growing, as is the need for buildings. Hence, the reduction of energy use and increased use of energy from renewable sources are important measures for climate change mitigation. The energy-saving potential in the building sector is massive and could yield global annual energy savings equivalent to the total energy use of buildings in the USA, UK, Russia, Germany, France, and China [2].

With increasing demand for energy-efficient buildings, the construction industry faces the challenge of ensuring that predicted energy performance is achieved once a building is in use. There are many studies that identify a performance gap between calculated/simulated energy use and actual measured energy use once buildings are in the user phase [3–20]. While some studies show a very large performance gap [5–7,13,19], others show a lower performance gap [8,10,20]. Some studies investigate the effect of deviating boundary conditions, such as internal loads and outdoor climate [3,4,11,16,18] and some normalise the measured energy use for some of the deviating boundary conditions with respect to outdoor climate [8,10]. It should be noted that studies showing a low performance gap have, to some extent, normalised measured energy use. However, none of the studies attempt to normalise measured energy use for both internal and external deviating boundary conditions [3–17].

Root causes of performance gaps have drawn the interest of researchers [3,5,6,15,18,19]. These causes may be sorted and attributed differently. However, root causes may be found in all stages in the building process, including the design stage and the procurement/construction stages, as well as the operational stage.

Examples of causes in the design stage may be related to inaccurate or uncertain input data [3,19]. Another cause could be the incorrect use of methods or tools for calculations and simulation [6,15]. During the construction stage, misunderstandings and incorrect execution may cause performance failure, e.g., insufficient air tightness and insulation [3,15]. Finally, the conditions during the actual use of a building play an important role, where occupant behaviour is often considered as the main cause of performance gaps [3,11,18,19].

Instead of normalising measured energy use, the initial simulation model, created during the design phase, may be calibrated to reflect the as-built status and the actual operating conditions during the user phase [19–21]. After calibration, the model may be rerun with initial operating conditions with respect to indoor temperature, operating hours, exterior climate, and occupant behaviour, etc., showing as-built verified energy performance, but with the initial operating conditions. Calibrated models may match, quite closely, with measured results [19,21]. In other words, it is possible to overcome a performance gap due to incorrect modelling methods or tools. However, the use of calibrated models is still under development and further work is required in order to develop a good approach [15,21]. Furthermore, the calibration of models requires extensive measurement, which sometimes may not be possible [15,21].

A normalisation method of measured energy, considering both internal and external deviating boundary conditions during the actual use of a building, may allow for a meaningful comparison and verification of energy use in buildings.

In Sweden, the National Board of Housing, Building, and Planning (Boverket) recently published a static method for normalising measured energy use, accounting for the deviation of hot water use, indoor temperature, exterior climate (outdoor temperature, solar radiation, and wind), plug loads, and lighting [22]. In addition to this static approach, the normalisation of measured energy use is permitted, based on the relationship between the simulated energy use for normal use and for a normal year, and the simulated energy use in the case of actual use and outdoor climate during the measurement year. The second option requires dynamic simulation.

The two different methods will, in this study, be referred to as static normalisation and dynamic normalisation, respectively. Boverket stated that the methods, while simplified and shortened, are the best available methods they have been able to define. Thus, the methods are not validated.

This study presents a Net-zero energy building (Net ZEB) built in Sweden, and investigates different methods for normalising the energy use in the user phase by testing the two methods for normalising measured energy use. In this study, the Net ZEB balance is based on the Swedish regulations on energy performance [23], which exclude energy use for plug loads and lighting. The chosen definition of a Net ZEB, used in this case, is summarised in Table 1, and is based on the framework [24] developed within the International Energy Agency (IEA) research project Towards Net-Zero Energy Solar Buildings [1].

The purpose of this study is twofold; firstly, it aims to share and test the two methods for the normalisation of measured energy use in buildings, in order to enable other researchers to use, evaluate, and develop these methods. Secondly, it aims to share knowledge of building technique for a Swedish Net ZEB.

The static model from Boverket has the objective of being a simple and straightforward normalisation method, closing the performance gap due to deviating conditions during the actual use of a building, which are often considered the main cause of performance gaps [3,11,18,19].

Table 1. Summary of Net-zero energy building (ZEB) definitions, based on the International Energy Agency (IEA) framework [24].

Criteria	Definition
Physical boundary	The building itself. Energy flowing to/from the building is measured.
Balance boundary	Energy use according to Swedish building regulations are included: heating, cooling, ventilation, hot water, and lighting in common areas and utility rooms. Plug loads (computers, TV, etc.) and lighting are not included.
Boundary conditions	Energy demand loads and lighting: 30 kWh/m ² a. Energy demand for domestic hot water: 20 kWh/m ² a. Set point for heating: +21 °C. Set point for cooling: +24 °C. Outdoor climate: typical meteorological year (TMY) based on the period 1961–1990.
Metrics	Weighted/primary energy.
Symmetry in weighting	Symmetric weighting is applied, i.e., the same factors are used for import and export of energy.
Time dependent accounting	Static weighting factors are used; 2.5 for electricity, 0.8 for district heating, and 0.4 for district cooling. All other energy carriers are multiplied by 1.0.
Balancing period	One year.
Type of balance	Demand/generation balance, i.e., annual weighted energy generation (based on renewables) > annual weighted energy demand.
Energy efficiency	Applied before energy generation is considered/added. The energy demand must be reduced to <75% of the limits recommended by Swedish building regulations.
Energy supply	Existing renewable energy in the grid cannot be accounted for; 50% of the renewable energy may be from off-site generation. Off-site renewable energy must be added capacity in the grid, based on the project investment.
Load matching	No requirements.
Grid interaction	No requirements.
Measurement and verification	Net ZEB compliance is based on dynamic simulations. However, measurements of energy performance must be conducted.

2. Method

2.1. Simulations

Simulations were conducted with VIP Energy [25], validated with ASHRAE 140 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) [26], in order to predict energy demand, solar energy generation, and quantities of solar energy which may be used within the building, as well as quantities of exported energy. The software, VIP Energy, was chosen as it is common in Sweden, and the consultants within the project were familiar with the software as well as its interface and the output data reports generated from the software. To enable analysis in hourly resolution, profiles for electric load for lighting and plug loads, hot water, and occupancy were created based on previous research [27–30] and Swedish recommendations for boundary conditions [31]. Previous research was used to create relative load profiles. Peak loads were set to result in annual energy use and heat gains according to Swedish recommendations [31].

The relative load profiles are presented in Figures 1 and 2. The peak load for hot water was set to 1.61 kW and the peak loads for plug loads and lighting were set to 1.41 kW. This corresponds to 6.25 W/m² and 5.48 W/m², respectively. However, based on Swedish recommendations for simulations [31], it was assumed that only 70% of the lighting and plug loads generate heat gains within the building. For example, with respect to energy use for hot food, this energy may be consumed by people who leave the building shortly after they have eaten. Due to this, the peak loads for heat generation from plug loads and lighting were set to 3.84 W/m². The maximum internal heat gains from occupancy presence were set to 1.25 W/m². The occupancy presence was assumed not to have a seasonal variation.



Figure 1. (a) Relative variation of hot water and time of the day, based on References [29–31]; (b) Relative variation of lighting and plug loads with respect to the time of day, based on References [27,28,31].

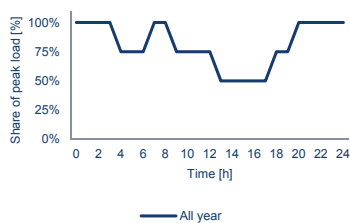


Figure 2. Relative occupancy presence based on time of the day, based on References [27,28].

2.2. Measurements

Measurements were conducted as a part of a research program related to nearly zero energy buildings, sponsored by the Swedish Energy Agency [32]. The measurement of energy use began in March 2015 when the occupants moved in, and are ongoing. Hourly values were collected and analysed for parameters presented in Table 2. In addition to the parameters presented and analysed in this article, temperature and relative humidity were measured in all constructions. Furthermore, data regarding temperature and flows for different mediums were collected from the ground source heat pump (GSHP) and the ventilation system. No measurements were conducted regarding occupancy presence.

Table 2. Measured parameters in Solallén.

Parameter	Measured Unit/Interval	Resolution of Data
Electricity for ground source heat pump (GSHP)	Wh/h	1/10 W
Electricity generated from photovoltaic (PV) panels	Wh/h	1/10 W
Electricity for free cooling pump	Wh/h	1/10 W
Electricity for fans for ventilation	Wh/h	1/10 W
Electricity for hot water circulation pump	Wh/h	1/10 W
Electricity for plug loads and lighting	Wh/h	1/10 W
Indoor temperature	°C/h	1/10 °C
Outdoor temperature	°C/h	1/10 °C
Outdoor relative humidity	%/h	1/10%
Hot water consumption	m ³ /h	1/100 m ³

2.3. Static Normalisation

The static normalisation from Boverket was carried out in four steps (see Figure 3), as also expressed in Equation (1).

$$E_{norm,stat} = E_{meas,DHW} - E_{corr,DHW} + \frac{E_{meas,SH} \times E_{corr,T} - E_{corr,IL}}{E_{corr,EI}} + E_{meas,C} - E_{corr,IL} + E_{aux} \quad (1)$$

where $E_{norm,stat}$ is the normalised energy performance based on static normalisation, $E_{meas,DHW}$ is the measured energy use for domestic hot water, $E_{corr,DHW}$ is a term used to normalise energy use for domestic hot water (Equation (2)), $E_{meas,SH}$ is measured energy use for space heating, $E_{corr,T}$ is a factor used to normalise energy use due to deviating indoor temperature (Equation (4)), $E_{corr,IL}$ is a term used to normalise energy use due to deviating internal loads from plug loads and lighting (Equation (5)), $E_{corr,EI}$ is a divisor used to normalise energy use due to deviating outdoor climate (Equation (6)), $E_{meas,C}$ is the measured energy use for cooling, and E_{aux} is the auxiliary energy used, e.g., fans, pumps, and elevators, etc. [23]. It should be noted that this method does not include any normalisation of auxiliary energy. The normalised energy performance should then be compared to the building regulations to check if the building fulfils the energy performance requirements. Also, a key interest is to compare the normalised energy performance with the predicted performance in order to validate and improve simulation methods used during the design stage.

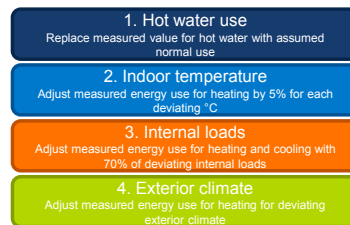


Figure 3. Static normalisation from the National Board of Housing, Building, and Planning in Sweden (Boverket).

The first step normalises the energy use for domestic hot water. The measured energy use is normalised according to Equation (2).

$$E_{corr,DHW} = E_{\alpha,DHW} - E_{meas,DHW} \quad (2)$$

where $E_{\alpha,DHW}$ is the normal energy use for domestic hot water, and $E_{meas,DHW}$ is the measured energy use for domestic hot water. According to the Swedish regulations [22], normal energy use for domestic hot water in residential buildings may be 20 kWh/m²a or 25 kWh/m²a. The larger value is used for residential buildings with three dwellings or more. The normalised value does not consider heat pumps, use of solar energy, or techniques that may reduce the energy use for hot water, e.g., a hot water heat exchanger, low-flow fixtures, or similar.

If energy use is measured including energy losses for hot water circulation, the static method from Boverket requires that 25% of the energy use for domestic hot water heating be assumed as energy loss due to hot water circulation, and should therefore not be included in the normalisation. Hence, these energy losses are expected to have the effect of heating the building, and should therefore be included as space heating energy. If domestic hot water is measured by volume, the energy use, $E_{meas,DHW}$, may be calculated according to Equation (3). Note that the calculated value excludes energy losses due to hot water circulation.

$$E_{meas,DHW} = \frac{(V_{DHW} \times 55)}{SCOP_{DHW}} \quad (3)$$

where V_{DHW} is the measured annual volume of domestic hot water (m^3), and $SCOP_{DHW}$ is the seasonal coefficient of performance (SCOP) for the heating of hot water. The equation is based on an assumption that incoming cold water from the municipality on average needs to be heated $47^\circ C$, e.g., from $8^\circ C$ to $55^\circ C$.

The second step of normalisation is related to indoor temperature. Based on the average indoor temperature during the heating season, the measured energy use for heating may be adjusted by 5% for each degree of deviation ($^\circ C$) according to Equation (4). For large buildings with different areas or parts with different temperatures, the factor should be adjusted based on the specific area or part of the building with the deviation in relation to the total building area. It should be noted that the deviation must be due to an active choice during operation. For example, if the deviation is due to flaws in the heating system and it is not possible for the users to reach the design indoor temperature, adjustment is not allowed according to Boverket.

$$E_{corr,T} = 1 + (T_\alpha - T_{meas}) \times 0.05 \quad (4)$$

where T_α is the normal indoor temperature during the heating season, and T_{meas} is the measured indoor temperature during the heating season.

The third step of normalisation is related to deviating internal loads. If the use of plug loads and lighting is expected to affect energy use for heating or cooling by more than $3 \text{ kWh}/m^2a$, energy use for heating and cooling may be adjusted according to Equation (5).

$$E_{corr,IL} = \frac{(E_{\alpha,IL} - E_{meas,IL}) \times I_h}{SCOP_{heating/cooling}} \quad (5)$$

where $E_{\alpha,IL}$ is the normal energy demand for plug loads and lighting, $E_{meas,IL}$ is the measured energy use for plug loads and lighting, I_h is the share of internal loads assumed to affect the heating or cooling, and $SCOP_{heating/cooling}$ is the SCOP for space heating or cooling. Regarding the share of internal loads that may be assumed to affect heating or cooling, a fixed value of 70% is used in relation to heating. Regarding cooling, no value is given. In this study, cooling is not normalised, due to the very low cooling load expected. Boverket has not specifically motivated the choice of I_h , set to 70%. It is most likely based on previous work, which has concluded that 70% is an appropriate value [33].

The last and fourth step relates to the deviating exterior climate. No specific method is given by Boverket, but they recommend that energy use for heating is normalised by using the energy index [34] from the Swedish Meteorological and Hydrological Institute (SMHI) [35]. The energy index $E_{corr,EI}$ gives a weighted adjustment divisor based on outdoor temperature, solar radiation, and wind. The functional unit of the energy index is the same as for heating degree days. The energy index may be given as a weighted value for a whole year or in a higher resolution, commonly month by month or day by day (see Equation (6)).

$$E_{corr,EI} = \frac{EI_{meas}}{EI_\alpha} \quad (6)$$

where EI_{meas} represents the measured heating degree days adjusted for solar radiation and wind, and EI_α represents the normal heating degree days adjusted for solar radiation and wind.

The static normalisation does not give any instructions regarding how to normalise solar energy, in this case electricity from photovoltaic (PV) panels. To account from deviating solar radiation, monthly generated energy from PV panels are divided with a divisor, $E_{corr,solar}$, according to Equation (7).

$$E_{corr,solar} = \frac{G_{meas,solar}}{G_{\alpha,solar}} \quad (7)$$

where $G_{n,solar}$ is the normal global solar radiation, and $G_{meas,solar}$ is the measured global solar radiation.

2.4. Dynamic Normalisation

In addition to the static normalisation, the normalisation of the measured energy use based on repeated dynamic simulation is also permitted. The second option implies that the initial dynamic simulation, carried out during the design phase, is repeated with updated boundary conditions regarding actual use of the building and exterior climate. The ratio between the first and second simulation is used as a factor for normalisation. Dynamic normalisation requires the use of dynamic simulations.

This method for normalisation is not found in the literature review carried out in this study [3–21]. The use of a calibrated energy model has some similarities, but is fundamentally different, as the energy performance is defined by the result from the energy model, not the normalised measured energy use.

As mentioned in the introduction this method, Boverket stated that neither the static nor the dynamic methods have been validated.

2.5. Analysis Method

In this study, the static normalisation from Boverket, supplemented with an adjustment for solar energy according to Equation (7), is compared with dynamic normalisation. The dynamic normalisation was carried out stepwise, changing the conditions in the same order as the static normalisation from Boverket. For each method, the adjustments based on monthly and yearly results are compared. Furthermore, the import-export balance is evaluated on an hourly basis. The import-export balance was not normalised.

To enable normalisation through the static method, measured data from domestic hot water use, indoor temperature, and internal loads were used for the first three steps. To enable normalisation for exterior climate and energy generation from PV panels, monthly values from SMHI were used.

To enable normalisation through the dynamic normalisation, new boundary conditions were defined based on measurements. Temperature and relative humidity in outdoor air were changed according to measured hourly data. The so-called imposed offset method was used to generate hourly values for solar radiation; monthly data from SMHI were used and the monthly relative deviation was used to change each month's hourly values. Hot water use and electricity use for plug loads and lighting were changed based on measurements. Since no measurements were conducted regarding occupancy presence, this was not changed.

3. Description of the Case Study

Sollällén consists of 21 dwellings in seven one-storey terraced houses, each house with three dwellings. The buildings were built in the southern part of Sweden in the outer parts of the city of Växjö (see Figure 4). The location's typical metrological year (TMY) has an average yearly temperature of 6.3 °C, global solar radiation of 912 kWh/m²a, and 3787 heating degree days (HDDs). Each building has a conditioned area of 258 m² (see Figure 5). The construction of the buildings started in June 2014, and residents began moving in during February 2015. Detailed measurements were carried out on house number four.



Figure 4. (a) Site map of Solallén; (b) Location of Växjö in Sweden.



Figure 5. (a) Layout of house number four, Solallén; (b) Facade towards the south.

Technical Description

The strategy for reaching a Net ZEB balance for the case study comprises a three-step approach. Firstly, the thermal losses were reduced in order to have a low heating demand. Secondly, a GSHP was chosen in order to lower the need for imported energy. Lastly, the building was equipped with photovoltaic (PV) panels on the roof facing south, to generate sufficient renewable energy in order to reach the Net ZEB balance.

The slab on ground foundation has 300 mm of underlying expanded polystyrene (EPS), giving a U-value of $0.11 \text{ W/m}^2\text{K}$. The edge footing was designed with a prefabricated F-element in EPS (see Figure 4). The external walls were constructed as prefabricated insulated wooden frameworks. In this project, a special stud was developed. It was constructed by assembling a $145 \times 45 \text{ mm}$ load-bearing wooden stud and a $70 \times 45 \text{ mm}$ outer wooden stud with 125-mm wood block distances, giving the assembled wall stud a width of 45 mm and a depth of 340 mm (see Figure 6). This construction was chosen in order to minimize transmission heat transfer and keep the construction at a low weight.

The $340 \text{ mm} \times 45 \text{ mm}$ wall stud was insulated with mineral wool. In addition, 45-mm insulation was added to the exterior side and 70 mm of insulated wooden framework was added to the interior side. This gives the construction a total insulation thickness of 455 mm and a thermal transmittance (U-value) of $0.09 \text{ W/m}^2\text{K}$. In order to minimize thermal bridges related to window-wall junctions, 20 mm of insulation was mounted prior to the window casings and window ledge (see Figure 7). All insulation used for exterior walls was composed of rock wool. The roof construction was insulated with 500–600 mm of blowing wool (also rock wool) giving the construction a U-value of $0.07 \text{ W/m}^2\text{K}$. Windows and doors were mounted with a U-value of $0.90 \text{ W/m}^2\text{K}$ and a solar energy transmittance of glass (g-value) of 0.50. The windows in the living rooms were given an external sun screen. The combination of window and external screen resulted in a g-value of 0.09. The external screen

reduces the daylight transmission. Hence, the screen is primarily intended to be used on warm sunny days when the residents are not present.

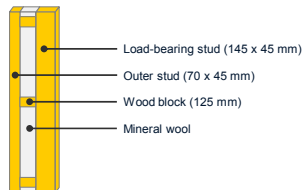


Figure 6. Construction of wooden stud with low weight and low transmission heat transfer.

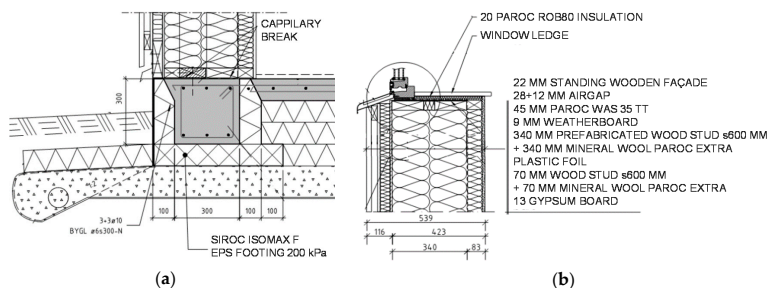


Figure 7. (a) Junction between slab on ground and exterior wall; (b) Junction between external wall and window.

The ventilation was designed with a mechanical balanced ventilation system with a heat recovery of 90%. The ventilation system has nominal ventilation, which gives the dwelling an air exchange rate of 0.5 air changes per hour (h^{-1}). The ventilation system has the capacity to increase the air flow to 1.0 h^{-1} , which may be done manually or programmed based on a chosen level of relative humidity or temperature.

A ground source heat pump was chosen to produce space heating and hot water. Heat for hot water is produced and supplied to a hot water storage tank. The SCOP of the heat pump used in the simulations was 3.0. The space heat is distributed via a floor heating system and supply air via heating coil in the ventilation unit.

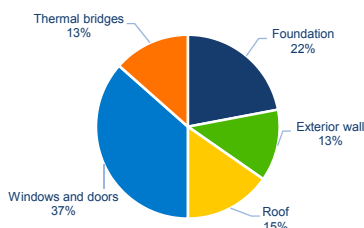
During the summer, the boreholes are used as a natural heat sink. The working fluid for the heat pump is circulated in the boreholes cooling the working fluid, which then is used to supply cooling via a cooling coil in the ventilation system. A circulation pump is used, but no compressors are used for cooling.

Each building was designed with 40 PV panels measuring roughly 66 m^2 , giving each building an installed capacity of 10 kWp .

A summary of the technical description is given in Table 3. The care for reducing thermal bridges resulted in low transmission heat losses via thermal bridges—13% based on the overall internal measurement (see Figure 8).

Table 3. Summary of technical description of case study, Solallén. All values are design values except for air tightness.

Type of Data/Description	Value
Conditioned area	258 m ²
Indoor air volume	667 m ³
Enclosing area/indoor air volume	1.11 m ⁻¹
Enclosing area/conditioned area	2.88
Window area/wall area	0.19
Foundation, 300-mm insulation, U-value	0.11 W/m ² K
Exterior wall, 455-mm insulation, U-value	0.09 W/m ² K
Roof, 500–600 mm insulation, U-value	0.07 W/m ² K
Windows and doors, U-value	0.90 W/m ² K
Total thermal bridges	17.27 W/K, house
Air tightness, measured at 50 Pa (q50/n50)	0.21 L/s, m ² /0.84 h ⁻¹
Ventilation heat recovery	90%
Ventilation specific fan power	1.50 kW/(m ³ /s)
Geothermal heat pump, seasonal coefficient of performance	3.0
Photovoltaic panels, 66 m ²	10 kWp

**Figure 8.** Distribution of calculated transmission heat losses for a building in Solallén.

4. Results

4.1. Results from Simulations

The simulations were based on the final design of the buildings and were presented previously [36,37]. The distribution of the energy use based on simulations is presented in Table 4. The results from the simulations predicted an energy demand, excluding plug loads and lighting, of 29.8 kWh/m²a. The PV panels were expected to generate almost 7900 kWh annually, which corresponds to 30.6 kWh/m²a for the investigated building. It should be noted that the Net ZEB balance excludes energy use for plug loads and lighting (see Table 1).

In the case study, the expected energy use for domestic hot water amounted to 6.7 kWh/m²a, based on the normal energy demand for hot water use set to 20 kWh/m²a and $SCOP_{DHW}$ set to 3.0 (see Tables 3 and 4). The hot water demand of 20 kWh/m²a is not consistent with the Swedish regulations. This is due to the fact that the design phase and simulations for the project were ongoing in the beginning of 2014, roughly two years before the regulations and values for normalisation were published.

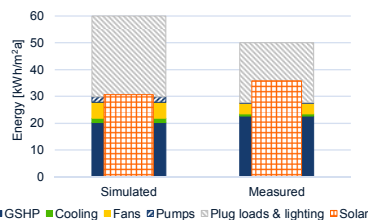
Table 4. Predicted energy demand and generation for Solallén, based on simulations.

Energy Use	kWh/year	kWh/m ² a
Fans	1546	6.0
Pumps	515	2.0
GSHP, heating	3496	13.5
GSHP, hot water	1718	6.7
Cooling	419	1.6
Total energy demand, excluding plug loads and lighting (disregarding PV panels)	7694	29.8
Plug loads and lighting	7766	30.1
Solar energy, direct use	−3832	−14.9
Solar energy, exported	−4053	−15.7

It should be noted that electricity should be weighted with a factor of 2.5 according to the chosen Net ZEB definition, summarised in Table 1. However, in this analysis no weighting factors are applied. The reason for this is twofold. Firstly, the building only demands and generates electricity; no other energy carriers are used. Secondly, the focus is to normalise and analyse energy performance. The authors believe that the results will be more transparent when showing the result without weighting factors.

4.2. Measured Results—Not Normalised

A comparison of simulated and measured results, not normalised, is presented in Figure 9. The Net ZEB balance is reached and outperformed. The generated electricity from PV panels, normalised by the conditioned floor area, amounts to 35.7 kWh/m²a, compared to a total energy demand of 27.6 kWh/m²a (excluding plug loads and appliances). The measured energy use values for GSHP and generated energy from PV panels were both higher than predicted in the simulations. Energy use for fans, cooling, pumps, plug loads, and lighting were lower than predicted.

**Figure 9.** Simulated and measured quantities of energy for the year 2016.

In Figure 10, the accumulated energy demand and generation, both simulated and measured, are presented. The expected seasonal variation of generated energy from PV panels corresponds rather well with the results from the simulation. The clearest deviation of energy generated from PV panels is seen in autumn and winter, both for 2015 and 2016, where the generated energy outperforms the expectations from the simulation. Based on the year of 2016, the electricity values generated from the PV panels were 16.5% higher, as compared to those of the simulations.

The measured energy use due to plug loads and lighting is constantly lower than expected from the simulations. A slightly seasonal variation can be seen, but it is not as significant as assumed within the simulations. Based on the year 2016, the electricity use values for plug loads and lighting were 26.0% lower, as compared to the simulations.

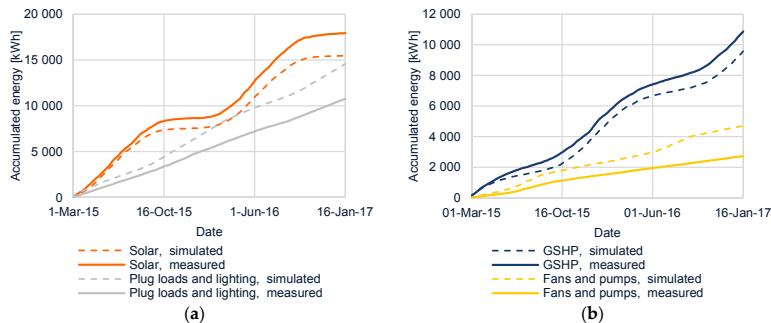


Figure 10. Simulated and measured accumulated quantities of energy from March 2015; (a) Energy generation from PV panels and energy use due to plug loads and lighting; (b) Energy use for ground source heat pump (GSHP), fans, and pumps.

With respect to the GSHP, the accumulated energy also follows a seasonal variation, which corresponds rather well with the results from the simulation. The clearest deviation is seen during summer, where the energy use is greater compared to the results from the simulation. Based on the year 2016, the electricity use for GSHP was 12.5% higher, as compared to the simulation.

Energy use for fans and pumps, including the pump that supplies free cooling during summer, is constantly lower as compared to results from the simulation. The expected increased energy use during summer due to increased ventilation and the use of free cooling is seen slightly during the first summer (2015), but not the second summer (2016). Based on the year 2016, the electricity use for fans, cooling, and pumps was 49.3% lower, as compared to the simulations.

In Figure 11, weekly results are shown regarding imported and exported energy, together with the direct use of solar energy. All values include energy use for plug loads and lighting. In the comparison, the slightly thicker and lighter bars represent measured data. The darker and narrower bars represent results from simulations. The time resolution is in hourly data, summarised for each week.

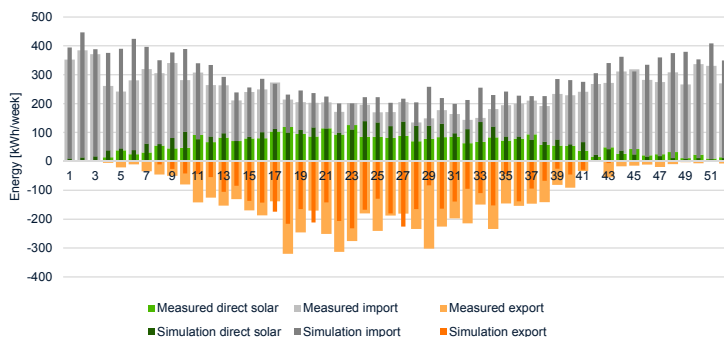


Figure 11. Weekly results comparing results from simulations and measurements. Thicker and lighter bars represent measured data. Darker and narrower bars represent results from the simulations. Export values are shown as negatives.

In general, the sums of direct solar energy use and imported energy were lower than predicted. However, the direct solar energy use values were usually below the values in the results from simulations. Over the year, the direct solar energy use was 12.0 kWh/m²a, as compared to the predicted 14.9 kWh/m²a. The measured values of import and export of energy were 38.1 kWh/m²a and 22.8 kWh/m²a, respectively, as compared to the values of 44.6 kWh/m²a and 15.7 kWh/m²a predicted using simulations. Thus, even though the energy demand was lower and the energy generation was higher, the direct use of solar energy was lower than predicted in the simulations.

4.3. Static Normalisation

To enable static normalisation, according to Boverket, values with respect to hot water use, indoor temperature (during heating season), plug loads, and lighting, as well as the energy index, were gathered. Table 5 shows these results together with data to enable the normalisation of energy generation from PV panels. Monthly values are presented together with a summarised value for the whole year. Regarding indoor temperature, the value for 2016 is the average value, not a summarised value. Since the data are used for the normalisation of energy use for heating, data from May–August (in brackets), are not used.

The effect from the normalisation is presented in Table 6. For each step, the total effect, including previous steps, are presented.

The first step, normalising energy use for domestic hot water, adjusts the measured result upwards. The measured result for domestic hot water shows an increase of 5.9%. However, the total increase in energy use for GSHP is less at 1.6%, since almost 70% of the energy use for the GSHP relates to space heating. The increase of the total energy demand is 1.3% after the first step. Since the normalisation is performed using absolute values, there is no difference between yearly or monthly normalisation.

The second step, normalisation due to deviating indoor temperature, results in the measured results being adjusted downwards due to higher indoor temperatures during the heating season as compared to the normal temperature. If adjustment for the total energy use for space heating is based on the average indoor temperature during the heating season, the measured energy use for space heating will be reduced by 5%. This is due to the fact that the average indoor temperature was 22 °C during the heating season. This results in a reduction of 3.6% for the GSHP. However, since the first step resulted in an increase of 1.6%, the result after the second step is a decrease of 2.0% for the GSHP.

If the normalisation is performed for each month separately, the decrease will only be 1.9%, resulting in a total decrease of 0.3% after the first two steps. The main reason for the differences in the normalisation is that the yearly normalisation is applied to all energy use for space heating (including the summer), whereas the monthly normalisation is only applied to energy use for space heating during the heating season.

The third step, normalisation due to deviating internal loads, is performed in absolute values (similar to the first step) and adjusts the measured results downwards since internal loads were lower when compared to normal use. The energy use values for plug loads and lighting were 7.7 kWh/m²a lower compared to normal use. Based on I_{fi} and $SCOP_{heating}$ of 70% and 3.0, respectively, measured results for space heating are reduced by 1.8 kWh/m²a, for both the monthly and yearly adjustment. The relative changes differ between yearly and monthly values due to different results from previous steps.

The fourth step, normalisation due to exterior climate, adjusts the measured results upwards due to lower energy index during measurements compared to the TMY. If the normalisation is based on the total energy index for 2016, it results in an increase of the energy use for space heating of 5.6%. Monthly normalisation results in an increase of the energy use for space heating of 5.9%. Since the GSHP also is used for domestic hot water, the adjustment is lower. Considering the first four steps, adjusting measured energy use for heating, yearly adjustment results in a reduction of measured energy use for GSHP by 6.5%, and the corresponding value for monthly adjustment is 4.6%.

In the fifth (and last) step, correction for energy generated from PV panels, there is an adjustment of measured energy downwards due to higher solar radiation during measurements compared to

the TMY. The global radiation during 2016 was roughly 10% higher compared to a normal year. Hence, the measured generated energy from PV panels is reduced by roughly 9%. If normalisation is done separately for each month, the reduction is slightly lower.

Table 5. Data for static normalisation. N: normal, M: measured; HDD: heating degree days.

Period	Domestic Hot Water (m ³)		Indoor Temperature (°C)		Plug Loads and Lighting (kWh)		Energy Index (HDD)		Global Solar Radiation (kWh/m ²)	
	N	M	N	M	N	M	N	M	N	M
Jan	8.6	8.0	21	21	799	500	699	749	11	13
Feb	7.8	6.6	21	22	722	452	624	581	28	32
Mar	8.6	8.3	21	22	771	564	579	516	62	74
Apr	8.1	7.7	21	22	561	476	386	385	105	105
May	7.3	7.9	(21)	(23)	573	466	215	151	146	172
Jun	6.9	6.9	(21)	(24)	455	454	111	74	157	175
Jul	6.2	6.1	(21)	(24)	471	399	57	57	146	159
Aug	7.3	4.5	(21)	(23)	481	392	82	109	123	127
Sept	7.3	7.4	21	24	595	497	215	141	73	92
Oct	8.6	8.2	21	21	788	531	389	409	38	35
Nov	8.4	7.7	21	21	763	503	535	562	15	17
Dec	8.6	9.3	21	22	788	546	661	577	8	9
2016	93.7	88.6	21	22	7767	5780	4553	4311	912	1007

Table 6. Absolute and relative changes of measured data based on static normalisation. Y: normalisation based on yearly average; M: normalisation based on monthly average.

Energy Use		Step 1		Step 2		Step 3		Step 4		Step 5	
		Y	M	Y	M	Y	M	Y	M	Y	M
GSHP	kWh/m ² a	0.4	0.4	-0.5	-0.1	-2.3	-1.9	-1.5	-1.0	-1.5	-1.0
	%	1.6	1.6	-2.0	-0.3	-9.9	-8.3	-6.5	-4.6	-6.5	-4.6
Total energy demand, excl. plug loads and lighting	kWh/m ² a	0.4	0.4	-0.5	-0.1	-2.3	-1.9	-1.5	-1.0	-1.5	-1.0
	%	1.3	1.3	-1.6	-0.3	-8.2	-6.8	-5.3	-3.8	-5.3	-3.8
Plug loads and lighting	kWh/m ² a	0.0	0.0	0.0	0.0	7.7	7.7	7.7	7.7	7.7	7.7
	%	0.0	0.0	0.0	0.0	34.4	34.4	34.4	34.4	34.4	34.4
Solar energy generation	kWh/m ² a	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.4	-3.3
	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-9.5	-9.2

The results from the five steps are presented in Figure 12. As can be seen, the difference between the final normalised results, comparing yearly and monthly normalisation, is low. Before normalisation, the measured energy use for GSHP was 12% higher as compared to the simulation. After normalisation, the corresponding values are 5.2% and 7.3% for yearly and monthly normalised values, respectively. The measured generated energy from PV panels was 16.5% higher compared to the simulation. After normalisation, the corresponding values are 5.5% and 5.8% for yearly and monthly normalised values, respectively. The largest relative deviation is with respect to energy use for cooling, fans, and pumps, which is not normalised.

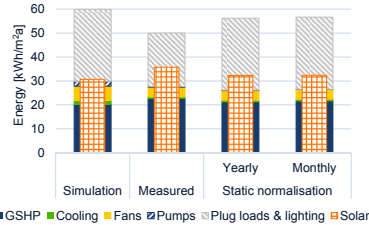


Figure 12. Results from simulation and measurements together with static normalisation.

4.4. Dynamic Normalisation

To enable dynamic normalisation, a new load profile for plug loads and lighting was needed. This profile was created based on the measured results. In Figure 13, the daily and monthly variation is shown. The new load profile is a slightly simplified profile compared to the measurements. The new load profile results in the same annual energy demand as measured.

The dynamic normalisation, through repeated simulation, is carried out stepwise in the same steps as the static normalisation in the previous section. The results are presented in Table 7.

The first step, normalisation of energy use for domestic hot water, gives the same result as that for static normalisation. The total energy use for GSHP is adjusted upwards by 1.6% and the total energy demand increases by 1.3% after the first step. There is no difference between yearly or monthly normalisation.

The adjustment for deviating indoor temperature (the second step) shows a rather high impact. When adjusting on a yearly basis, the reduction of the energy use for space heating is 16.0%. This reduces energy for GSHP by 11.4%, to a total reduction of 9.9% considering the first two steps. If adjustment is made on a monthly basis, the adjustment is slightly larger. The reduction for space heating is then 17.8%, resulting in a reduction of energy for GSHP of 12.6%, and thus a total reduction of 11.2% when considering the first two steps.

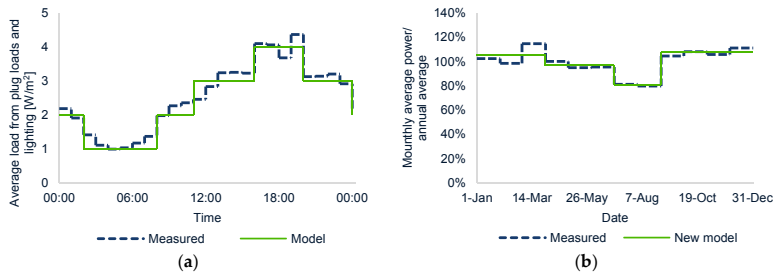


Figure 13. (a) Daily variation of energy use for plug loads and lighting. Measured results and new model for load profile. (b) Monthly variation of energy use for plug loads and lighting. Measured results and new model for load profile.

When applying the new load profile for plug loads and lighting in the third step, this results in a further reduction of the measured energy for space heating. The energy use for plug loads and lighting was reduced by 7.7 kWh/m²a in the simulation, following the load profiles presented in Figures 13 and 14. This resulted in an increased demand for space heating, disregarding the SCOP from the GSHP

of 5.5 kWh/m²a, which corresponds to an increase in space heating demand of 11.4% for a whole year. Applying the annual adjustment further reduces energy use for GSHP by 6.9%, leading to a total reduction of 16.1%. Monthly adjustment reduces the energy use for GSHP by 5.0%, leading to a total reduction of 15.6%.

The fourth step, normalisation due to exterior climate, adjusts the measured results for space heating upwards. The increase is higher if yearly adjustment is applied compared to monthly adjustment. The total adjustment of GSHP, considering all four steps and comparing yearly and monthly adjustment, is almost the same, with a reduction of roughly 12%.

The fifth (and last) step, when the energy generation from PV panels is adjusted, results in a reduction of measured generation of roughly 10%.

Table 7. Absolute and relative changes of measured data based on the dynamic normalisation. Y: normalisation based on yearly average, M: normalisation based on monthly average.

Title		Step 1		Step 2		Step 3		Step 4		Step 5	
		Y	M	Y	M	Y	M	Y	M	Y	M
GSHP	kWh/m ² a	0.4	0.4	-2.3	-2.6	-3.7	-3.6	-2.7	-2.8	-2.7	-2.8
	%	1.6	1.6	-9.9	-11.2	-16.1	-15.6	-12.1	-12.2	-12.1	-12.2
Total energy demand ¹	kWh/m ² a	0.4	0.4	-2.3	-2.6	-3.7	-3.6	-2.7	-2.8	-2.7	-2.8
	%	1.3	1.3	-8.2	-9.3	-13.3	-12.9	-10.0	-10.1	-10.0	-10.1
Plug loads and lighting	kWh/m ² a	0.0	0.0	0.0	0.0	7.7	7.7	7.7	7.7	7.7	7.7
	%	0.0	0.0	0.0	0.0	34.4	34.4	34.4	34.4	34.4	34.4
Solar energy generation	kWh/m ² a	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.7	-3.6
	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-10.3	-10.0

¹ Total energy demand excludes energy demand for plug loads and lighting.

The results from the five steps are presented in Figure 14. As can be seen, there is almost no difference between the final normalised results, comparing yearly and monthly normalisation. Before normalisation, the measured energy use for GSHP was 12.5% higher as compared to the simulation. After normalisation, the corresponding values are -1.1% and -1.3% for yearly and monthly normalisation, respectively. The measured generated energy from PV panels was 16.5% higher compared to the simulation. After normalisation, the corresponding values are 4.6% and 4.8% for yearly and monthly normalisation, respectively. In the same way as for the static normalisation, energy use for cooling, fans, and pumps has not been normalised.

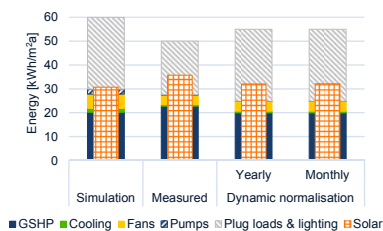


Figure 14. Results from simulation and measurements together with dynamic normalisation.

5. Discussion

Within this study, the quantity and/or presence of residents was not documented. This causes some uncertainty in the results, as the effect from predicted versus actual heat gains from occupancy are not included in the normalisation. Furthermore, since the equipment for measurements was calibrated

and installed by sub-contractors, the authors did not control the calibration. However, the tests of the normalisation methods bring up interesting aspects for discussion.

Regarding the normalisation of energy use for hot water, this adjustment had the lowest effect as compared to the other adjustments. There are no differences in the results when comparing the static and dynamic normalisation. This is due to the fact that the simulation software considers the domestic hot water demand and the assumed SCOP for the heating production for hot water to calculate energy use for domestic hot water production. As such, the effect of the hot water storage tank was not included in the simulation. Furthermore, the production of heat for hot water was not measured (only the quantity of hot water use was measured). Therefore, it was not possible to evaluate and analyse the SCOP for hot water production. Hence, the energy use for hot water was based on quantities of hot water use and not measured energy use. This is a weakness which gives the results from the study some uncertainty. Upcoming studies of similar projects should widen their measurements in order to give more certainty to their results.

Normalisation due to indoor temperature showed the largest difference when comparing static and dynamic normalisation. The dynamic normalisation resulted in a reduction of 16.0% and 17.8% for the space heating demand, where the lower value was based on yearly adjustment. These results correspond rather well to previous studies [10,16,18], which showed increased energy use for heating of around 12.2% to 20.0% when indoor temperatures were increased by 1 °C within the indoor temperature interval of 20–25 °C. Other studies showed a lower impact, from 8.0% to 10.0% per °C [7,38]. Regardless, no study showed an impact of 5% per °C, which indicates that the recommended adjustment of 5% per °C given in the Swedish regulations is low. It should be noted that the studies included above are passive-/low-energy houses. This means that the absolute deviation may be considered to be low, between 1.5 and 3.0 kWh/m²a.

The effect of deviating the use of plug loads and lighting showed a rather high impact, both for static and dynamic normalisation. The dynamic normalisation showed that a reduction of heat gains from plug loads and lighting by 7.7 kWh/m²a resulted in an increased heating demand of 5.5 kWh/m²a. This corresponds well to the share of internal loads assumed to affect heating or cooling, given by Boverket, of 70% [22]. In this case, the static normalisation resulted in an adjustment of energy demand by 5.4 kWh/m²a (70% of 7.7 kWh/m²a). Based on a SCOP of 3, the adjustment for energy use for GSHP was 1.8 kWh/m²a. The result did not differ between yearly or monthly adjustments since the adjustment was in absolute values. The dynamic normalisation, which used the ratio between simulations for step 2 and step 3 as an adjustment factor, resulted in a lower adjustment compared to the static normalisation. The adjustment of energy use for GSHP was 1.4 kWh/m²a and 1.0 kWh/m²a, for yearly and monthly normalisation, respectively. This indicates that an adjustment of energy use due to deviating internal loads may give a more accurate result conducted in absolute values.

Regarding normalisation due to deviating exterior climate, these adjustments were the second-lowest of the adjustments. The adjustments were also relatively equal, regardless if they were normalised by the static or dynamic method, with yearly or monthly adjustment. Except for the normalisation of hot water, normalisation due to deviating exterior climate showed the smallest difference between static and dynamic normalisation. This indicates that normalisation by energy index is a static normalisation which gives realistic results.

Differences regarding the two methods for normalisation of energy generation from PV panels were low. This is most likely due to the fact that both methods were based on monthly deviations based on data from SMHI. Upcoming studies of similar projects should widen their measurements in order to provide greater certainty of their results.

Comparing the static and dynamic normalisation, dynamic normalisation resulted in a normalised value for GSHP closer to the predicted energy demand than did static normalisation. The measured and dynamically normalised energy demand values for GSHP were roughly 1% lower than those found in the results of the simulation, as compared to static normalisation where the measured and normalised energy demand was approximately 5–7% higher. The measured and dynamically

normalised energy generation values from PV panels were roughly 4% higher than those found in results from simulations, as compared to static normalisation where the measured and normalised energy generation was roughly 5% higher.

The deviation of energy use for fans and pumps was rather high, almost 50% lower compared to the results from the simulation in the design phase. The deviation was mainly due to the better performance of fans and pumps, not deviating boundary conditions such as a greater use of increased/forced ventilation, etc.

6. Conclusions

Monitoring energy use is important to ensure that predicted energy use is achieved in the actual use of buildings. This study shows that it is important to normalise the measured energy use in order to determine an accurate energy performance. The normalisation of measured energy use may, to a large extent, close performance gaps and explain deviations between simulations and measurements, and thus between predictions and reality.

It is important that the normalisation not only considers deviation in exterior climate. Therefore, the monitoring of energy use should always be done in a way that enables normalisation for important parameters. Such parameters, highlighted in this study, are the use of domestic hot water, indoor temperature, internal loads, and outdoor climate. Measurements of outdoor climate should include at least outdoor air temperature, relative humidity, wind speed, and solar radiation.

This study normalises the energy use for heating, hot water, and solar energy generation. This includes the energy use for the GSHP (used for both heating and hot water) and the generated energy from the PV panels. Before normalisation, the performance gap between the design simulation and measured energy use for the GSHP was 2.5 kWh/m²a, which corresponds to 12%. The static and dynamic normalisation reduced the performance gap (based on yearly adjustment) to 1.5 kWh/m²a and −0.2 kWh/m²a, respectively, which corresponds to 5% and −1%. The normalisation of energy generation from PV panels reduced the performance gap from 5.1 kWh/m²a to 1.7 kWh/m²a and 1.4 kWh/m²a, for static and dynamic normalisation, respectively (based on yearly adjustments), which corresponds to a reduction of the performance gap from 17% to 5%, for both static and dynamic normalisation (see Figure 15).

This study shows that the dynamic normalisation of heating gives normalised values closer to those predicted in the simulation, as compared to static normalisation. However, this study is only indicative since it is based on a single case. More studies are needed to investigate which normalisation method will give more accurate results.

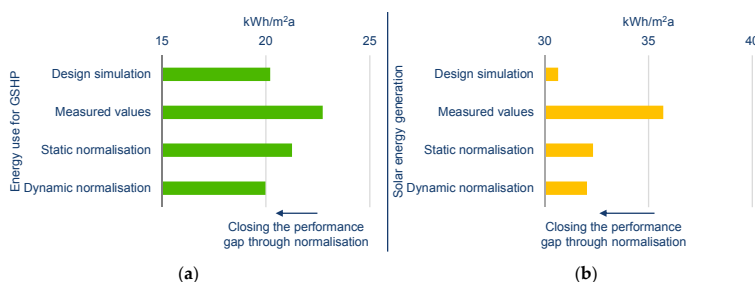


Figure 15. Comparison of energy use/energy generation with respect to the design simulation, measured values (not normalised), static normalisation, and dynamic normalisation (yearly adjustment), closing the gap between the design simulation and the measured energy use; (a) Energy use for GSHP; (b) Energy generation from PV panels.

The static method for normalisation is simple and straightforward. Hence, it is also feasible for use in other countries with similar boundary conditions. The static method should be easier to use compared to more complex methods such as dynamic normalisation and calibration of energy models. However, more research should be done to verify and improve the method. Normalisation due to indoor temperature showed the largest difference, comparing static and dynamic normalisation. Further verifications and improvements could start there. Further research and development should also investigate how to include the normalisation of more parameters. Examples include heat gains from occupants and cooling energy use due to internal heat gains and solar radiation.

Finally, this study shows that it is possible to build a Net ZEB in a Swedish climate with technologies existing on the market today. However, the import-export electricity balance is hard to predict, even if dynamic simulations are conducted with detailed load profiles.

Author Contributions: B.B. were responsible for measuring and compiling data, B.B. and M.W. analysed data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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Article 5

Article

State of Knowledge of Thermal Bridges—A Follow up in Sweden and a Review of Recent Research

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Abstract: It is important to minimize transmission heat transfer losses through the building envelope when designing and building energy efficient buildings in heating dominated climates. In such a climate, a large part of the space heating demand is caused by transmission heat transfer losses through the building envelope. Calculations of these losses must be carried out in a correct way to ensure a properly sized heating system and a good indoor climate. Furthermore, underestimating the transmission heat transfer may lead to energy costs that exceed expectations. A Swedish study was published five years ago which concluded that the state of knowledge was low and simplified methods used were not accurate. Five years has passed since the previous study. The purpose of this follow-up is to investigate whether the state of knowledge among Swedish consultants has increased and to review the progress within the international field. The study shows that little has changed in Sweden. The state of knowledge regarding different measuring methods and the effect on thermal bridges is still not satisfying. Furthermore, the review of recent research shows that the relative effect of thermal bridges vary greatly. More guidelines and education/training are needed. Further research should be carried out with a holistic approach where thermal bridges are investigated with varying construction types, energy efficiency of building envelopes and different measuring methods.

Keywords: thermal bridges; EN ISO 13789; EN ISO 10211; transmission heat transfer; dimensions; buildings; review; survey; Sweden

1. Introduction

Globally, buildings account for 40% of the primary energy use and 24% of the generation of greenhouse gases [1]. Hence, the building sector has a large potential to reduce CO₂ emissions and primary energy use, by reduced energy demand, increased efficiency in energy supply chains and greater use of renewable resources for materials and fuels. Different strategies can be used to grasp this potential, where one is to set requirements in building regulations, e.g., requirements on energy use or requirements regarding thermal insulation of building envelopes.

In order to strive for an increased energy performance of buildings within the European Union, the European Parliament approved the directive on Energy Performance of buildings (EPBD) in 2002 [2] and a recast in 2010 (EPBD2) which states that all buildings by the end of 2020 shall be “nearly zero-energy buildings” (NZEB) [3]. In short; A NZEB is a building that has a very high energy performance and the required energy should be covered to a very significant extent by energy from renewable sources. Furthermore, EPBD2 states that member states shall set energy requirements for building elements and/or building envelope. Methodology for calculations should take into account European standards and be expressed in a transparent manner.

To design and build an energy efficient house, different strategies may be applied. They differ slightly but a common first step is usually to reduce the energy demand, which in a heating dominated

climate is achieved by constructing an air tight and well insulated building envelope combined with balanced mechanical ventilation with high heat recovery efficiency. Designing a building according to these principles will result in that the majority of the heating demand is due to transmission heat transfer through the building envelope. Hence, it is important to calculate the transmission heat transfer in a correct way and not underestimate or exclude potential thermal bridges.

A heating dominated climate may be defined as a climate where 70% or more of the space conditioning needs is related to heating [4]. It should be noted that also in a heating dominated climate up to 30% of the space conditioning needs may be related to cooling. Hence, buildings still need to be designed to avoid excess temperatures during the warmer part of the year.

As mentioned, EPBD2 states that methodology for calculations should take into account European standards and be expressed in a transparent way. Standards are important as they provide reliability, predictability and security. Furthermore, they facilitate communication between different actors, minimizing the risk of misunderstanding. This leads to profits, both from a business perspective and from a macroeconomic perspective [5].

A commonly used standard to calculate transmission heat transfer through a building envelope is EN ISO 13789 [6] which in turn refers to two standards regarding thermal bridges; EN ISO 14683 [7] provides a simplified method including default values of linear thermal transmittance and EN ISO 10211 [8] provides a framework for detailed calculations of thermal bridges in building construction.

Regardless of method applied, to calculate transmissions heat transfer coefficients for a building, the building envelope needs to be divided into different building elements. Measuring in order to quantify the building elements may be conducted in different ways. Three different ways are clearly defined and referred to in all three standards mentioned above; internal, overall internal and external dimensions. The different methods are visualized in Figure 1.

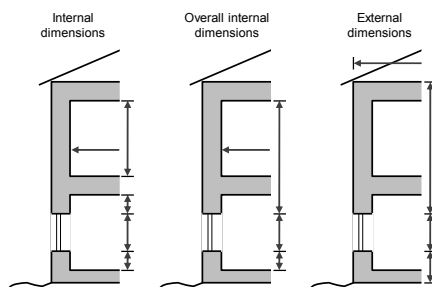


Figure 1. Three different methods of measuring according to EN ISO 10211, EN ISO 13789 and EN ISO 14683.

Thermal bridges are defined as part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, and/or a change in thickness of the fabric, and/or a difference between internal and external areas, such as occur at wall/floor/ceiling junctions according to EN ISO 10211 [8].

The linear thermal transmittance of the thermal bridge (ψ) is calculated according to Equation (1).

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \quad (1)$$

where L_{2D} is the thermal coupling coefficient obtained from a 2-D calculation, U_j is the thermal transmittance of the 1-D element j and l_j is the length of the 1-D element j .

The point thermal transmittance of the thermal bridges (χ) is calculated as in Equation (2).

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{k=1}^{N_k} \psi_k \cdot l_k \quad (2)$$

where L_{3D} is the thermal coupling coefficient obtained from a 3-D calculation, A_i is the area of element i , ψ_k is the linear thermal transmittance calculated according to Equation (1) and l_k is the length of the thermal linear thermal bridge. Other symbols as described together with Equation (1).

As the measuring of areas and lengths may be conducted in three different ways (Figure 1), the specific values for thermal bridges may differ. In order to avoid misunderstanding and enable comparison, the chosen measuring method should always be included when specific values of thermal bridges are reported. Subscripts presented in Table 1 should be used, which is used in EN ISO 14683.

Table 1. Subscripts to clarify method of measuring.

Subscript	Definition
I	Internal dimensions
Oi	Overall internal dimensions
E	External dimensions

A comprehensive review of the building codes in the European Union conducted in 2016 including 26 of the 28 members countries (Croatia and Luxemburg, not included) concluded that all countries have restrictive criteria in building regulations regarding U-values [9]. Furthermore, 23 of 26 countries (88%) include thermal bridges. However, most national regulations have adopted the simplified method according to EN ISO 14683.

Regardless of the standard used, different stakeholders may apply measuring methods differently, imposing a risk of misunderstanding. A consistent application of method for dimensions is important in order to correctly calculate the average U-value (\bar{U}), according to Equation (3). Furthermore, simplified methods always have limitations. Poor calculations of transmission heat transfer through the building envelope may lead to increased heating demand, increasing the maximum power for heating that may have large marginal effects due to that the power demand will be high, since the energy demand in a heating dominated climate already is high. Furthermore, underestimating the transmission heat transfer may lead to undersized heating systems, poor indoor climate and energy costs that exceeds expectations. The resulting consequences may be uneconomical for the client, the builder and/or the consultant.

$$\bar{U} = \frac{\sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{k=1}^{N_k} \psi_k \cdot l_k + \sum_{j=1}^{N_j} \chi_j}{A_{om}} \quad (3)$$

where A_{om} is the enclosing area of a building. Other symbols as described together with Equations (1) and (2).

To investigate the state of knowledge and the risk of performance failure, a study was conducted in Sweden in which concluded that the state of knowledge were low and simplified methods used were not accurate [10]. The study further concluded that only 11% of the academic publications included in the study [11–28] clearly defined how they quantified building elements (i.e., measuring method).

Five years have passed since the Swedish study was published and the subject of thermal bridges has been under further research and development. The purpose of the follow-up study is to investigate whether the state of knowledge among Swedish consultants has increased since the previous study. Furthermore, recently published research articles are reviewed in order to investigate the progress within the international field. Also, the method used, to investigate the state of knowledge, is presented and evaluated in order for other researchers to use the method to investigate the state of knowledge within their geographical area of operation.

2. Methodology

2.1. The Survey

Major engineering, architect and construction firms in Sweden were contacted via their official contact information, available on their web sites. When contact was established, it was explained that a survey related to energy performance of buildings and thermal bridges would be conducted. Furthermore, they were asked whether they had employees, which had work assignments related to this area. If so, contact information in the form of e-mail addresses were gathered. This is the same method, which was used in the previous survey [10]. The new contact information was merged with the contact information from the previous survey. Through this method, 176 recipients were gathered. This method was chosen with the intention that those who were surveyed would have relevant competence and background.

The questions in the questionnaire were the same as in the previous survey, with two additional questions at the end, broken down in three sections. First, four questions were asked regarding measuring methods. Two questions were asked to identify how the respondents would quantify a building's envelope in order to calculate its energy performance, and how they would quantify a building's enclosing area. The questions were asked without any specific definition or reference to the Swedish building regulations. The same two questions were then asked once more; this time citing the definitions from the Swedish building regulations.

Secondly, the respondents were asked to review six different junctions, see Figure 2, and whether the transmission heat transfer would increase in addition to the losses included in quantified building elements or not. Regarding junction A–C, the calculated transmission heat transfer may not increase due to less insulation material or penetration of the insulation layer. i.e., whether the transmission heat transfer increases or not is related to how the respondent quantify building elements. Regarding junction D–F the insulation in the junction is penetrated by another material. However, whether the calculated transmission heat transfer increases or not in these junctions are also related to how the respondent quantify building elements. In junction E and junction F, the transmission heat transfer increases due to the wooden studs. However, the effect of different internal and external area is bigger. The effect of a junction regarding transmission heat transfer, based on chosen method for quantification of building elements, is presented in Table 2.

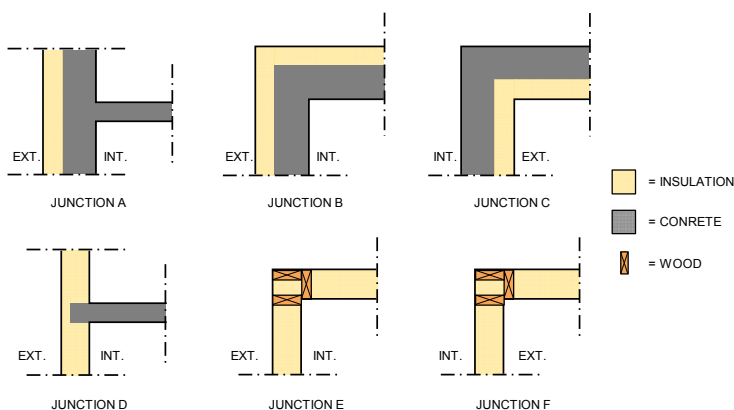


Figure 2. Schematic/simplified junctions as they appeared in the questionnaire. External environment is marked EXT. Internal environment is marked INT.

Table 2. Summary of the effect of the junction on the calculated transmission heat transfer based on chosen method for quantification of building elements.

	Junction A	Junction B	Junction C	Junction D	Junction E	Junction F
Internal dimensions	Increase	Increase	Decrease	Increase	Increase	Decrease
Overall internal dimensions	No effect	Increase	Decrease	Increase	Increase	Decrease
External dimensions	No effect	Decrease	Increase	Increase	Decrease	Increase

Finally, nine general questions regarding background and work methods were asked, compared to seven questions in the previous survey. The additional questions asked whether the respondent had answered the same questionnaire before and how they would rank the importance of different parts of a multi-family building envelope related to energy performance. The questions were given in Swedish to avoid misunderstanding due to language. The complete (translated) questionnaire is presented in Appendix A.

The survey was evaluated from three different aspects. First, it was evaluated how consultants in Sweden work today and how they quantify building elements. Secondly, based on how the respondents chose to quantify building elements, A_i in Equation (2), the respondents' answers regarding the junctions were analyzed. Finally, the execution of the survey was evaluated based on the time spent for the respondents.

The survey were conducted during September 2016. Two reminders were sent out. It was possible for the respondents to do a part of the survey, close the web survey, and start again where they left off, by using the link that was sent out. The previous survey were conducted in September 2010, using the same method as above [10].

2.2. Review of Research

A systematic desktop search was carried out in order to investigate the development within this field of research during the recent years through scientific databases available via Lund University; Science direct [29], Scopus [30] etc. The search term "thermal bridges" was used to search in titles and keywords. In order to narrow the desktop search, only research published after the previous study [10] were gathered and the search was restricted to the following journals; Applied Energy [31], Applied Thermal Engineering [32], Building and Environment [33], Energy [34], Energy and Buildings [35] and Sustainability [36]. Through this method a little over 200 publications were found. The abstracts were reviewed; articles which investigated the impact of thermal bridges were included, which narrowed it down to almost 60 articles. These articles were included in the review. If an article in the review gave references to other research, which were considered to be related to the impact of thermal bridges in buildings, these were also included in the review. Overall; 74 research articles and conference papers were reviewed. A summary of the sources is given in Table 3.

Table 3. Summary of sources for reviewed research.

Source/Journal	Publications Reviewed
Energy & Buildings [35]	36
Energy Procedia [37]	15
Applied Thermal Engineering [32]	7
Applied Energy [31]	5
Sustainability [36]	3
Construction & Building Materials [38]	2
Building & Environment [33]	1
Civil Engineering and Management [39]	1
Energy [34]	1
Environmental Sciences Procedia [40]	1
IBPSA Building Simulation Conference 2015 [41]	1
World sustainable buildings Conference 2014 [42]	1

3. Results

3.1. The Survey

Out of the 176 who received the questionnaire, 91 responded, which corresponds to 52%. The previous survey received 73 responses out of the 100 who received the survey (73%). Out of the respondent in the new survey, 93% had experience in energy calculations, compared to 84% in the previous survey. Furthermore, 74% had more than five years work experience, compared to 63% in the previous survey. The respondents' answers regarding experience in energy calculations and general work experience is presented in Figure 3. The most significant difference between the survey conducted in 2010 and 2016 is that the relative share of respondents' with experience in energy calculations and 6–10 years' experience has increased, while respondents with experience in energy calculations and 1–5 years' experience has decreased. Out of the 91 respondents, 13 respondents (14%) had answered the survey conducted in 2010. However, 17 respondents (19%) did not remember whether they had answered the survey or not.

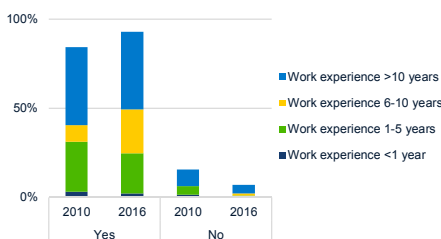


Figure 3. Answers regarding experience in energy calculations (Q12), sorted by answers regarding work experience (Q17).

Some of the respondents spent more than 60 min on the survey; 14% in the new survey compared to 7% in the old survey. Most of the respondents who spent more than 60 min on the survey finished the survey on a different day compared to the starting day (69%). i.e., they did not complete the survey in one sweep. Most respondents spent 11 min on the new survey, compared to 8 min in the old survey. The median time were 13 min in the new survey compared to 10 min in the old survey. It should be noted that the new survey had two additional questions compared to the old survey.

Internal dimensions are most frequently used by the respondents to quantify building elements for energy calculations and has increased slightly compared to the previous study, see Figure 4. The use of overall internal dimensions has increased by almost ten percent, while external dimensions decreased by roughly the same share.

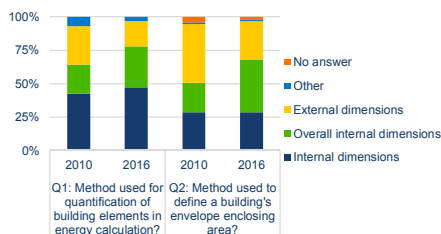


Figure 4. Distribution of answers to Q1 and Q2 for the old survey from 2010 and the new survey conducted in 2016.

Regarding quantification of enclosing area, the shift from external dimensions towards overall internal is greater compared to the shift in quantification of building elements. Measuring by overall internal dimensions are now the most common method, used by 40% of the respondents. However, the results show that there is no measuring method which could be considered to be the norm in Sweden regarding quantifications related to energy calculations.

When the respondents were given the definitions of building elements (A_i) and enclosing area (A_{om}), as defined in the Swedish building regulations, the results were more uniform, see Figure 5. The definition of A_i is “The surface area of the structural element i in contact with heated indoor air” and the definition of A_{om} is “Total surface area of the building envelope facing the heated indoor air” [43]. Regarding A_i , there is an increased use of internal dimensions, almost 15% compared to previous research. Interpretations of A_{om} has slightly changed compared to the previous study.

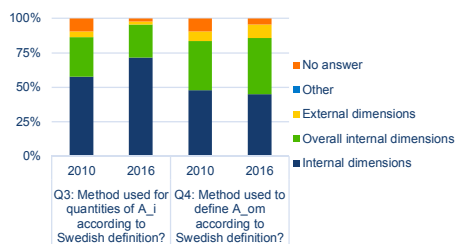


Figure 5. Distribution of answers to Q3 and Q4 for the old survey from 2010 and the new survey conducted in 2016.

Regarding how thermal bridges are handled in general, there is a shift towards simplifications. In the old survey, the most common method to consider thermal bridges (44%) was to gather lengths of linear thermal bridges and quantities of point thermal bridges. These quantities were multiplied with default- and/or standard values based on guidelines, experience or available default values in the preferred software. The second most common method (22%) in the old survey was to increase the transmission heat transfer losses with a certain percentage. The third most common method (20%) was detailed calculations with numeric software.

The new survey showed that the most common method is to increase the transmission heat transfer losses with a certain percentage (49%). The second most common method (25%) is to gather lengths and quantities of thermal bridges combined with default- and/or standard values. The application of detailed calculations has decreased to 14%. The applied percentage factor to increase the transmission heat transfer losses has increased. In the old survey, almost 60% of the respondents who applied the percentage increase method used a percentage factor lower than 20%. In the new survey 60% of the respondents used 20% or more.

Regarding analysis and calculation of thermal bridges, 55% of the respondents in the new survey executed thermal bridges calculations, compared to 47% in the old survey. Out of the respondents who executed thermal bridges calculations, 83% explicitly used advanced software in the new survey (such as Therm [44], HEAT [45] and Flixo [46]), compared to 43% in the old survey.

As mentioned, a consistent application of method for dimensions is important. i.e., the total enclosing area must be the same as the sum of all building elements, A_i , to enable calculation of average U-value in a correct way. By cross examining the answers in this survey, related to how the respondents quantify building elements and how they quantify total enclosing area, it is possible to see the share of respondents who are not consistent.

The respondents who interpreted the definition of A_i as overall internal dimensions were most consistent; 68% quantify single building elements and enclosing area in the same way.

The corresponding values for internal dimensions and external dimensions were 60% and 50% respectively. Overall 62% of the respondents were consistent and interpret the definition of building elements and enclosing area in the same way (question three and four, see Appendix A).

To further investigate the respondents' understanding, the answers from the assessment of the junctions has been sorted based on chosen dimensioning method for quantification of A_i . E.g., if a respondent answered that A_i is defined by external dimensions and afterwards answered that junction A is a thermal bridge; the answer is incorrect and therefore listed as incorrect. i.e., junction A may only be a thermal bridge if there are differences in external and external areas, which is not the case if one quantifies building elements based on external dimensions. The results are gathered and compared with the previous study in Figures 6 and 7.

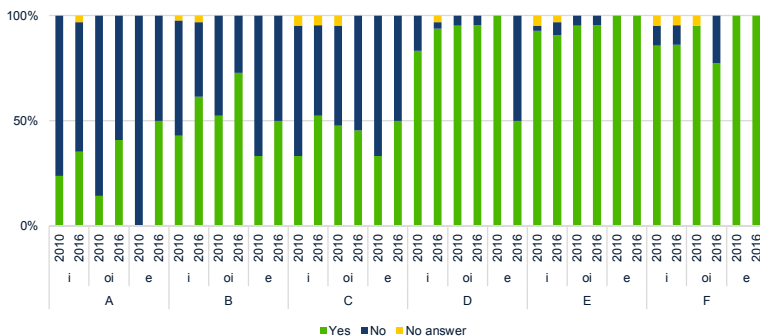


Figure 6. Distribution of answers regarding if junction A–F, by chosen method for dimensioning of A_i and old/new (2010/2016) survey. Answers given by the respondents to the question: Will this junction increase the transmission heat transfer losses in addition to the losses included in building elements?

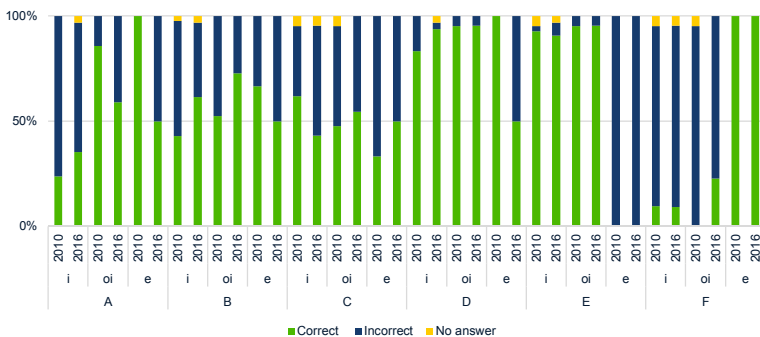


Figure 7. Distribution of answers regarding if junction A–F, by chosen method for dimensioning of A_i and old/new (2010/2016) survey. Correct and incorrect answers.

Regarding the first three junctions (A–C), which may only be thermal bridges due to differences in the external and internal area, 51% of the respondents in the new survey gave a correct answer, regardless of chosen dimensioning method. This result is almost the same as in the old survey, where 50% gave a correct answer.

The fourth junction (D) is a thermal bridge regardless of chosen dimensioning method. The main reason for the thermal bridge is the partial penetration of the building envelope, by the concrete interior slab, with a material with a significantly higher thermal conductivity. The assessments showed a significantly higher correctness level in this case; 92% correct assessments in the new study. Also in this case the result is close to the same as in the old study, where 89% gave a correct answer.

As mentioned in the method section; in the last two junctions (E–F) the transmission heat transfer increases due to the wooden studs. However, the effect of different internal and external area is bigger. Regarding these junctions, 88% of the respondents in the new survey answered that these junctions would increase the transmission heat transfer losses in addition to the losses included in building elements, regardless of dimensioning method. The corresponding value in the old survey were 92%. The respondents in general, in both the old and the new survey, seem to make the assessment that the effect of the wooden studs are larger than the geometrical effect due to differences in internal and external areas.

The share of correct answers among the respondents who interpret quantification of A_i as internal dimensioning (the most common interpretation of A_i) has increased slightly to 56% in the new survey. Also the share of correct answers among respondents who interpret quantification of A_i as overall internal dimensioning (the second most common interpretation of A_i) has increased slightly to 67% in the new survey. The share of correct answers among respondents who interpret quantification of A_i as external dimensioning (the least common interpretation of A_i) has decreased to 50% in the new survey. Overall, the share of correct answers, regardless of method for measurement, has increased slightly to 58% in the new survey compared to 56% in the old survey. The breakdown is presented in Table 4.

Table 4. Number of answers in the assessment of junctions based on correct, incorrect and no answers. Related to the respondents' interpretation of dimensioning for A_i .

Method of Measurement	Year of Survey	Allocation of Answers		
		Correct Answers	Incorrect Answers	No Answers
Internal	2010	132	113	7
	2016	217	159	14
Overall internal	2010	79	45	2
	2016	88	44	0
External	2010	12	6	0
	2016	6	6	0
Total	2010	223	164	9
	2016	311	209	14

In the third section of the survey, the respondents were given the three definitions of a thermal bridge according to EN ISO 10211 [8], and were asked which of these they considered to define a thermal bridge. The distribution of answers is given in Table 5. Only 18% of the respondents in the new survey chose all three definitions. However, this is an increase compared to the old survey where only 5% of the respondents chose all three definitions.

Table 5. Share of answers “Yes”, related to how the respondents defined a thermal bridge.

	Share of Respondents, Year of Survey	
	2010	2016
Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity.	81%	84%
Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by a change in thickness of the fabric.	22%	29%
Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by difference between internal and external areas, such as occur at wall/floor/ceiling junctions.	19%	35%

3.2. Review of Research

Out of the reviewed research, the most common approach when investigating thermal bridges were case studies focusing on thermal bridges. Roughly 40% of the reviewed research were some sort of case study where thermal bridges were analyzed in the context of the effect on a building [47–79]. A large part of the studies, 28%, investigated thermal bridges in a limited context, usually a part of a wall section [80–101]. Most studies, which investigated the effect of thermal bridges in the context of a building, did not present specific values for the thermal bridges. Furthermore, they did not specify whether the quantification of building elements were based on internal dimensions, overall internal dimensions or external dimensions. One study was identified where the specific values for different thermal bridges were presented together with the chosen method, internal dimensions [74], for a complete building.

Out of the identified studies, less than 10% clearly defined the method for quantification of building elements [54,58,66,74,94,97,98]. Except for the study mentioned above [74], only two more studies were identified where both specific values for thermal bridges were presented in combination with a clearly defined method for quantification of building elements [97,98].

The previous study [10] highlighted that different stakeholders may apply different measuring methods, imposing a risk of misunderstanding. Out of the reviewed research, roughly 11% referred to results from this previous study [47,53,58,59,76,89,94,101]. However, only two of these studies clearly defined a measuring method [58,94].

Overall, the most common approach found to express the impact of thermal bridges was to quantify the effect in percentages. The effect varied commonly from 10% to 30%. However, examples were also found where the relative impact may be below 10% [48,53] and above 30% [10,57], where the low relatively impact was related to historical buildings with already poor insulation and the relatively high impact was related to buildings corresponding to passive house standard.

4. Discussion

4.1. The Survey

Regarding the response rate on the questionnaire and the number of respondents, the quantity of recipients increased from 100 to 176 while the response rate decreased from 73% to 52%. At the same time, the quantity of recipients increased more than the decrease in response rate. Furthermore, the respondents in the new survey has longer experience and more direct experience of energy calculations. This indicates that the demand for professionals who carry out energy calculations has increased and could also be interpreted as increased work load on these professionals, as fewer respond to the survey.

Over all, the survey gathered answers from almost 100 respondents, where more than 90% had experience from energy calculations and more than 70% had more than five years work experience. This indicates that the intention to find professionals in this field succeeded.

The purpose of the survey was to, in an effective way, determine the state of knowledge among professionals who work with energy calculations, related to thermal bridges. Disregarding the respondents who finished the survey on a different day compared to starting day, 94% of the respondents spent less than 60 min to answer it. The respondents who spent more than 60 min to answer the survey may have started to answer the survey, taking a break for coffee or attending a meeting before finishing the survey. Overall, the time spent on answering, indicates that the survey may be an effective way to determine the state of knowledge.

Regarding quantification of building elements and buildings' enclosing area, the biggest shift, comparing the old and the new survey, was the increased use of overall internal measuring when quantifying a buildings' enclosing area. However, there is still a big spread among the answers. With the exception for the definition of A_i according to the Swedish building regulations (Question 3), there is no measuring method that is chosen by more than 50% of the respondents when asked to define building elements and buildings' enclosing area. The survey show that there is still no widespread and established view among engineers and architects in Sweden regarding how to quantify building elements as input for calculation of transmission heat transfer losses.

Several consultants are usually involved in the design and construction phase of a building. Hence, it is possible to imagine a scenario in which an architect will be asked to provide quantities of building elements and junctions, a construction engineer to calculate U-values and specific values for thermal bridges and a HVAC-consultant to do energy calculations and sizing of heating- and cooling system. In such a scenario, misinterpretations and therefore incorrect calculations of transmission heat transfer losses may occur.

An increased use of Building Information Modelling, BIM, may pave the way for more standardized and automatic way to use input data, which could minimize such errors. On the other hand, this could also be a potential source of error if quantity take offs (data export from the model e.g., floor-, roof-, wall areas etc. to text data) are used from the BIM model without a critical review of the data from the model.

Regarding how thermal bridges are taken into account, there is a trend among engineers and architects towards simplification. Almost a majority of the respondents (49%) used a method where they leave out the calculation of thermal bridges and instead increased the transmission heat transfer through the building envelope by a percentage factor (22% in the old survey). However, the percentage factor has increased, indicating that e.g., architects and engineers have a greater respect for thermal bridges today, while they unfortunately do not have the time to consider them in a thorough way.

This survey also indicated that engineers and architects do not fully understand when or where thermal bridges may occur. No substantial improvement was identified comparing the old and the new survey, especially not when a thermal bridge is due to differences between internal and external areas. This is concerning. If an engineer or architect does not consider a junction to be a potential thermal bridge, it is not likely that the junction will be investigated, which could lead to large errors in energy calculations and sizing of heating- and cooling systems.

This survey was carried out among Swedish engineers and architects and the results should therefore be viewed from that perspective. From a more global perspective, it would be beneficial to carry out a global survey based on the survey used here. Such a survey could highlight differences between different countries and regions and highlight where there is a need for more guidelines and standardization.

Furthermore, when defining answers related to the junctions as incorrect or correct, we assume that the respondents understands the task given to them. Some respondents may have misunderstood the survey. i.e., the results should be viewed keeping this in mind. However, as the majority of the

respondents has a solid background within this field. This error should be low. In order to minimize this possible error further studies could review and try to improve the questions.

As most respondents only consider the definition of a thermal bridge to be one; “Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity”, this is most likely the reason for the high share of incorrect answers. To ensure that respondents understand their definition, further investigations with surveys could be carried out in a way where the respondents are asked to review specific junctions based on their chosen definition or definitions.

4.2. Review of Research

The review of the recent research showed that there is a rather large quantity of research related to case studies and thermal bridges in their specific cases. Standard and/or default values exist today (e.g., ISO 14683 [7]). However, previous research showed that specific values may vary greatly. i.e., the case studies showed that it is not possible to define default values in a simple way.

Many of the investigated studies mainly discussed the impact of thermal bridges in relative terms. As the results show, the impact from thermal bridges may be below 10% and above 30%. It should therefore not be recommended to use relative terms in energy calculations and sizing of heating- and cooling systems for buildings. Hence, the research who presents the results in relative terms makes it difficult for other researcher to use in further studies. Furthermore, presenting results in relative terms makes it difficult for other researchers to verify the results.

Many researchers cite EN ISO 10211 [8]. This standard states that the method used for measuring when calculating thermal bridges should be presented together with the calculated values. Still, an overwhelming majority of the research fails to include this information when they present their results. This underlines the need to increase knowledge and compliance related to standards among researcher, reviewers and editors.

5. Conclusions

5.1. The Survey

The results from the survey show that little has changed in Sweden since the previous survey was conducted. Still, the state of knowledge regarding different measuring methods and the effect on thermal bridges is not satisfying. The share of correct answers, when assessing junctions as potential thermal bridges, has increased slightly to 58% in the new survey compared to 56% in the old survey.

When asked how to quantify a building envelope for energy calculations, there is no measuring method used by more than 50% of the respondents. More guidelines and education/training are needed. Hence, no clear norm/practice can be identified regarding measuring method used.

The survey usually took less than 60 min to answer. It would be beneficial to carry out a global survey based on the survey used here in order to highlight where there is a need for more guidelines and standardization.

5.2. Review of Research

The literature review shows that thermal bridges are treated in different ways and that information about the method used for measuring, when calculating thermal bridges, is often not presented together with the results. More than 70% of the reviewed research focus on case studies, investigating the effect of thermal bridges where the most common approach was to quantify the effect in percentages. Less than 10% of the studies clearly defined measuring method used. Only three studies were found which included both specific values for thermal bridges and clearly defined measuring method used.

The relative effect of thermal bridges may vary greatly and should therefore not be considered in relative terms as input data in energy calculations and sizing of heating- and cooling systems for buildings.

Further research should be carried out with a holistic approach where thermal bridges are investigated when the following is varied: Construction types (e.g., concrete sandwich walls, wooden frame walls, etc.), energy efficiency (e.g., quantity and type of insulation) and method of measuring (internal, overall internal and external).

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Appendix A. Questionnaire

This questionnaire is translated from the original in Swedish.

Introduction

This questionnaire roughly takes five-fifteen minutes to answer.

The questionnaire aim is to investigate how you interpret different definitions and junctions between different building elements. The purpose is to identify if there is a need for clarifications, guidelines, etc. in relation to calculations and quantifications of thermal bridges and building envelopes related to energy performance of buildings.

The questionnaire begins with four questions regarding how you interpret different definitions. Then you will give your opinion regarding six different junctions between different building elements, whether these are thermal bridges or not. The investigation ends with nine general questions related to your work and background.

All answers are processed anonymously.

In case of any questions, please contact: bjorn.berggren@ebd.lth.se
Lund University, Div. of Energy and Building Design.

1. If you were given the task to quantify a building envelope for energy calculations, which of the methods below would you choose?

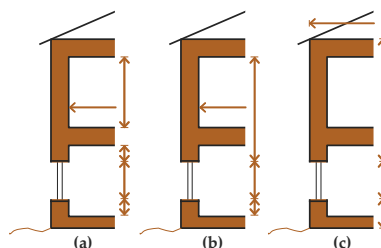


Figure A1. Different methods of measuring, figure included in questionnaire. (a) Internal dimensions; (b) Overall internal dimensions; (c) External dimensions.

- Internal dimensions, measured between the finished internal faces of each room (Figure A1a).
- Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A1b).
- External dimensions, measured between the finished external faces of external elements of the building (Figure A1c).

Other, please describe:

2. If you were given the task to quantify a building's enclosing area, which of the methods below would you choose?

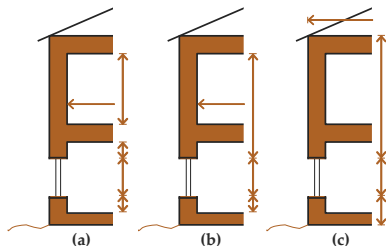


Figure A2. Different methods of measuring, figure included in questionnaire. (a) Internal dimensions; (b) Overall internal dimensions; (c) External dimensions.

- Internal dimensions, measured between the finished internal faces of each room (Figure A2a).
- Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A2b).
- External dimensions, measured between the finished external faces of external elements of the building (Figure A2c).
- Other, please describe:

3. In the Swedish building regulations, the term A_i is used and referred to as: "The surface area of the building element i in contact with heated indoor air (m^2). For windows, doors, etc., A_i is calculated using external frame dimensions." Which of the definitions below, do you think best describes this definition?

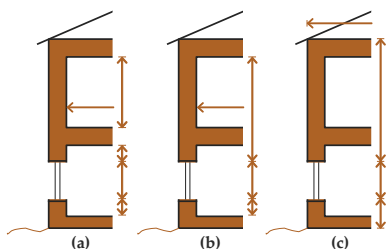


Figure A3. Different methods of measuring, figure included in questionnaire. (a) Internal dimensions; (b) Overall internal dimensions; (c) External dimensions.

- Internal dimensions, measured between the finished internal faces of each room (Figure A3a).
- Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A3b).
- External dimensions, measured between the finished external faces of external elements of the building (Figure A3c).
- Other, please describe:

4. In the Swedish building regulations, the term A_{om} is used and referred to as: "Total surface area of the building envelope facing the heated indoor air (m^2).” Which of the definitions below, do you think best describes this definition?

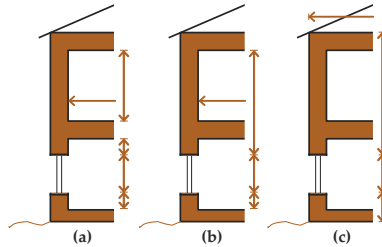


Figure A4. Different methods of measuring, figure included in questionnaire. (a) Internal dimensions; (b) Overall internal dimensions; (c) External dimensions.

- Internal dimensions, measured between the finished internal faces of each room (Figure A4a).
- Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A4b).
- External dimensions, measured between the finished external faces of external elements of the building (Figure A4c).
- Other, please describe:

You will now be asked to examine six different junctions between building elements. For each junction, we want you to answer whether you consider the junction to be a thermal bridge or not.

By thermal bridge, we imply a part of the building envelope where the transmission heat transfer losses increases in addition to the transmissions heat transfer losses which are already included in relation to the building elements.

5. The figure below describes an interior concrete floor slab connected to an exterior concrete wall. The exterior wall is insulated on the exterior side. Would you consider this junction to be a thermal bridge?

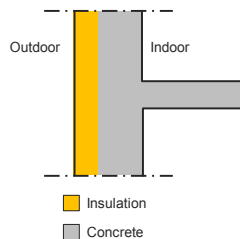


Figure A5. Schematic/simplified junction, figure included in questionnaire.

- Yes
- No

6. The figure below describes a concrete wall corner. The exterior wall is insulated on the exterior side. Would you consider this junction to be a thermal bridge?

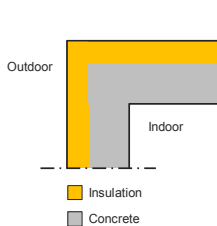


Figure A6. Schematic/simplified junction, figure included in questionnaire.

- Yes
- No

7. The figure below describes a concrete wall corner. The exterior wall is insulated on the exterior side. Would you consider this junction to be a thermal bridge?

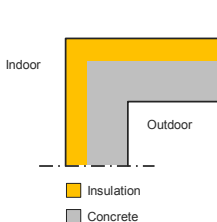


Figure A7. Schematic/simplified junction, figure included in questionnaire.

- Yes
- No

8. The figure below describes an interior concrete floor slab connected to an exterior infill wall. The infill wall is insulated. Would you consider this junction to be a thermal bridge?

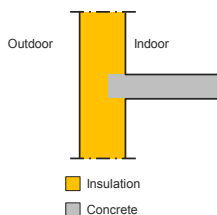


Figure A8. Schematic/simplified junction, figure included in questionnaire.

- Yes
- No

9. The figure below describes a wall corner for an insulated wood framework wall. The corner requires one extra wood stud (marked with red). Would you consider this junction to be a thermal bridge?

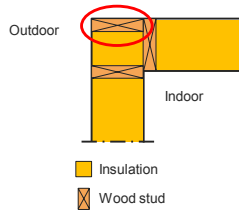


Figure A9. Schematic/simplified junction, figure included in questionnaire.

- Yes
- No

10. The figure below describes a wall corner for an insulated wood framework wall. The corner requires one extra wood stud (marked with red). Would you consider this junction to be a thermal bridge?

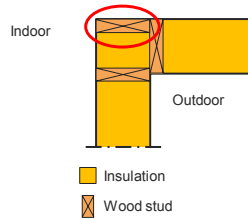


Figure A10. Schematic/simplified junction, figure included in questionnaire.

- Yes
- No

You will now be asked nine general questions.

11. What is your profession?

- Architect
- Structural engineer
- HVAC engineer
- Energy engineer
- Other, please describe:

12. Do you have experience from energy calculations/simulations?

- Yes
- No

13. According to you, what is the most common way to consider thermal bridges in energy calculations/simulations?

- Increasing the heat transfer through the building envelope by a percentage factor, please give a percentage (%):

- Gather quantities of thermal bridges and applying default- and/or standard values from software, EN ISO 14683, etc.
- Gather quantities of thermal bridges and applying results from detailed calculations (HEAT, COMSOL, THERM, etc.).
- Other, please describe:

14. Do you have experience from thermal bridges calculations?

- No
- Yes, please shortly describe preferred software, methods, etc.:

15. According to you, who should be responsible for thermal bridges calculations?

- Architect
- Structural engineer
- HVAC engineer
- Energy engineer
- Other, please describe:

16. According to you, which of the following definitions define a thermal bridge? (It is possible to choose one, two or three definitions)

- Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity.
- Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by a change in thickness of the fabric.
- Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by difference between internal and external areas, such as occur at wall/floor/ceiling junctions.

17. How long is your work experience?

- <1 year
- 1–5 years
- 6–10 years
- >10 years

18. Did you participate in the previous survey, conducted roughly five years ago?

- Yes
- No
- Do not remember

19. In relation to an apartment building with a well-insulated building envelope, how would you rank the following measures in order to reduce the transmission heat transfer losses through the building envelope? (1 = highest priority, 8 = lowest priority)

- __More insulation in the building foundation
- __More insulation in the roof construction
- __More insulation in exterior walls

- __Windows with lower U-value
- __Glazed elements with lower U-value (not regular windows)
- __Doors with lower U-value
- __Improving thermal bridges
- __Improving air tightness

Thank you for your participation!

The questionnaire is now completed.

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Article 6

Article

Review of Constructions and Materials Used in Swedish Residential Buildings during the Post-War Peak of Production

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Abstract: One of the greatest challenges for the world today is the reduction of greenhouse gas emissions. As buildings contribute to almost a quarter of the greenhouse gas emissions worldwide, reducing the energy use of the existing building stock is an important measure for climate change mitigation. In order to increase the renovation pace, there is a need for a comprehensive technical documentation that describes different types of buildings in the existing building stock. The purpose of this study is to analyse and describe existing residential buildings in Sweden. The data are based on published reports from 1967 to 1994 that have not been publicly available in a database for other researchers to study until now. Data from the reports have been transferred to a database and analysed to create a reference for buildings and/or a description of building typology in Sweden. This study found that there is a rather large homogeneity in the existing residential building stock. However, it is not possible to use a single reference building or building technique to cover the majority of the existing buildings. In Sweden, common constructions for exterior walls in multi-dwelling buildings which should be used for further studies are insulated wood infill walls with clay brick façades, lightweight concrete walls with rendered façades and concrete sandwich walls. The most common constructions for one- and two-dwelling buildings are insulated wooden walls with clay brick façades or wooden façades. Furthermore, roof constructions with insulated tie beam and roof constructions where the tie beam is a part of the interior floor slab are frequently used and should be included in further studies.

Keywords: renovation; residential buildings; reference building; building stock data base

1. Introduction

One of the greatest challenges for the world today is the reduction of greenhouse gas emissions. Worldwide, energy use in buildings accounts for over 40% of the world's primary energy usage and 24% of the greenhouse gas emissions [1]. Within the European Union (EU), Switzerland and Norway, the largest portion of the housing stock is residential houses, with a current growth rate of around 1% [2]. Thus, even if policy-makers set strict energy requirements for the new construction of residential houses, the effect may be low. Hence, reducing the energy use in the existing building stock is an important measure for climate change mitigation. Specifically, in Sweden, there are 4.5 million homes and the Swedish National Board of Housing, Building and Planning (Boverket), estimated that 75 percent of these dwellings must undergo major renovations before 2050 [3]. Boverket further concluded that the pace of renovation of existing buildings must increase as an important climate change mitigation measure.

Several projects and studies have demonstrated that there is a large potential to reduce the energy demand in existing buildings by improving the building envelopes and technical installations [4–23]. A

recent study from Italy also described different approaches for U-value assessment, including infrared thermography, which may be used to assess the U-value of constructions in existing buildings [24]. Detailed analyses for energy performance can be found in different studies [9,12–16,20–23] where energy performance was investigated for cities, boroughs and buildings. However, the description/input data collected from the buildings are generic in most of the mentioned studies. Descriptions of building envelopes are presented as U-/R-values, rather than describing the construction. Only four of the mentioned studies present the building envelopes and/or renovation measures in more detail [20–23].

Studies have also shown that many of the existing buildings in Europe were built between 1940 and 1980, and opportunities to use prefabricated building systems for the energy renovation of these building envelopes have been identified [17–19,25]. These opportunities are partly based on the finding that there is a large homogeneity in this building segment (buildings constructed between 1940 and 1980) [4,18,19,26,27]. In Sweden, this homogeneity is partly because during the most intense construction period, the so-called “Miljonprogrammet” (the million homes programme), the undertaking of projects with 1000 or more apartments in similar buildings was encouraged through rules on mortgages [26]. The million homes programme represents the era that was driven by the 1966 Swedish Parliament’s decision that one million new homes would be built in a decade (1965–1974) [28].

However, there is a risk that the assumption of homogeneity is too general, since it is largely based on the architectural design of the buildings, i.e., not looking into differences among different regions within Sweden and differences regarding load bearing structure. For example, it may be possible to renovate a lightweight concrete exterior wall with a rendered façade by applying additional insulation on the exterior side of the wall followed by a new layer of rendered façade. The same measure cannot be applied on a lightweight infill wall with a ventilated façade. A more regional analysis is important in the Swedish context, since many contractors focused on renovation may be active in a limited region.

Another issue concerning building envelope improvement is that even if an increased thermal resistance of building envelopes can improve the energy performance of existing buildings, it is seldom profitable [4,9], especially concerning the exterior walls. Thus, there is a need for the development of more cost-effective methods or prefabricated building elements that can substantially increase the thermal resistance of the building envelopes of existing buildings. To enable this development, there is a need for a comprehensive technical document that describes different types of buildings in the existing building stock in Sweden as well as the building systems and materials used.

In Sweden, such a technical description exists and includes the method of production and materials used, among other aspects. Between 1967 and 1994, Statistics Sweden (SCB) [29] published a compilation of the data every year, covering from 1962 up until 1992 [30]. However, the yearly-published data are not available in a database, which makes the information difficult to analyse in a generic way for renovation purposes. The data come from applications for state loans, where technical descriptions of the buildings were made based on a predefined template. The loans, granted by the state, ended in 1992 [28].

It should be noted that the idea of describing a building stock or reference buildings is not new. The recast of the energy Performance of Buildings Directive (EPBD) [31] required that member states set minimum requirements for energy performance based on optimal cost levels, highlighting the need for reference buildings to allow optimal cost levels to be defined. An extensive research project, TABULA [32], was conducted in 2009–2012. It included the creation of residential building typologies for 13 European countries in order to make the energy refurbishment processes in the European housing sector transparent and effective. Within this project, a report describing the Swedish situation was published. The report defined three different geometries for residential buildings. Based on these three building geometries, the effects of different energy-saving measures were investigated [33]. In many of these cases, the construction of the existing exterior walls was not defined.

Two general Swedish reference buildings were defined by The Swedish National Board of Housing, Building and Planning (Boverket) in 2010 [34]. Later, based on the EPBD recast, Boverket defined ten reference buildings in order to calculate optimal cost levels for energy performance in 2013 [35].

However, only five different geometries and three different exterior wall constructions were defined, as other parameters varied, such as ventilation and heating systems.

A Special Issue of the journal *Energy and Buildings* was recently published with a focus on monitoring, mapping and modelling the existing building stock in Europe [36–46]. However, of the previous studies that compiled and described a specific building typology, only one Spanish case [46] where the constructions of different buildings were described more in detail was found.

There are several Swedish-based studies that describe the building typology and renovation measures more in detail [20,21,47–49]. However, some concerns still exist. Three of the studies [20,47,48] based their topologies on previous work carried out by Boverket [34], who produced an inventory of 1400 residential buildings. However, it was pointed out that it is unclear whether these buildings are statistically representative or not [20]. Furthermore, none of these three studies present differences in building typology based on geographic location. The fourth study [21] uses reference houses without any specification regarding underlying data for these. The last of the mentioned studies [49] bases its building typology on architectural books [50,51], which describe architectural trends rather than statistical data.

As mentioned at the beginning of the introduction, Boverket estimated that 75 percent of the existing homes in Sweden must undergo major renovation before 2050 [3]. There are no specific data related to how existing homes are renovated today. However, the inventory carried out by Boverket in existing buildings [34] shows that the amount of insulation in existing buildings is low compared to Swedish regulations today. Buildings before 1990 can be expected to have less than 100 mm of insulation in ground constructions, less than 200 mm of insulation in exterior walls and less than 300 mm of insulation in roof constructions.

No Swedish-based study has conducted a bottom-up analysis to create reference buildings and/or a description of building typologies, including type of buildings, load bearing constructions, materials used, etc., for different regions in Sweden. A recent Swedish-based study presents a method for creating a synthetic building stock [52]. The study underlines the lack of data available for building stock characterization, which necessitates the use of a synthetic model.

Therefore, in this article, data from the SCB reports [30] were compiled to enable generic bottom-up analyses, which describe the data in order to create references for further studies. This may enable strategic development of more cost-effective and robust methods or prefabricated building elements that can substantially increase the thermal resistance of building envelopes in existing buildings. All of the compiled data is available for other researchers for further studies.

The first part of this article introduces the research problem and the purpose of the article. The second part gives an overview of definitions and nomenclature used in this study. The third part describes the available data. The fourth part describes the method used to analyse data followed by the fifth part, which presents the results. The sixth part discusses the results and compares them with previous research. In the final part of this article, conclusions and recommendations for further research are given.

2. Definitions and Nomenclature

Swedish residential buildings have some characteristic aspects, which were registered by SCB. These characteristics are explained below and are presented in Figures 1–3.

- Multi-dwelling building A building containing three or more dwellings. The building may be a balcony access building, point block building, slab block building or terraced building, as explained below and in Figure 1.
- One- or two-dwelling building A building containing one or two dwellings. The building may be a one-dwelling building, two-dwelling building, linked building or terraced building, as explained below and in Figure 2.
- Balcony access building A multi-dwelling building with one (or more) common staircase. The dwellings are accessed through a common balcony on each storey.

- Point block building A multi-dwelling building with one central core/common staircase in the centre of the building.
- Slab block building A multi-dwelling building with two or more common staircases.
- Terraced building A multi-dwelling building or two-dwelling building, usually with almost identical dwellings, which shares one or two walls with a neighbouring dwelling.
- One-dwelling building A building containing one dwelling.
- Two-dwelling building A building containing two dwellings, usually with almost identical dwellings stacked on top of each other.
- Linked building A number of buildings (may be more than two) which are connected via a complementary building (not used as a dwelling), such as a garage or storage area.
- Transverse load-bearing A superstructure of a building (usually slab block buildings or balcony access building) based on a system where the gable walls and interior walls are load-bearing. The load-bearing walls are oriented transversely in relation to the building’s dominant longitudinal direction.
- Longitudinal load-bearing A superstructure of a building where the load-bearing walls are oriented in the same direction as the building’s dominant longitudinal direction. The gable walls may also be load-bearing.
- Column construction A superstructure of a building where the dominant load-bearing wall is based on columns.
- Malmö region Includes the municipalities of Bara, Burlöv, Dalby, Genarp, Kävlinge, Lomma, Lund, Löddeköpinge, Malmö, Månstorp, Räng, Skannör, Staffanstorp, Svedal, Södra Sandby, Trelleborg, Veberöd and Vellinge.
- Göteborg region Includes the municipalities of Askim, Fjärås, Göteborg, Härryda, Kungsbacka, Kungälv, Lerum, Löftadalen, Mölndal, Nödinge, Onsala, Partille, Skepplanda, Starrkärr, Stenungsund, Styrso, Tjörn and Öckerö.
- Stockholm region Includes the municipalities of Botkyrka, Danderyd, Djurö, Ekerö, Gustavsberg, Haninge, Huddinge, Järfälla, Lidingö, Nacka, Salem, Sigtuna, Sollentuna, Solna, Stockholm, Sundbyberg, Tyresö, Täby, Upplands-Bro, Upplands-Väsby, Vallentuna, Vaxholm, Värmdö and Österåker.
- Non-metropolitan regions Includes all municipalities except for the ones listed above.

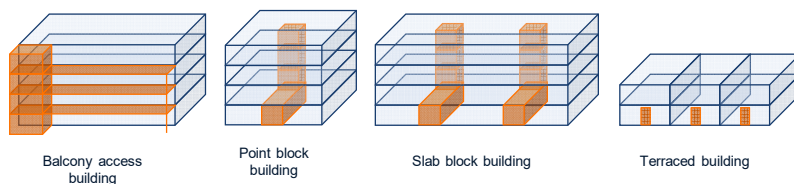


Figure 1. Different types of multi-dwelling buildings. The orange/dark sections represent the common areas/staircases/entrances where the residents enter their dwellings (presented in light blue).

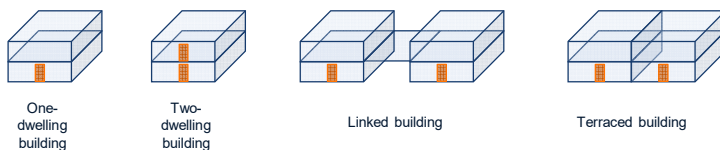


Figure 2. Different types of one- and two-dwelling buildings. The orange/dark areas represent entrances where the residents enter their dwellings (presented in light blue).

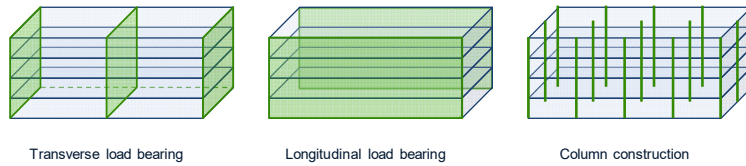


Figure 3. Different load bearing systems. The green/dark areas represent the load-bearing constructions.

3. Available Data

The available data from state loans cover the years 1962–1992 and are described in Appendices A and B.

This research focuses on residential buildings produced from 1960 up until 1990. During this period, roughly 1,250,000 dwellings were produced in multi-dwelling buildings [53]. The available data from the Statistical Reports (SR) from the state loans cover almost 1,151,000 dwellings, i.e., 92% of the produced dwellings. During the same period, roughly 900,000 dwellings were produced in one- and two-dwelling buildings. The available data cover almost 620,000 dwellings (69%). There are two main reasons for the lower coverage. The first reason is that SCB did not publish statistics from state loans for one- or two dwelling buildings in 1960–1965. The second reason is that in 1988–1990, they only published data for dwellings where the applicant of state loan was not the same as the final resident. For 1966–1987, the published data cover 83% of the dwellings. A comparison of the number of newly constructed dwellings (NC) and the data from Statistical Reports (SR) is presented in Figure 4.

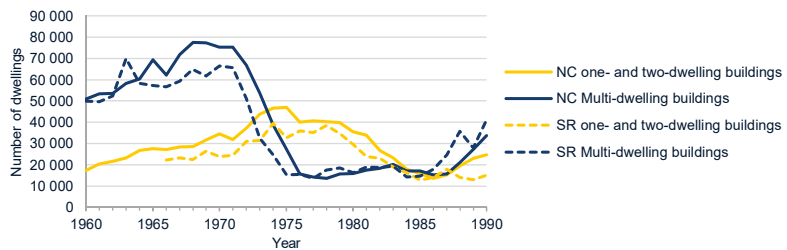


Figure 4. Newly constructed dwellings in Sweden. Comparison of data from newly constructed (NC) dwelling statistics [53] and Statistical Reports (SR) [27].

Figure 4 shows that the number of dwellings reported in statistical reports (SR) was sometimes higher than reported number of newly constructed dwellings (NC). This is probably due to the offset between the grant of a state loan for a building and the completion of that building.

4. Method

The study was carried out in four steps, as described in Figure 5. Each step is further described in this section.

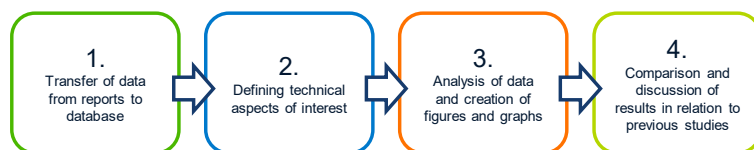


Figure 5. Diagram of the method used for this study.

4.1. Step 1—Transfer of Data

Specific data were gathered from the annual reports from SCB and transferred into a database (Excel [54]) for analysis. As data from 56 reports were transferred manually, imposing a risk of error, a quality check was carried out after the data transfer by randomly choosing ten reports and comparing the data contained in them with the data in the database.

4.2. Step 2—Defining Technical Aspects of Interest

Previous literature was examined to identify the most interesting technical aspects of multi-dwelling buildings and one- or two-dwelling buildings.

For multi-dwelling buildings, the type of building, number of storeys, type of superstructure and materials used for exterior walls were determined to be the most interesting technical aspects. As the roof constitutes a relatively small share of the building envelope in multi-dwelling buildings, roofs were not included in the analysis.

For one- and two-dwelling buildings, the type of building, number of storeys (including the presence of a cellar) and materials used were determined to be the most interesting technical aspects.

4.3. Step 3—Analysis of Data

Based on the technical aspects defined in the previous step, the existing data were analysed for different regions to create a basis for reference buildings and/or a description of building typology in Sweden. The results from step 3 are presented in the results section.

4.4. Step 4—Comparison of Results in Relation to Previous Studies

The results from the analysis were compared with previous research related to building typology to enable a discussion about differences between the results from this study and previous research. The comparison is presented in the discussion section.

5. Results

As previously mentioned, many of the existing buildings in Europe were built between 1940 and 1980. In Sweden, many of the existing dwellings were built during the so called “Miljonprogrammet” (the million homes programme). Figure 4 shows that roughly 70% of the dwellings in Sweden were built as multi-dwelling buildings during the 1960s and early 1970s. At the beginning of the 1970s, the production of dwellings in multi-dwelling buildings dropped significantly, while the production of one- and two-dwelling buildings increased, and in 1974, the production of dwellings in one- or two-dwelling buildings became higher compared to multi-dwelling buildings.

5.1. Multi-Dwelling Buildings

In Figure 6, the distribution of multi-dwelling buildings is presented by region and year. In 1960–1965, SCB did not present the distribution of dwellings by region. However, the total number of dwellings in Sweden was presented. To indicate the possible distribution, the data for the total amount of dwellings were based on available data for the overall distribution of dwellings in the specific decade [55]. Hence, data for that period are presented as hatched, as there is uncertainty regarding the distribution.

In 1966–1975, 59% of the dwellings in multi-dwelling buildings were produced in non-metropolitan regions. This means that they were not produced in the regions of Malmö, Göteborg or Stockholm. The production of multi-dwelling buildings dropped harshly in the mid-1970s. After a long period of low production, from the mid-1970s to the mid-1980s, an increase in the non-metropolitan regions occurred in the end of the 1980s. For the same period, no significant increase occurred in the metropolitan regions.

During the million homes programme, more than 80% of the dwellings were slab block buildings (see Figure 7). After the mid-1970s, the number of dwellings in slab block buildings remained constant

at a low level for a long period of time, with a small increase at the end of the 1980s. Instead, other building types became more common. The share of point block buildings and balcony access buildings increased, but there were also increases in other types of buildings.

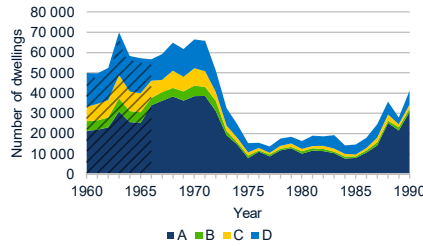


Figure 6. Distribution of dwellings in multi-dwelling buildings for different regions and years, as determined by state loans: (A) non-metropolitan regions, (B) Malmö region, (C) Göteborg region, (D) Stockholm region.

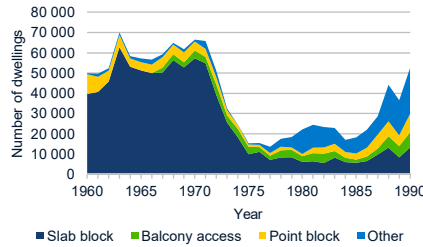


Figure 7. Distribution of dwellings in multi-dwelling buildings by type of building and year of state loan.

The distribution of different types of buildings in different regions was rather equal in 1966–1975 (there are no specific data for different regions for 1960–1965) with the exception of the Stockholm region, where the shares of balcony access buildings and point block buildings dwellings were higher compared to the rest of Sweden (see Figure 8). However, when the share of dwellings in slab block buildings decreased from the mid-1970s, it did not decrease as much in the Stockholm region compared to in the rest of Sweden (see Figure 8).

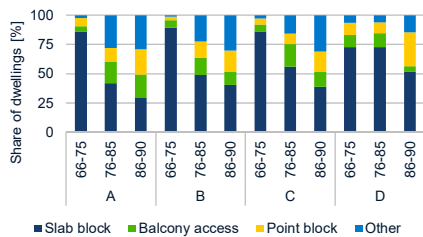


Figure 8. Share of dwellings in multi-dwelling buildings by type of building for different periods and regions: (A) non-metropolitan regions, (B) Malmö region, (C) Göteborg region, (D) Stockholm region.

Regarding the number of storeys, data are available for 1962–1993 (see Figure 9). Regional data for the number of storeys combined with region is available from 1968. Up until the late 1960s, dwellings in multi-dwelling buildings with three or four storeys represented more than 50% of the total dwellings. There is a clear tendency for more high-rise buildings to be built in the metropolitan regions, especially in Stockholm (see Figure 10). As much as 81% of the dwellings in multi-dwelling buildings built outside metropolitan regions are four storeys high or lower. However, in the Stockholm region, only 35% of dwellings fit into this category.

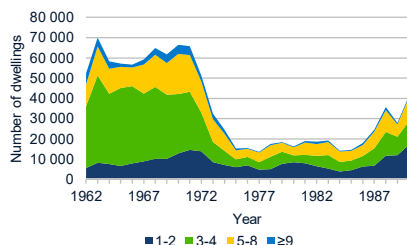


Figure 9. Distribution of dwellings in multi-dwelling buildings by the number of storeys and year of state loan.

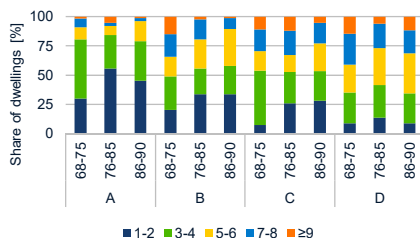


Figure 10. Share of dwellings in multi-dwelling buildings by the number of storeys for different periods and regions: (A) non-metropolitan regions, (B) Malmö region, (C) Göteborg region, (D) Stockholm region.

The type of superstructure was only presented by SCB for 1968–1972. However, this period is during the peak of multi-dwelling building production—the million homes programme. Therefore, it is interesting to analyse these data (see Figure 11). During this period, there was roughly a 50/50 distribution of longitudinal load bearing and transverse load bearing superstructures in the Malmö region and non-metropolitan regions. The use of transverse load bearing was roughly 10% greater in the Göteborg region and 10% lower in the Stockholm region.

In the beginning of the 1960s, residential buildings were almost exclusively designed with rendered façades or clay brick façades. The use of rendered façades reduced during the late 1960s, and concrete façades were rather frequently used during this period (see Figure 12). Throughout the analysed period, clay brick façades were most commonly used except for in dwellings with state loans from 1966 when rendered façades were used slightly more often and in dwellings with state loans from 1972 when concrete was used slightly more often.

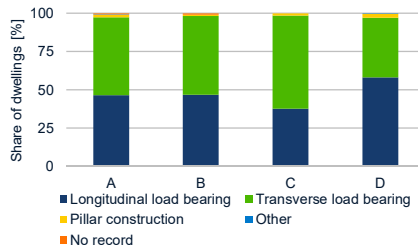


Figure 11. Share of dwellings in multi-dwelling buildings by type of superstructure for different regions (1968–1972): (A) non-metropolitan regions, (B) Malmö region, (C) Göteborg region, (D) Stockholm region.

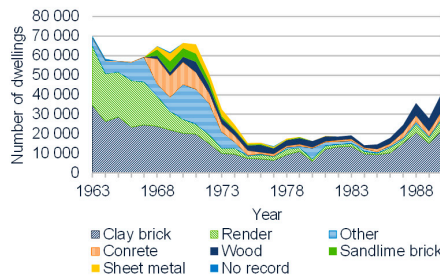


Figure 12. of dwellings in multi-dwelling buildings by façade material and year of state loan.

The façade materials used in different regions are presented in Figure 13. The data show that clay brick façades were not the most commonly used façade throughout Sweden for the whole analysed period. From the late 1960s to mid-1970s clay brick façades were common in non-metropolitan regions and the Malmö region, but not in the Göteborg and Stockholm regions. In the Stockholm region, rendered façades were the most common type of façade. In the Göteborg region, clay brick façades were the most common type of façade, but they were only used slightly more often than concrete façades.

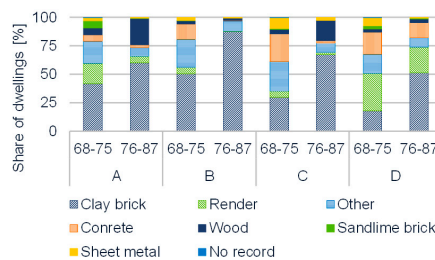


Figure 13. of dwellings in multi-dwelling buildings by façade material for different periods and regions: (A) non-metropolitan regions, (B) Malmö region, (C) Göteborg region, (D) Stockholm region.

In 1963–1979, SCB also published the combinations of façade material and inner material used in exterior walls, the data are shown in Figure 14. For the most common façade material, clay brick, the most common inner material was wood, followed by lightweight concrete, clay bricks and concrete.

The second most common façade material, render, was usually applied on lightweight concrete or concrete. Concrete façades were almost exclusively constructed with concrete as their inner material, except for some examples with wood and lightweight concrete. Façades of wood, sandlime brick or sheet metal were mostly designed in combination with wood as the inner material within the walls.

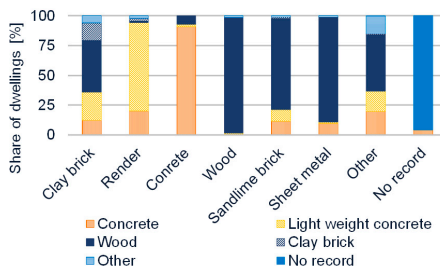


Figure 14. Share of dwellings by different inner material in exterior walls for different façade materials (1963–1979).

5.2. One- and Two-Dwelling Buildings

Regarding one- and two-dwelling buildings, the process for attaining a state loans differs depending on whether the applicant of the state loan is the final resident or not. If the applicant is not the final resident, the applicant is first given a preliminary decision before the start of the construction work. A second and final decision regarding state loans is given once the building has been completed. If the applicant is the final resident, the process is simpler, with one decision, and the applicant receives the decision about the state loan before the start of the construction work [27].

For buildings with two decisions, more data are gathered. Throughout the period where data from both one and two decisions were gathered (1966–1987), dwellings with two decisions represent 53% of the total data (see Figure 15).

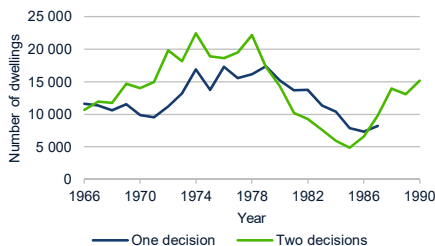


Figure 15. Distribution of dwellings in one- or two-dwelling buildings by one or two-decision state loans and year of state loan.

The distribution of dwellings in different regions is based on data from dwellings with two decisions (see Figure 16). In 1968–1980, 70% of the dwellings in one- or two-dwelling buildings that were given state loans following two decisions were produced in non-metropolitan regions. This means that they were not produced in the regions of Malmö, Göteborg or Stockholm. The production of one- or two-dwelling buildings dropped in the late-1970s. In the mid-1980s, an increase occurred in the non-metropolitan regions. In the metropolitan regions, no significant increase occurred.

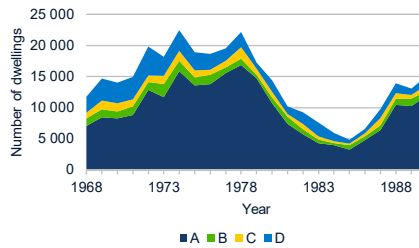


Figure 16. of dwellings in one- or two-dwelling buildings per region for different regions and years of state loan (with two decisions for state loans): (A) non-metropolitan regions, (B) Malmö region, (C) Göteborg region, (D) Stockholm region.

Regarding different types of one- and two-dwelling buildings, data for different types of buildings with one decision were only gathered in 1966–1967. However, 99% of the dwellings with one decision during that period were one-dwelling buildings. Based on this, it can be assumed that more than 95% of the dwellings with one decision are one-dwelling buildings.

In Figure 17, different types of buildings with two decision loans are presented together with the quantity of dwellings with one decision. One dwelling buildings together with one decision dwellings contributed to the largest share of dwellings. Together they made up between 60% and 70% of the dwellings. The largest portion of the dwellings with two decisions were terraced buildings, whose development increased significantly at the end of the 1980s. Linked buildings were rather common from the late 1960s until the mid-1970s, but their construction dropped in the late 1970s and remained rather uncommon throughout the 1980s.

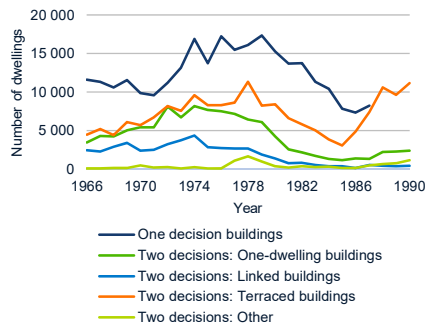


Figure 17. of dwellings in one- and two-dwelling buildings by type of building and year of state loan. More than 95% of the dwellings with one decision may be assumed to be one-dwelling buildings.

Compared to the Göteborg and Stockholm regions, in the Malmö region and in non-metropolitan regions, the share of dwellings built as one-dwelling buildings was rather high from the late 1960s to mid-1970s. Hence, the increase of terraced buildings had a greater effect on the distribution of different buildings in the Malmö region and in non-metropolitan regions (see Figure 18).

Regarding the number of storeys, data are available for 1970–1987 (see Figure 19). The number of storeys combined with regions is not available. At the beginning of the 1970s, dwellings in one- and two-dwelling buildings with one storey contributed to more than 60% of the total number of dwellings. However, as the production of dwellings with one storey was rather constant, the number of 1.5-storey buildings increased significantly, and in the mid-1970s, most of the state loans were given to dwellings

built with one and a half storeys. The number of dwellings built as hillside buildings and buildings with two storeys roughly varied between 2000 and 4000 dwellings/year in the 1970s. The production dropped in the 1980s and the corresponding interval was then 1000–2000 dwellings/year.

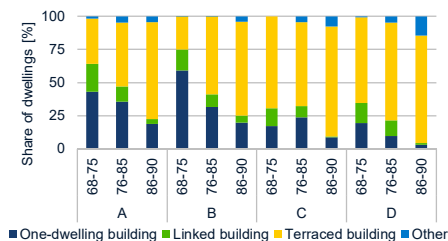


Figure 18. of dwellings in one- and two-dwelling buildings by type of building, for different periods and regions (with two decisions for state loans): (A) non-metropolitan regions, (B) Malmö region, (C) Göteborg region, (D) Stockholm region.

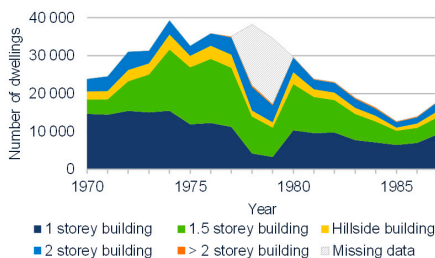


Figure 19. of dwellings in one- and two-dwelling buildings by number of storeys and year of state loan. Missing data refers to dwellings for which data were provided to Statistics Sweden (SCB), but the number of storeys was not specified.

Buildings with cellars were rather common at the beginning of the 1970s (Figure 20), almost 50% of the dwellings in one- and two-dwelling buildings had cellars. However, dwellings with cellars decreased during the 1970s and 1980s. In the late 1980s, almost 90% of the dwellings were built without a cellar.

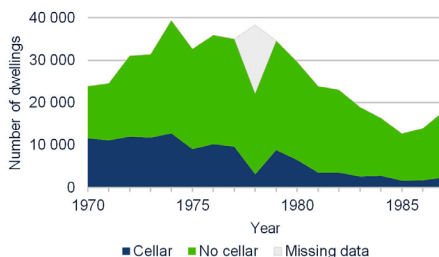


Figure 20. of dwellings in one- and two-dwelling buildings based on whether they had a cellar or not. Missing data refers to dwellings for which data were provided to the SCB, but information regarding cellars was not specified.

Information regarding material used for load-bearing structure in exterior walls and façade material was gathered for 1966–1987 and 1966–1990, respectively. Regarding the material used for load-bearing in exterior walls, wood was the dominant material throughout the period (see Figure 21).

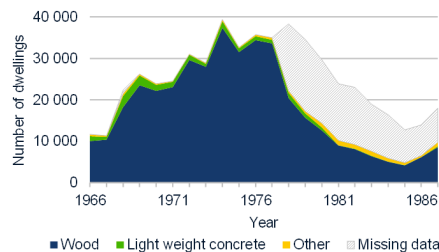


Figure 21. of dwellings in one- and two-dwelling buildings based on the material used for load-bearing in the exterior walls. Missing data refers to dwellings for which data were provided to the SCB, but the load-bearing material was not specified.

Regarding façade material, wood and clay brick façades were the most commonly used materials. Together, their share made up between 70% and 95% of the dwellings in 1966–1990. In the mid-1960s, façades with clay bricks were most common and accounted for almost 70% of the dwellings. The use of wood became more and more common, and at the beginning of the 1980s, wood was used for more than 70% of the dwellings, see Figure 22.

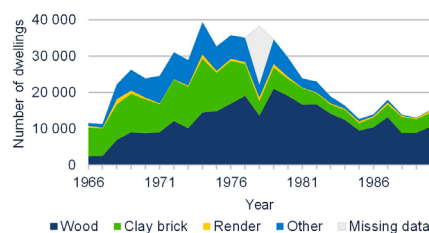


Figure 22. Dwellings in one- and two-dwelling buildings based on façade material. Missing data refers to dwellings for which data were provided to SCB, but the façade material was not specified.

6. Discussion

The data from Statistics Sweden based on Swedish state loans covers a limited period of time in Swedish history and does not cover all dwellings built during this period. However, the information is extensive and covers, to a large extent, the peak of dwelling production in Sweden, enabling a bottom-up analysis. Hence, it is interesting to compare these results with previous research related to building typology and to discuss differences. It should be noticed that previous research that involved the creation of building typologies may have had a different purpose to this research (gathering, describing and sharing data to enable further studies). For example, if the purpose of a study is to make a rough assessment of the energy performance of a building stock, not to discuss applicable refurbishment measures in detail, detailed information regarding materials used is not required.

The large share of dwellings built during the million homes programme has also been identified by previous studies as an important part of the Swedish building stock to focus on [3,11,18]. The distribution of regions corresponds rather well with previous findings [23] that 65% of the dwellings built during the million homes programme were built in non-metropolitan regions. However, after

separating all the dwellings into multi-dwelling buildings and one- and two-dwelling buildings, the data from state loans show that 59% of the multi-dwelling buildings were in non-metropolitan regions and 70% of the one- and two-dwelling buildings were built in non-metropolitan regions. It is important to highlight the rather large share of dwellings built in non-metropolitan regions, since the economic conditions are likely to be different in these regions compared to those in metropolitan regions.

6.1. Multi-Dwelling Buildings

The overall findings about the distribution of multi-dwelling building types (slab block, point block and balcony access buildings) correspond well to previous studies [11,18]. Furthermore, findings regarding the number of storeys also correspond rather well with previous studies [11,18,23,24]. However, it is important to highlight that even though the largest portion of the dwellings in multi-dwelling buildings from the million homes programme were to be found in slab block buildings with three or four storeys, roughly 50% of the dwellings were designed in another way. Still, many studies have based their work on a single reference building. Furthermore, it is common for multi-dwelling buildings in the metropolitan regions to have five storeys or more.

One of the most recently published studies describes 46 typical buildings of the Swedish building stock [46]. Considering multi-dwelling buildings built during the 1970s, the study defined three different buildings, all with six storeys or more. Two of these have a building footprint, which is typical of point block buildings. Looking at the available data, the point block buildings represent roughly 5% of the multi-dwelling buildings built during the 1970s. The third type of building (a slab block building with nine storeys) represents roughly 4% of the dwellings. Altogether, the defined typical buildings for multi-dwelling buildings built during the 1970s represent less than 10% of the dwellings in the building stock.

The fact that there is a rough 50/50 distribution of superstructure types is important because it provides different possibilities for energy renovation. Buildings with transverse load bearing systems can undergo major renovations to their exterior walls without major effects on the superstructure, but this is not the case for buildings with longitudinal load bearing systems. Based on statistics regarding the frequency of slab block buildings, previous studies have concluded that such buildings all use the same building technique including a transverse load bearing system and light infill walls [18,30,32]. This conclusion is wrong as the data presented here show a rough 50/50 distribution for the superstructure type.

Regarding the use of façade materials and inner material in the exterior walls, the results show that although certain materials are predominant, there is still a diverse range of materials used. For example, the most common material in walls behind clay brick façade is wood (43%). However, almost 25% of the dwellings with clay brick façades have an inner material of lightweight concrete. Clay bricks (15%) and concrete (12%) also make up for more than 25%. There are also rather large regional differences regarding common façade materials.

The TABULA study, which investigated potential energy savings in the Swedish building stock in 2012 [30], defined all existing multi-dwelling buildings as three-storey buildings and did not define the exterior wall constructions. The reason for this definition may have been an assumption that the energy-saving measures could be applied regardless of wall construction. This is a simplification that is likely not true.

In 2010, Boverket, the Swedish National Board of Housing, Building and Planning, concluded that the average multi-dwelling building in Sweden was built in 1959 [31]. This is likely to be the mean value of all multi-dwelling buildings. This is an incorrect description of the most common building in Sweden. If the analysis was based on median values instead of mean values, it would show that the most common multi-dwelling building was built during the million homes programme.

The most detailed study from Boverket [32] analysed the cost-optimal energy performance requirements for existing and new buildings. Regarding existing multi-dwelling buildings, Boverket based their analysis on two reference buildings: a three-storey building from the 1950s with lightweight

concrete exterior walls covered with render and a nine-storey building from the 1970s with concrete sandwich walls. The chosen reference exterior walls cover only approximately 25% of the existing buildings built during the million homes programme in Sweden. Furthermore, they did not include the most common exterior wall construction: wooden infill walls with clay brick façades.

It should be noted that the data used by Boverket from 1400 buildings to define their reference buildings is of high quality. The reason for the inadequate choice of reference buildings is due to poor use of the data.

6.2. One- and Two-Dwelling Buildings

The data for one- and two-dwelling buildings show that the production of dwellings with two decisions where the applicant was not the final resident was higher at its highest point and lower at its lowest point, compared to dwellings with one decision. This indicates that residents who build their own home are not as sensitive to the market as construction companies may be.

The fact that almost all dwellings in one- and two dwelling buildings were built with wooden constructions makes further work easier, because it means that mainly variations of façade material need to be considered in future work.

For one- and two-dwelling buildings, it will be important to study both the roof and wall constructions. Hence, it is interesting to know whether buildings are 1.5-storey buildings or not, since these buildings have very different conditions, from the perspective of adding insulation to the roof construction.

Regarding one- and two-dwelling buildings, the TABULA study based their work on two reference buildings which were both one-storey buildings with lightweight exterior walls covered with render and horizontal insulation in the roof [30]. Thus, the study does not cover any 1.5-storey buildings. This is a rather strange reference building. The chosen wall construction is likely to cover less than 5% of the existing buildings and the choice to not include 1.5-storey buildings excludes roughly 30–40% of the existing one- and two-dwelling buildings.

The study from Boverket in 2010 [31], concluded that the average one- and two-dwelling building in Sweden is a building built in 1953. As previously mentioned, this is likely to be a mean value; an analysis based on median values would show that the most common one- and two-dwelling building was built during the million homes programme.

The most detailed study from Boverket [32] based its analysis on two reference buildings: a 1.5-storey building and a two-storey building. Both reference buildings have wooden constructions for the exterior walls and roof, and also the façades are wooden. None of the reference buildings include a cellar. By including both a 1.5-storey building and a two-storey building, the study included almost all existing roof constructions. However, by only including wooden façades, roughly 50% of the façade constructions were excluded. Cellars, which may be found in roughly 30% of the existing one- and two-dwelling buildings, were not included in the study.

A recent study that included renovation measures [21] included two different types of exterior walls: wood and lightweight concrete. Further studies on one- and two-dwelling buildings could exclude exterior walls with lightweight concrete and increase their focus on different types of roof constructions and/or façade materials, as they vary more.

The study that suggested 46 different typical buildings to represent the existing building stock [46] argued that a 1.5-storey building was the most common building type to be built during the 1970s and should be the choice of a typical building as it would represent 65% of the buildings from that decade. However, looking at the available data, the most common building has one storey. Roughly 40% of the buildings from the 1970s have one storey.

7. Conclusions

This study shows the importance of studying differences among building constructions in the existing building stock when studying renovation measures and analysing the renovation potential. It

shows that there is a set of constructions and building techniques that were commonly used in the existing building stock in Sweden during the million homes programme and in the decades before and after. It is important to underline that there is no single construction type or building that has been predominant. Furthermore, regional differences exist.

Previous studies have often assumed a rather large homogeneity and did not always include the most common constructions and building types in their studies. This concerns studies regarding the development of prefabricated building elements and studies regarding cost calculations for renovation and energy efficiency measures. Furthermore, studies that used a large set of buildings to create a building typology created typologies that cannot be confirmed by the data in this study.

If assumptions of large homogeneity are misjudged, they may cause higher costs for renovation measures than predicted, and developed prefabricated building elements may apply on fewer buildings than expected. This may limit the reliability of potential studies and slow down the renovation pace or limit the actual renovation measures.

To speed-up the renovation of the existing building stock in the EU and in other regions, further studies are needed to form a basis for making well-informed decisions regarding political directives and incentives and regarding actual renovation measures. Furthermore, as buildings will always be unique, the development of prefabricated building systems needs to have flexibility to enable their use on a larger scale.

Based on the available data, it is possible to draw some conclusions regarding construction types, which should be prioritised in further research regarding the Swedish building stock.

7.1. Multi-Dwelling Buildings

The most commonly used façade materials in multi-dwelling buildings are clay bricks, render and concrete. Façades with clay bricks are common throughout Sweden. The most common inner material used for clay brick façades is wood, which indicates that it is most likely found in light infill walls. Rendered façades are most common in the Stockholm region and are also rather common in non-metropolitan regions. The rendered façades are almost exclusively paired with lightweight concrete as the inner material. Concrete façades are common in Malmö, Göteborg and Stockholm regions. Concrete façades are almost exclusively paired with concrete as the inner material. Based on these findings, the most common constructions that should be investigated in future studies are summarised in Table 1. The constructions include both load-bearing walls and light infill walls in the existing building stock.

Table 1. Summary of common constructions for exterior walls in multi-dwelling buildings in Sweden produced in the post-war period.

Type of Construction	Region			
	Non-Metropolitan	Malmö-Region	Göteborg-Region	Stockholm-Region
Insulated wood infill walls with clay brick façades	X	X	X	X
Lightweight concrete walls with rendered façades	X			X
Concrete sandwich walls		X	X	X

7.2. One- and Two-Dwelling Buildings

The most common façade materials used in one- and two-dwelling buildings are clay bricks and wood. Together, these two materials represent more than 80% of the dwellings from the studied period. Almost all exterior walls are constructed with wood as the inner material. Furthermore, roof constructions with an insulated tie beam and roof constructions where the tie beam is also part of an interior floor slab (in 1.5-storey buildings) need to be studied. Based on these findings, the most

common constructions for further studies are summarised in Table 2. As can be seen, there are no regional differences regarding the most common constructions.

Table 2. Summary of common constructions for exterior walls and roofs in one- and two-dwelling buildings in Sweden constructed in the post-war period.

Type of Construction	Region			
	Non-Metropolitan	Malmö-Region	Göteborg-Region	Stockholm-Region
Insulated wood walls with clay brick façades	X	X	X	X
Insulated wood walls with wood façades	X	X	X	X
Roof constructions with insulated tie beam	X	X	X	X
Roof constructions for 1.5-storey buildings	X	X	X	X

Supplementary Materials: The following are available online at <http://www.mdpi.com/2075-5309/9/4/99/s1>.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. —Multi-Dwelling Buildings

Table A1. Available data for multi-dwelling buildings, via supplementary data file.

Type of Data	Available Parameters	Period for Available Data
Type of building	Balcony access building; Point block building; Slab block building; Terraced building; Other	1960–1993 *
Area of construction	Göteborg region; Malmö region; Stockholm region; Sweden excluding metropolitan regions	1966–1993 **
Storeys	1–2; 3; 4; 5–8; ≥9	1962–1993
Type of superstructure	Transverse load bearing; Longitudinal load bearing; Pillar construction; Other	1968–1972
Material for superstructure	Autoclaved aerated concrete; Clay bricks; Concrete; Wood; Other	1963–1987
Method of production for superstructure	On site; Prefabricated	1968–1979
Façade material	Asbestos; Autoclaved aerated concrete; Clay bricks; Concrete; Render; Sandlime bricks; Sheet metal; Wood; Other	1963–1993 ***
Inner material in exterior wall	Autoclaved aerated concrete; Clay bricks; Concrete; Wood; Other	1963–1979
Method of production for exterior wall	On site; Prefabricated	1968–1979
Roofing	Asbestos; Clay tiles; Concrete tiles; Roof felt; Sheet metal; Other	1969–1993

* Terrace buildings were reported separately from 1979. Before 1979; they are included in “Other”; ** From 1987, data regarding façade material were reported by western Sweden (expanded Göteborg region), southern Sweden (expanded Malmö region) and eastern Sweden (expanded Stockholm region); *** Up until 1980, the main material for façades was reported if a mix of different façade materials were used. 1980–1993, mixed façades were reported including the two main materials.

Appendix B. —One- and Two-Dwelling Buildings

Table A2. Available data for one- and two-dwelling buildings, via supplementary data file.

Type of Data	Available Parameters	Period for Available Data
Type of building	One-dwelling building; Two-dwelling building; Linked building; Terraced building; Other	1966–1994
Area of construction	Göteborg region; Malmö region; Stockholm region; Sweden excluding metropolitan regions	1968–1994
Storeys	1; 1.5; 2; >2	1970–1987
Material for superstructure	Autoclaved aerated concrete; Clay bricks; Concrete; Wood; Other	1966–1987
Method of production for superstructure	On site: Prefabricated; Partly prefabricated	1968–1993
Façade material	Asbestos; Autoclaved aerated concrete; Clay bricks; Concrete; Render; Sandlime bricks; Sheet metal; Wood; Other	1966–1993 *
Insulation in exterior wall	Expanded polystyrene; Wood insulation/wood wool/wood shavings; Autoclaved aerated concrete; Mineral wool	1966–1972
Roofing	Asbestos; Clay tiles; Concrete tiles; Roof felt; Sheet metal; Other	1966–1993

* Up until 1973, the main material for façades was reported if a mix of different façade materials was used. 1973–1993, mixed façades were reported including the two main materials.

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Conference paper 7

The importance of a common method and correct calculation of thermal bridges

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KEYWORDS: Thermal bridges, EN ISO 13789, EN ISO 10211, energy, plus-energy, buildings

SUMMARY:

This paper elucidates the increased need of correct calculations of thermal bridges for low/near zero energy buildings. The variability of the results from calculations of transmission losses for a building can be large if the calculation method within EN ISO 13789:2007 is not fully understood. A survey has been carried out which shows that there are no consensus in Sweden regarding how to define the transmitting area for a 1-D building component as input for energy calculations and that there is confusion regarding the definition of thermal bridges. It seems that the most common misunderstanding regarding thermal bridges is that the geometrical effect; thermal bridges caused by the fact that they have different internal and external area. Based on the survey different scenarios have been analyzed regarding the impact on a building's energy demand and peak load for space heating. The analysis shows that energy needed for heating and peak load for heating increases by 43% respectively 25% when the worst case scenario is compared with correct calculations. In order to minimize the risk of misunderstanding of areas and thermal bridges should subscripts always be used.

1. Introduction

On the 18th of May 2010, the members of the European Parliament approved the changes to the Energy Performance of Buildings Directive, EPBD (European Parliament, 2010). The recast specifies that by the end of 2020 all new buildings shall be "nearly zero-energy buildings". The nearly zero-energy building is a building with a very high energy performance which means that the energy required should be nearly zero or very low. According to Dokka (2004) the energy design of a nearly zero-energy building should be based on a five step approach:

1. Reduce heat losses
2. Use energy efficient equipment
3. Utilize solar energy
4. Display and control energy consumption
5. Select energy source

To ensure a robust and energy efficient residential building in a Nordic climate, not dependent on complex energy generating installations, the first step is always to reduce the buildings' energy losses. It is therefore important not to underestimate the buildings' heat transmission losses or to evaluate/calculate the heat transmission coefficients in a simplified and incorrect way. Calculation of transmission losses for a whole building or part of a building should follow a standardized calculation method. A common European method is shown in EN ISO 13789 (SIS 2007a).

In design of low energy or near zero energy buildings, a poor estimation of thermal bridges, and thus the space heating demand, could lead to severe economical consequences for the builder, the client and/or the consultants. This paper elucidates the increased need of correct calculations of thermal bridges and presents that the Swedish state of knowledge regarding thermal bridges.

2. Calculation of heat transfer according to the European and International standard EN ISO 13789

The EPBD states that the methodology for calculating the energy performance of buildings should take into account European standards. EN ISO 13790 (SIS, 2008) is a commonly used standard which is also referred to in the national building regulations in most Nordic countries, for example in Norway (KRD, 2010) and Finland (Ympäristöministeriö, 2007). EN ISO 13790 refers to the calculation of transmission and ventilation heat transfer coefficients in EN ISO 13789. In Sweden, there is no standard for calculation the energy performance set in the building regulations, BBR. However, BBR refers to calculations of the average heat transfer coefficient in EN ISO 13789 (Boverket, 2009).

This section focuses on heat transfer according to EN ISO 13789 and the normative standard for thermal bridges in construction, EN ISO 10211 (SIS, 2007b). There are more normative standards which are not in detail studied here. The normative standards are visualised in FIG 1.

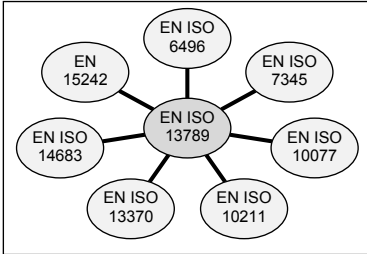


FIG 1. EN ISO 13789 with normative standards

The transmission heat transfer coefficient is calculated according to Equation 1.

$$H_T = H_D + H_g + H_U + H_A \quad (1)$$

Where H_D direct heat transfer coefficient (W/K)
 H_g steady-state ground heat transfer coefficient (W/K)
 H_U transmission heat transfer coefficient through unconditioned spaces (W/K)
 H_A transmission heat transfer coefficient to adjacent buildings (W/K)

The direct heat transfer coefficient is calculated according to Equation 2.

$$H_D = \sum_i A_i U_i + \sum_k l_k \Psi_k + \sum_j \chi_j \quad (2)$$

Where A_i area of element, i (m^2)
 U_i thermal transmittance of element, i ($W/m^2 \cdot K$)
 l_k length of linear thermal bridge (m)
 Ψ_k linear thermal transmittance of thermal bridge ($W/m \cdot K$)
 χ_j point thermal transmittance through point thermal bridges (W/K)

To apply the calculation method for direct heat transfer, the building envelope needs to be clearly defined and divided into different elements as shown in FIG 2.

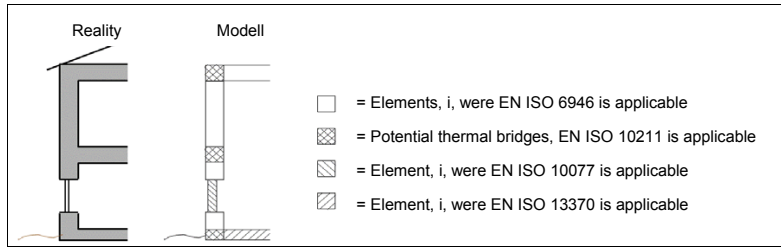


FIG 2. Breakdown of building in different elements and thermal bridges

Measuring of elements can be done according to one of the three methods; internal, overall internal or external dimensions. The differences between the different measuring concepts are visualised shown in FIG 3.

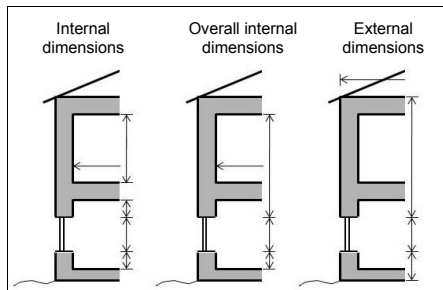


FIG 3. Different types of dimensions according to EN ISO 13789

Calculations to define values for thermal bridges are presented in Equation 3 and Equation 4, where Equation 3 defines linear thermal transmittance and Equation 4 defines point thermal transmittance.

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \quad (3)$$

Where L_{2D} thermal coupling coefficient obtained from a 2-D calculation (W/m·K)
 U_j thermal transmittance of 1-D component, j (W/m²·K)
 l length over which U_j applies (m)

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{j=1}^{N_j} \Psi_j \cdot l_j \quad (4)$$

Where L_{3D} thermal coupling coefficient obtained from a 2-D calculation (W/K)
 U_i thermal transmittance of 1-D component, i (W/m²·K)
 A_i area over which U_i applies (m²)
 Ψ_j linear thermal transmittance calculated according to Equation 3 (W/m·K)
 l_j length over which Ψ_j applies (m)

The sum of transmission losses through building elements, the term $\sum A_i U_i$, will vary depending on the chosen measuring method. Consequently, the thermal bridges, Ψ -values and χ -values will vary. To

clarify which measuring method that will be used to calculate the thermal transmittance of each thermal bridge, the subscripts presented in TABLE 1 will be used:

TABLE 1. Subscripts to clarify used method for measuring

Subscript	Definition
i	Internal
oi	Overall internal
e	External

3. The state of knowledge and application of different methods in Sweden

3.1 The survey

A web based questionnaire was sent out to 100 engineers and architects who had experience from building projects with focus on energy efficiency. The questionnaire was divided into three sections:

- Question 1-4, area concepts:
Four questions were asked regarding measuring methods used to define different areas in energy calculations and according to BBR
- Question 5-10, assessment of different junctions:
Six different junctions were presented, as shown in FIG 4, together with the question: Should this junction be regarded as a thermal bridge which increases heat transmission losses in addition to the losses included in building elements?
- Question 11-17, professional background, etc:
Six different questions regarding professional background, work experience, if they were familiar with energy calculations and calculations to define thermal bridges etc.

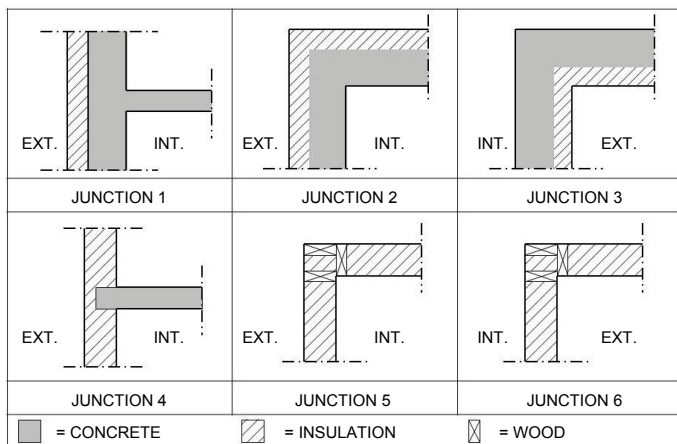


FIG 4. Schematic presentation of junctions, included in the questionnaire. External environment is marked EXT. Internal environment is marked INT.

3.2 Results from the survey

Of the questionnaires sent out; 73 responses were received. Two reminders were sent out. Of the respondents, 84 percent had experience in energy calculations. 53 percent had more than ten years experience. This indicates that most of the respondents have good knowledge of energy calculations.

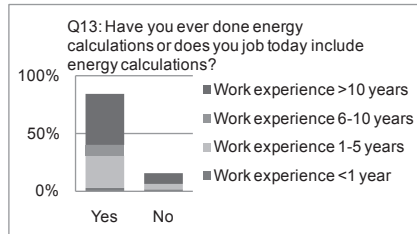


FIG 5. Answers to question 13, sorted on work experience

In the first two questions the respondents were asked how they would measure building elements and a building's enclosing area in order to compile data for energy calculations. The result shows that internal area is most used to measure building elements and external area is most used to define a building's enclosing area. The other measuring options are also used to an extent that exceeds 20 % for each measuring method. In question three and four the respondents were asked how they would interpret the Swedish definitions of A_i and enclosing area, A_{om} , according to BBR:

A_i Surface area of building element, i , in contact with heated indoor air (m^2)

A_{om} Total surface area of the enclosing parts of the building in contact with heated indoor air (m^2)

The result is more uniform when a definition is given; 57 % respectively 48 % use interior measurement to define A_i and A_{om} according to BBR. Breakdown of the responses is shown in FIG 6.

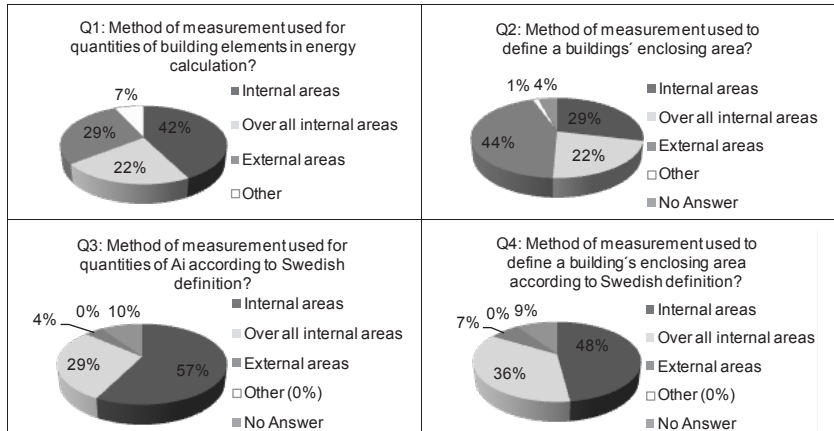


FIG 6. Answers to questions 1-4

As stated in Section 2, the Ψ -values and χ -values will vary depending on the chosen measuring method. In TABLE 2 the effect of the thermal bridges is presented sorted by different measuring

methods. The last junction; J6, is a junction where the insulation is penetrated by wood which results in increased thermal transmittance. The effect of the difference between internal and external area is however larger which results in that Ψ_i and Ψ_{oi} should be added into the energy calculations as thermal bridges which decrease the direct heat transfer coefficient.

TABLE 2. The junctions' impact on the thermal heat losses based on choice of measuring method

Junction	Ψ_i	Ψ_{oi}	Ψ_e
Junction 1 – J1	Increase	None	None
Junction 2 – J2	Increase	Increase	Decrease
Junction 3 – J3	Decrease	Decrease	Increase
Junction 4 – J4	Increase	Increase	Increase
Junction 5 – J5	Increase	Increase	Decrease
Junction 6 – J6	Decrease	Decrease	Increase

The answers from question 5-10, assessment of junctions, have been sorted depending on how they choose to measure A_i . The first three junctions (J1-J3), which are thermal bridges due to the effect of difference between internal and external areas shows a large number of errors in the qualitative assessments. The percentage of correct answers for junctions; J1 and J2 is 47 and 48 % respectively. In the assessment of J3; 56 percent of the respondents give a correct answer. The junctions J4-J5 are thermal bridges both due to the effect of differences between internal and external area, and by full or partial penetration of the building envelope by materials with a different thermal conductivity. The assessments from the respondents shows a significantly higher correctness when these answers are examined; 88 respectively 89 % of the respondents do a correct assessment. In assessment of junction J6; only 11 % assess the junction correctly.

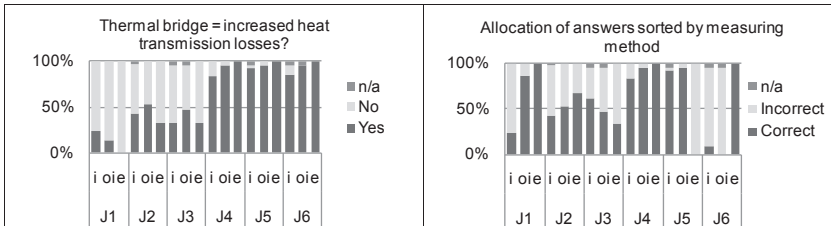


FIG 7. Answers to questions 5-10, sorted by the respondents' choice of measuring method to define A_i

There is little difference in the distribution of correct/incorrect answers based on measurement method.

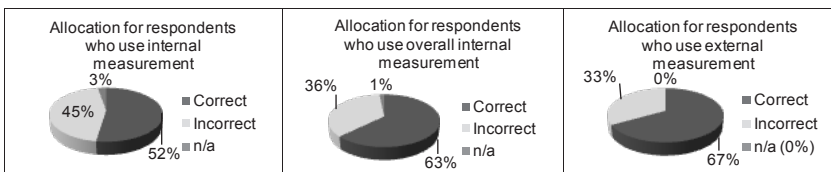


FIG 8. Distribution of correct/incorrect answers to questions 5-10, sorted by the respondents' choice of measuring method to define A_i

The respondents were also asked if they carry out calculations to determine specific values for thermal bridges, 47 % replied yes. Respondents who replied yes were asked to describe the used method. 43 %

of the respondents who carry out calculations for thermal bridges use some sort of computer software, the most commonly used software is HEAT (Blocon).

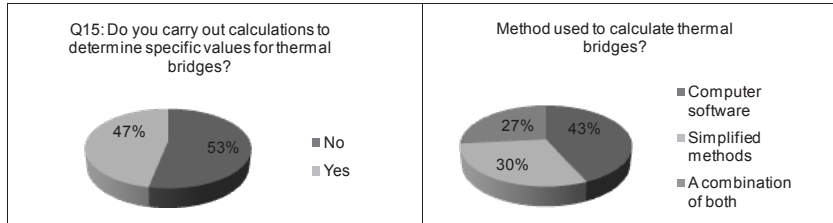


FIG 9. Answers to questions 15, “Do you carry out calculations to determine specific values for thermal bridges?” Respondents who replied yes were asked to describe the used method. The methods have been divided into; computer software, simplified methods and a combination of both.

The most common method to account for thermal bridges today, used by 44 % of the respondents, is to quantify the amount of thermal bridges and apply existing default values for the thermal transmittance. The second most common method, used by 22 percent of the respondents, is to increase thermal transmittance of building components by a certain percentage, i.e. 5-20 % (mean percentage used; 15%).

4. Conclusions

The result from the Swedish survey regarding state of knowledge, interpretation of different measuring methods of a building’s dimensions and the assessment of junctions to determine whether they were thermal bridges is not satisfying. The result from the study shows that there is a great difference between which method of measurement the respondents use to quantify building elements and a building’s enclosing area. Today, usually several consultants are involved in the design and construction phase of a building. It is possible to imagine a scenario in which the architect will be asked to provide quantities of building components and junctions, the constructor calculates U-values and specific values for thermal bridges and the installation consultant or energy coordinator carries out the actual energy calculation. It seems that the most common misunderstanding regarding thermal bridges is that the geometrical effect of thermal bridges is not understood, in other words; thermal bridges caused by the fact that they have different internal and external area.

We are constantly increasing the use of Building Information Modelling, BIM, in the design and construction of buildings. In order to use models created in BIM-tools as a basis for energy calculations, these tools must be able to distinguish different area definitions.

In order to minimize the risk of misunderstanding of areas and thermal bridges the subscripts, presented in TABLE 1, should always be used. Furthermore, a need has been identified for guidelines how to use the available standards.

5. Acknowledgements

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Conference paper 8

A parametric study of the energy and moisture performance in passive house exterior walls



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Summary

Adding insulation to improve the energy performance of a building with a traditional Swedish wooden construction may increase the risk of mould growth in the wooden construction. There is a need to address this potential problem since the amount of passive houses and low energy buildings are increasing as a means to reduce energy use, energy dependency and greenhouse gas emissions.

This paper evaluates energy performance and moisture performance simultaneously in order to create a more holistic approach. Space heating demand, peak load for space heating and risk for mould growth are evaluated.

The analysis of these three different aspects shows that there is no contradiction between moisture safety design and energy efficient design. It may however not be suitable to increase the amounts of insulation in traditional wooden constructions without considering risk of mould growth.

Keywords: passive house, energy, moisture, performance, mould, hygrothermal, WUFI, IDA ICE

1. Introduction

Problems with mould growth and high humidity levels in building constructions have been increasing over the last years in Sweden. A Swedish study has shown that many cold attics suffer from high humidity levels and mould growth [1]. These problems are already appearing in roof constructions with amounts of insulation which may be considered as standard amounts; 400 mm [2]. The amount of passive houses built in Sweden is increasing [3] and one of the key measures in passive house design is to reduce heat losses [4]. To reduce the heat losses through the building envelope, improved air tightness and reduction of thermal transmittance measures are therefore frequently used in order to achieve a low energy demand for dwellings. To reduce the thermal transmittance more insulation is added to the building envelope or insulation with lower heat conductivity is used. The reduction of thermal transmittance through the building envelope will result in a different microclimate within the building envelope. For example, in a Nordic climate the outer parts of a wall will be colder as the thermal resistance increases, which might give a higher risk for mould growth. Today, the Swedish building regulations, BBR, states that every material used in a building must have a certain maximum moisture level that should not be exceeded during the life cycle of the building. This moisture level is based on the critical moisture level for the actual material including a safety margin. The critical moisture level has to be defined for every material, by the supplier or similar. If it is not defined, 75% relative humidity, RH, should not be exceeded for the material at any time [5]. As 75 % RH is a very strict demand and mould growth is very much dependent not only on RH, but also on temperature and duration [6], there is a need to evaluate

the risk for mould growth by considering all of these parameters. This paper discusses energy performance and moisture performance for building envelopes to evaluate the issues of energy use and risk of mould growth together, creating a more holistic approach.

2. Methods

2.1 Description of case study

The case study is based on a terraced house with three dwellings in the southwestern parts of Sweden Göteborg. Characteristics of the building are presented in Table 1 and Fig 1.

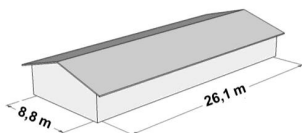


Fig. 1 Case study

Table 1 Characteristics of reference building (measuring is based on internal dimensions)

Characteristic	Data	Unit
Heated area	229.7	m ²
Window and door area	40.9	m ²

It is assumed that the building is designed with constructions which have a thermal transmittance suitable for passive houses. The exterior walls are constructed with standard amounts of insulation but the builder wishes to investigate the effect of increased amounts of insulation.

2.2 Simulations

Simulations are conducted to:

- Evaluate if there is a remarkable increased risk of mould growth on wood in an exterior wall with low thermal transmittance compared to an exterior wall with thermal transmittance considered as standard
- Evaluate the different constructions' effect on the space heating demand and peak load for heating

Taking the step from an outer exterior wall construction with standard amounts of insulation ($U_c=0.17 \text{ W/m}^2\text{K}$) to an exterior wall with low thermal transmittance ($U_c=0.09 \text{ W/m}^2\text{K}$), that is suitable for a passive house, is done comparing two different approaches:

- Traditional approach; the thermal transmittance is decreased by increasing the amount of insulation to the construction on the inner side of the load bearing structure, w1 in Fig. 2. Exterior insulation, w2, is kept to 0 mm. The benefit of this approach is that the carpenters relatively fast can achieve a wind protected and, fairly increased, thermal indoor environment which creates a better working environment for the carpenters
- Decreasing thermal bridges and keeping the wooden structure warm. This approach firstly focuses on decreasing the thermal transmittance by adding insulation to the outer side of the load bearing structure, to a maximum of 70 mm, w2 in Fig. 2, before more insulation is added to the inner side of the load bearing construction, w1

All other constructions are kept constant. A summary of constructions used in the simulations is presented in Table 2 and Table 3.

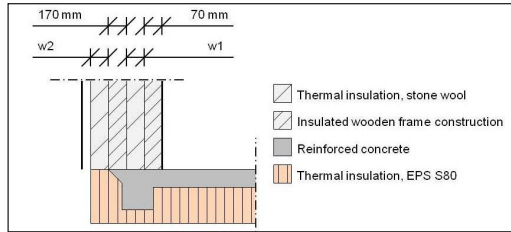


Fig. 2 Sketch of exterior wall and ground construction

Table 2 Constructions for the building envelope used in all simulations and calculations

Construction	Description
Roof	Wooden roof truss with 620 mm of loose stone-wool insulation. $U=0.07 \text{ W/m}^2\text{K}$
Slab on ground	Concrete slab on ground, insulated with 350 mm EPS S80. $U=0.08 \text{ W/m}^2\text{K}$
Windows	Triple glazed window, LE-coatings + Argon filling. $U_w=0.90 \text{ W/m}^2\text{K}$
Window doors	Triple glazed window, LE-coatings + Argon filling. $U_w=0.90 \text{ W/m}^2\text{K}$
External doors	$U = 1.0 \text{ W/m}^2\text{K}$

Table 3 External walls in different cases (references to w1 and w2 are according to Fig 2)

Case	Description
Base line	w1 = 0 mm w2 = 0 mm $U=0.17 \text{ W/m}^2\text{K}$
Scenario 1.1 traditional approach	w1 = 70 mm w2 = 0 mm $U=0.13 \text{ W/m}^2\text{K}$
Scenario 1.2 minimizing thermal bridges	w1 = 0 mm w2 = 70 mm $U=0.13 \text{ W/m}^2\text{K}$
Scenario 2.1 traditional approach	w1 = 220 mm w2 = 0 mm $U=0.09 \text{ W/m}^2\text{K}$
Scenario 2.2 minimizing thermal bridges	w1 = 145 mm w2 = 70 mm $U=0.09 \text{ W/m}^2\text{K}$

2.2.1 Hygrothermal simulations

Hygrothermal simulations are conducted using the numerical software WUFI 1D Pro [7]. A summary of the boundary conditions and input data used in the hygrothermal calculations are shown in Table 4.

Table 4 Boundary conditions and input data for WUFI Pro 1D 5.0

Data	Value
Time span	3 years
Cloud cover	0.66
Cardinal direction	South facade
Ventilation of air gap	50 h^{-1}
Initial RH, all materials	80 %
Outdoor temperatur, Göteborg (mean, min, max)	$8.8^\circ\text{C}, -12.2^\circ\text{C}, 27.8^\circ\text{C}$
Outdoor relative humidity, Göteborg (mean, min, max)	74%, 19%, 94%
Fraction of driving rain leakage	1%
Indoor climate	According to equation 1 and equation 2

$$T_i = \begin{cases} 20, T_{outdoor} \leq 10 \\ 15 + 0.5T_{outdoor}, 10 < T_{outdoor} < 20 \\ 25, T_{outdoor} \geq 20 \end{cases} \quad (1)$$

Where

T_i Indoor temperature

$T_{outdoor}$ Outdoor temperature

$$RH_i = \begin{cases} 30, T_{outdoor} \leq -10 \\ 40 + T_{outdoor}, -10 < T_{outdoor} < 20 \\ 60, T_{outdoor} \geq 20 \end{cases} \quad (2)$$

Where

RH_i : Relative humidity in indoor air

2.2.2 Energy simulations

Calculations of thermal transmittance for constructions and thermal bridges follow EN ISO 6946 [8], EN ISO 13370 [9] and EN ISO 10211 [10] calculated with HEAT 3D 5.1 [11]. IDA ICE 4.1 [12] is used to simulate the annual energy demand for space heating and peak load for heating. A summary of the boundary conditions and input data used in the energy simulations are shown in Table 5. Input data for materials in the HEAT calculations are summarised in Table 6.

Table 5 Boundary conditions and input data for IDA ICE 4.0

Data	Value
Climate data	Göteborg 1977
Indoor temperature	21 °C
Ventilation	0.35 l/s, m ² heated floor area
Temperature efficiency of heat exchanger	80 %
Internal heat gains	4 W/m ² heated floor area

Table 6 Boundary conditions and input data for HEAT 3D 5.1

Material	Design thermal conductivity [W/mK]
Mineral wool	0.037
Wood	0.13
Gypsum board	0.25
Insulation under floor slab	0.038
Insulation under footing	0.033
Contrete 1 % reinforcement	2.3
Ground soil	2.0
Flooring	0.18

2.3 Evaluation of the results – the m-model

To quantify the results of the simulations, energy needed for heating, peak load for heating and risk of mould growth are analysed. Energy needed for heating and peak load for heating are extracted from IDA ICE 4.0. To analyse the risk for mould growth relative humidity and temperature at the interior side of the wind barrier are extracted from WUFI Pro 1D and analysed. This specific section of the wall is chosen due to that it has direct contact to the load bearing wood studs and it is predicted that the highest risk of mould growth is in this section. The analysis is carried out using a model which makes it possible to evaluate the risk for mould growth on wood called the m-model. The following part of this section gives an overview of the theory behind the m-model. A more complete and extensive description of the m-model is given in [13].

The m-model uses critical moisture levels that follow the directions in [14] and [15]. In all, a total of six critical moisture durations are used, presented in Fig. 3.

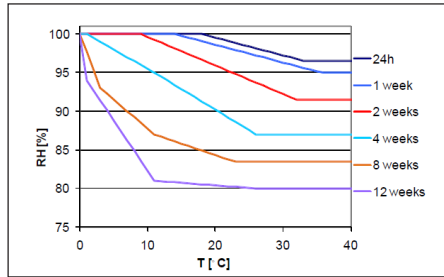


Fig. 3 Six critical moisture levels, data from Nilsson [14] and Viitanen [15]. Six durations, or critical risk times, are used: 24 h, 1 week, 2 weeks, 4 weeks, 8 weeks and 12 weeks. Figure from [13]

A parameter, called m , is calculated based on relative humidity, temperature and duration as shown in equation 3.

$$m = \frac{RH_{act}(t)}{RH_{crit}(T(t))\gamma} \quad (3)$$

where

- $RH_{act}(t)$ The actual relative humidity in the material, at time t [h]
- $RH_{crit}(T(t))$ The critical relative humidity at temperature T and time t [h], based on the relations in Fig. 3. There is a mathematical relation between temperature and RH_{crit} for every critical duration, i.e. six mathematical expressions of RH_{crit} .
- γ Safety factor that is used when implementing the m -model, for example in moisture safety design. In this analysis is the factor set to 0.97.

$m \geq 1$ implies that the actual conditions have exceeded the critical levels during one time step. For each time step m is calculated for each of the six critical durations as shown in Fig. 3. All time steps where $m \geq 1$ are summarized separately for each duration, and constitutes the accumulated risk time. The m -model also handles dehydration, which means that it does not add two separate periods where $m > 1$ without dealing with the dehydration that occurs in between. The accumulated risk time for each duration curve is divided with the critical risk time. The quota is called critical duration quota, CDQ. If $CDQ \geq 1.0$, mould will in theory be initiated.

3. Results

Two examples of relative temperature distribution are shown in Fig 4. The relative temperature distribution is close to equal, comparing the two different approaches; step 1.1 and step 1.2. However, it is possible to see that the wooden studs (light yellow in the schematic descriptions) in step 1.2, which are given an external insulation, have a relatively warmer micro climate.

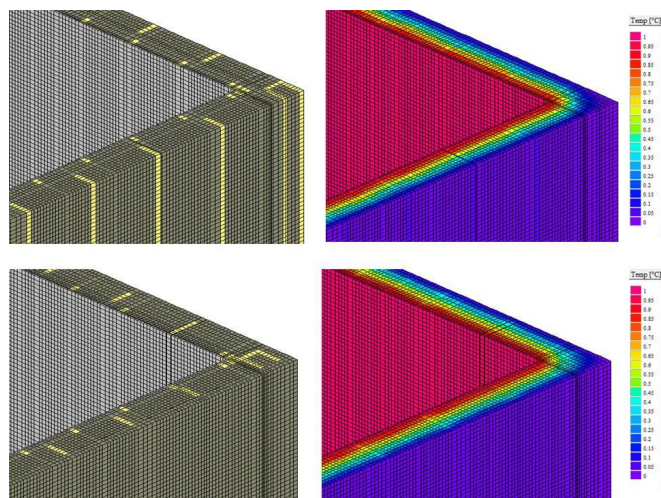


Fig. 4
 Top left; schematic description of external wall corner: Scenario 1.1
 Top right; relative temperature description of external wall corner: Scenario 1.1
 Bottom left; schematic description of external wall corner: Scenario 1.2
 Bottom right; relative temperature description of external wall corner: Scenario 1.2

Thermal bridges for the different steps are presented in Table 7. The vast majority of the thermal bridges decrease as more insulation is used, but not all. This is mainly due to geometrical effects. For example; more insulation results in larger window bays which increase the transmitting area. Adding insulation to the outer side of the wooden frame construction results in lower peak load for space heating and energy needed for space heating compared to the traditional approach of adding insulation on the inner side, which can be seen in Fig 5.

Table 7 Linear thermal transmittance

Junction	Linear thermal transmittance Ψ_l [W/mK]				
	Base case	Scenario 1.1	Scenario 1.2	Scenario 2.1	Scenario 2.2
External wall – internal load bearing wall	0.059	0.043	0.042	0.026	0.026
External wall – interior non load bearing wall	0.017	0.013	0.013	0.009	0.009
External wall corner	0.058	0.035	0.045	0.027	0.028
External wall – window/door	0.026	0.031	0.019	0.043	0.030
External wall – roof construction (long sides)	0.048	0.038	0.040	0.031	0.030
External wall – roof construction (gables)	0.053	0.041	0.041	0.033	0.032
External wall – ground slab	0.220	0.191	0.159	0.202	0.174

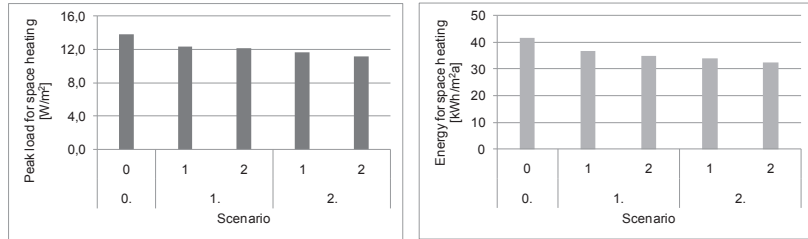


Fig. 5 Results from the IDA ICE simulations. Left; Peak load for space heating. Right; annual energy needed for space heating

The maximum CDQ is presented in Fig 6. The analysis shows that adding insulation in moderate quantities using the traditional approach (Scenario 1.1) and reaching a U-value of 0.13 W/m²K, will not result into CDQ>1. If more insulation is added in the traditional way (Scenario 2.1), mould growth will theoretically be initiated. By applying the simple measure of adding insulation to the outer side of the wooden frame construction results in a slightly lower CDQ in Scenario 1.2 and a low increase of CDQ in Scenario 2.2. Choosing the approach of minimizing thermal bridges will result into a more energy efficient and moisture safe design see Fig 7.

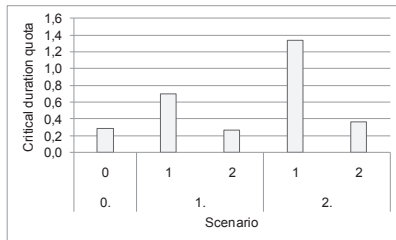


Fig. 6 Maximum critical duration quota

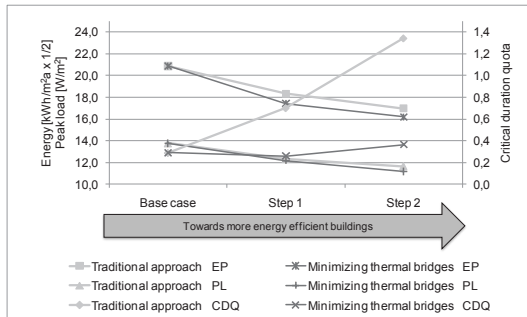


Fig. 7 Annual energy needed for heating (EP), Peak load for heating (PL) and Critical duration quota (CDQ) displayed simultaneously. Note: to get the annual energy demand, the value given in the y-axis should be multiplied with 2

4. Discussion and conclusions

The analysis of these three different factors shows that there is no contradiction between moisture safety design and energy efficient design. It may however not be suitable to increase the amounts of insulation in traditional wooden constructions without considering a risk of mould growth.

It is obvious that increased amounts of insulation will lead to a colder micro climate in exterior parts of building envelopes. However, it does not have to be considered as a great risk if appropriate measures are applied. Insulation, or other materials, added to the exterior side of a wooden frame construction must have a critical moisture level which exceeds wood.

It is important to point out that this analysis has been carried under a specific set of boundary conditions. For example a wall facing south was chosen which, in the Göteborg climate, is the cardinal direction most afflicted by driving rain. Changing the boundary conditions such as cardinal direction, fraction of driving rain leakage etc. will of course change the results. In other words, this study does not claim to show that a certain construction will suffer from mould growth or not. It does however show that, by applying simple measures, it is possible to substantially reduce the risks.

5. Acknowledgements

This paper is part of the project; Klimatskal (building envelope) 2019, a project funded by The Development Fund of the Swedish Construction Industry and Skanska Sverige AB. The purpose of the project is to develop a method to evaluate energy- and moisture performance for building envelopes.

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Conference paper 9

Thermal bridges in passive houses and nearly zero-energy buildings



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Summary

An important strategy for climate mitigation is reduction of energy use in buildings. One approach is to build or renovate buildings applying passive house design or a zero-energy building approach. The first step towards passive house design is reduction of heat losses, and therefore improving the thermal resistance of the building envelope. This is reached by adding more insulation and/or insulation with low thermal conductivity. A recent study shows that professionals unfortunately are not always aware of the concept of thermal bridges combined with different definitions of measuring of building elements. Furthermore, the effect of thermal bridges is usually taken into account using simplified methods which may not be correct. This paper explains the differences in different measuring methods which may be applied today according to European standards, and the possible impact on the specific values of linear thermal bridges. The results show that the relative effect of thermal bridges may increase when the thermal resistance of the building envelope is improved. It also shows that the difference between simplified calculations and more accurate calculations increases when the thermal resistance of the building envelope is improved. The case study shows that the effect of misunderstandings or carelessly handling of thermal bridges in the design phase may lead to an underestimation of peak power for space heating and energy demand for heating by 29 % and 37% respectively. To minimize the risk for undersized heating systems and increased space heating demand, subscripts indicating the applied measuring method (used in calculations to determine specific values of thermal bridges) should always be used when thermal bridges are presented.

Keywords: passive house, thermal bridges, energy, EN ISO 13789, EN ISO 10211

1. Introduction

Buildings today account for 40% of the world's primary energy use and 24% of the greenhouse gas emissions [1]. The building sector is expanding. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures required to reduce energy dependency and greenhouse gas emissions.

The share of dwellings constructed as low energy buildings and passive houses has increased markedly in the recent years in Sweden. The proportion of dwellings built as low energy buildings has increased from 0.7% in 2008 to 7.2% in 2010. If one considers only the segment of multi dwelling buildings the share is even higher; 11.2 % in 2010 [2]. In the recast of the Energy Performance of Buildings Directive, EPBD, the European parliament has stated that by the end of 2020 all new buildings shall be "nearly zero-energy buildings" [3]. The nearly zero-energy building is defined as a building with a very high energy performance, which means that the energy required should be nearly zero or very low.

A common concept to design and build an energy efficient building is to apply the Passive House design principle. The first step in the Passive House design principle is to reduce heat losses by constructing a well insulated and air tight building envelope in combination with balanced

ventilation with high system heat recovery efficiency [4].

When a building is designed according to these principles, the major part of the energy needed for space heating will be related to thermal transmission through building elements and thermal bridges. Poor calculation of thermal bridges may therefore lead to an increased space heating demand and poor indoor climate. Further, this may lead to economical consequences for the builder, the client and/or the consultants. It may also lead to decreased credibility for energy efficient buildings if the calculated/simulated energy performance does not correlate with the measured energy performance. It may also lead to reduced thermal comfort in the building.

A Swedish study based on a questionnaire has been carried out which shows that the definitions of a thermal bridge is not fully understood and that even professionals are not always fully aware of the implications of the different methods used to calculate transmission losses [5]. The study also indicates that the calculations to determine the size of thermal bridges today often are done with simplified mathematical methods, which usually are 1-D, or by increasing the thermal transmittance of building elements by a certain percentage factor. To exemplify the impact and to elucidate the increased need of correct calculations of thermal bridges for passive houses and nearly zero-energy buildings comparative calculations have been carried out for two junctions where the thermal bridges are calculated using 1-D and 2-D analysis. Furthermore, a case study has been carried out where the annual space heating demand, peak load for heating and the needed supply air temperature (if the building is to be heated by pre heated supply air) have been calculated for a building designed as a passive house in Sweden. These analyses are based on different scenarios regarding consideration of thermal bridges.

2. Method

2.1 Theoretical background – Calculation of heat transfer through building elements and thermal bridges

This section focuses on heat transfer according to EN ISO 13789 [6] and thermal bridges according to EN ISO 10211 [7].

In order to calculate heat transmission through a building envelope there is a need to calculate a heat transfer coefficient according to Equation 1.

$$H_D = \sum_i A_i U_i + \sum_k l_k \Psi_k + \sum_j \chi_j \quad (1)$$

Where A_i area of element, i (m²)
 U_i thermal transmittance of element, i (W/m²·K)
 l_k length of linear thermal bridge (m)
 Ψ_k linear thermal transmittance of thermal bridge (W/m·K)
 χ_j point thermal transmittance through point thermal bridges (W/K)

Calculations for thermal bridges are presented in Equation 2 and Equation 3, where Equation 2 defines linear thermal transmittance and Equation 3 defines point thermal transmittance.

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \quad (2)$$

Where L_{2D} thermal coupling coefficient obtained from a 2-D calculation (W/m·K)
 U_j thermal transmittance of 1-D component, j (W/m²·K)
 l_j length over which U_j applies (m)

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{j=1}^{N_j} \Psi_j \cdot l_j \quad (3)$$

Where L_{3D} thermal coupling coefficient obtained from a 2-D calculation (W/K)
 U_i thermal transmittance of 1-D component, i (W/m²·K)
 A_i area over which U_i applies (m²)
 Ψ_j linear thermal transmittance calculated according to Equation 3 (W/m·K)
 l_j length over which Ψ_j applies (m)

Measuring of lengths and areas for Equation 1, Equation 2 and Equation 3 can be done according to one of the three methods; internal, overall internal or external dimensions. The differences between the different measuring concepts are visualised in Fig. 1.

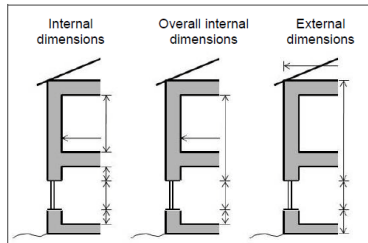


Fig. 1 Different types of dimensions according to EN ISO 13789

The sum of heat transmission through building elements, the term $\sum A_i U_i$, will vary depending on the measuring method chosen. Also the specific values for thermal bridges, Ψ -values and χ -values, will vary. To avoid misunderstandings the subscripts in Table 1, showing the used measuring method, will be used when thermal bridges are presented.

Table 1 Subscripts to clarify used method for measuring

Subscript	Definition
i	Internal
oi	Overall internal
e	External

2.2 Calculations and simulations

Calculations to determine thermal transmittance, for building elements and thermal bridges, are carried out using HEAT 2D 7.1 [8]. The effective thermal conductivity, λ' , for quasi-homogeneous layers is calculated according to Equation 4.

$$\lambda' = \frac{d}{\frac{A}{L_{3D}} - R_{si} - R_{se} - \sum \frac{d_j}{\lambda_j}} \quad (4)$$

Where d thickness of the thermal inhomogeneous layer (m)
 A area of building component (m²)
 L_{3D} thermal coupling coefficient of building component (W/K)
 d_j thickness of any homogeneous layer in the building component (m)
 λ_j thermal conductivity of homogeneous layer (W/m·K)

The simplified method, 1-D analysis, is shown in Equation 5.

$$\Psi_{1D} = U_{th} \cdot l_{th} \tag{5}$$

Where U_{th} thermal transmittance of 1-D component, th , with reduced heat resistance (W/m^2K)
 l_{th} length over which U_{th} applies (m)

To simulate the annual energy use for heating IDA ICE 4.1 [9] is used. The peak load for heating is calculated according to the Swedish criteria for passive houses [10]. The supply air temperature, if preheated supply air is used for space heating, is calculated according to Equation 6.

$$T_{supply} = \frac{P}{q \cdot \rho \cdot c_p} + (T_{outdoor} + \eta \cdot (T_{indoor} - T_{outdoor})) \tag{6}$$

Where P peak load for space heating (W)
 q ventilation air flow (l/s)
 ρ density of air (kg/m^3)
 c_p heat capacity of air (J/kg, K)
 η efficiency of heat exchanger in ventilation unit (%)
 $T_{outdoor}$ Design outdoor temperature at the specific location ($^{\circ}C$)
 T_{indoor} Design indoor temperature ($^{\circ}C$)

2.2.1 Differences in calculated thermal transmittance through thermal bridges based on 1-D and 2-D analysis

In the first example comparative calculations are carried out for two junctions, Junction 1 and Junction 2 (J1 & J2). The thermal bridges calculated using 1-D and 2-D analysis are shown in Fig 2. J1 represents a light-weight infill wall connected to an intermediate concrete floor. The slab edge, a thermal bridge, is insulated with 100 mm of mineral wool. J2 represents a window connected to a precast concrete sandwich wall. To be able to mount the window; the inner concrete construction is thickened into the window bays. To reduce the thermal bridge, the end of the thickened section is insulated with 30 mm of mineral wool. In J1, w_1 is varied from 100 to 400 mm which results in U-values from 0.24 to 0.10 W/m^2K . In J2, w_2 is varied from 90 to 320 mm which results in U-values from 0.26 to 0.09 W/m^2K . Note that the amount of insulation over the thermal bridge is not varied. Input data for the analysis is presented in Table 3.

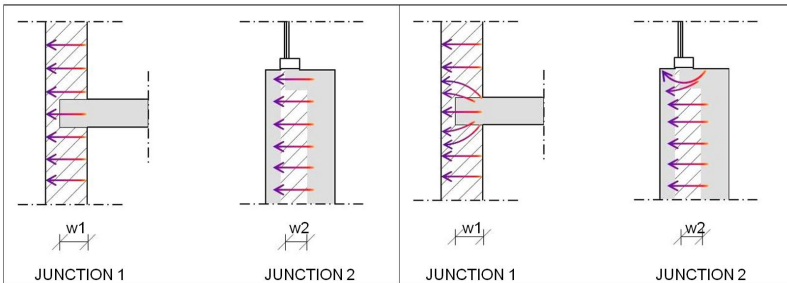


Fig. 2 Schematic presentation of junctions; J1 and J2 In the figures to the left an incorrect assumption, 1-D heat flow, is visualised, in the figures to the right a 2-D heat flow is visualised. The grey area represents concrete, the hatched area the insulated section.

2.2.2 Differences in calculated thermal transmittance through thermal bridges based on different measuring methods

As already explained in the theoretical background, the calculated thermal transmittance of a thermal bridge may differ due to the chosen measuring method. In Fig 3 nine different possible thermal bridges are presented. Linear thermal transmittances for the junctions are calculated based on all three measuring methods. Input data for the analysis is presented in Table 3.

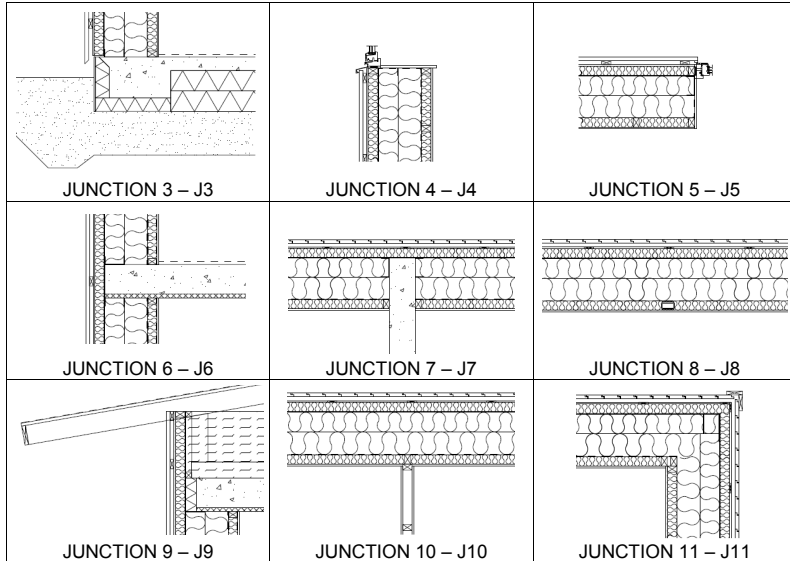


Fig. 3 Schematic presentation of junctions; J3-J11

J3: non load bearing infill wall mounted on a ground floor slab

J4: window connection to a non load bearing infill wall with marble window sill

J5: window connection to a non load bearing infill wall with gypsum window bay

J6: non load bearing infill wall connected to an intermediate floor

J7: non load bearing infill wall connected to a load bearing intermediate wall

J8: load bearing steel pillar inside the a non load bearing infill wall

J9: non load bearing infill wall connected to an attic floor

J10: non load bearing infill wall connected to non load bearing intermediate wall

J11: external wall corner

2.2.3 Possible differences in energy needed for space heating

The junctions presented in Fig 3 are used in a fictive terraced house, designed as a passive house in Sweden. The building contains four dwellings with a varying heated area; 118-130 m². The characteristics of the building are presented in Fig 4 and Table 2. The annual energy use for heating, peak load for heating and the needed supply air temperature (if the building is to be heated by pre heated supply air) have been calculated for five different scenarios:

- Scenario 1
External measuring used to determine A_t , no thermal bridges added
- Scenario 2
Over all internal measuring used to determine A_t , thermal bridges considered by increasing thermal transmittance by 15 percent
- Scenario 3

Internal measuring used to determine A_i , thermal bridges considered by increasing thermal transmittance by 15 percent

- Scenario 4
Internal measuring used to determine A_i , thermal bridges added by applying values for Ψ_e
- Scenario 5
Internal measuring used to determine A_i , thermal bridges added by applying values for Ψ_i

In the scenarios described above, scenario 5 is correct and all other scenarios examples of possible misunderstandings.

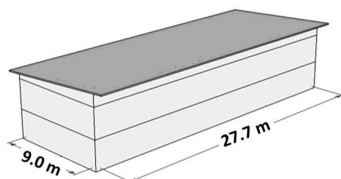


Fig. 4 Reference building

Table 2 Characteristics of reference building (measuring is based on internal dimensions)

Characteristic	Data	Unit
Heated area	498.0	m ²
Window and door area	72.5	m ²
Quantity of J3	73.4	m
Quantity of J4	52.6	m
Quantity of J5	157.8	m
Quantity of J6	73.4	m
Quantity of J7	40.0	m
Quantity of J8	80.6	m
Quantity of J9	73.4	m
Quantity of J10	110.1	m
Quantity of J11	20.0	m

Table 3 Input data for calculations in HEAT 2D 7.1 and IDA ICE 4.1

	Input data	Unit	Comments
Climate data	Göteborg		Latitude 58°N
Indoor temperature	21	°C	-
Design outdoor temperature	-15	°C	-
Air permeability	0.5	h ⁻¹	At 50 Pa, EN 13829
Ventilation	0.35	l/s, m ²	m ² , heated area
η , ventilation heat exchanger	80	%	-
Internal heat gains	4	W/m ²	From people and electrical equipment
Ground	$\lambda = 2.0$	W/mK	According to EN ISO 13370
Concrete	$\lambda' = 2.3$	W/mK	Concrete 1% steel reinforcement
Insulation under floor slab	$\lambda = 0.038$	W/mK	EPS S80
Insulation under footing	$\lambda = 0.033$	W/mK	EPS S400
Mineral wool	$\lambda = 0.037$	W/mK	Standard mineral wool
Insulated layer in J1	$\lambda' = 0.050$	W/mK	Insulated wood frame construction
Insulated layer in J2	$\lambda' = 0.033$	W/mK	EPS C80 + reinforcement ladders
Outer part of walls J3-J8	$\lambda' = 0.034$	W/mK	High density mineral wool
Insulated stud section1 J3-J8	$\lambda' = 0.072$	W/mK	Insulation + slotted steel studs
Insulated stud section2 J3-J8	$\lambda' = 0.050$	W/mK	Insulated wood frame construction
Floors	$\lambda = 0.24$	W/mK	Equal to high density plywood
Steel	$\lambda = 50.0$	W/mK	According to EN ISO 10456
Gypsum board	$\lambda = 0.25$	W/mK	According to EN ISO 10456
Marble window sill	$\lambda = 3.50$	W/mK	According to EN ISO 10456
Fixed triple glazed window	$U_w = 0.90$	W/m ² K	LE-coatings + Argon filling
Surface resistance	$R_{si} = 0.13$	m ² K/W	Used in all calculations
Surface resistance	$R_{se} = 0.04$	m ² K/W	Used in all calculations

3. Differences in calculated thermal transmittance when applying different analysis measuring methods

3.1 Differences in calculated thermal transmittance through thermal bridges based on 1-D and 2-D analysis

The comparison shows that the specific thermal transmittance decreases slightly with the increased wall thickness if a 1-D analysis is carried out. This is due to that the thermal resistance increases slightly due to increased amount of concrete at the part of the section where the thermal bridge occurs. The amount of insulation, 100 and 30 mm respectively, is the same. If a proper 2-D analysis is carried out, the specific linear thermal transmittance for the thermal bridge will increase as the heat resistance for the wall increases. This is due to the effect of 2-D heat flow. Results from calculations and the relative difference (%) between simplified (1-D) and 2-D analysis are presented in Fig 5. The analysis shows that the difference between simplified (1-D) calculations and 2-D-analysis may be as much as 40% if the external wall is well insulated.

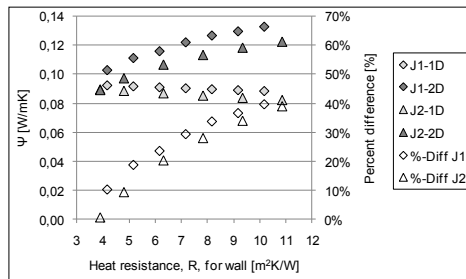


Fig. 5 Results from simplified (1-D) and 2-D-analysis of junctions; J1 and J2

A comparison is also made regarding how much the U-value should be increased to account for the thermal bridge. In the comparison, it is assumed that the relationship between quantities of junctions (m) and wall (m²) is 1/3. The result is shown in Fig 6. The analysis shows that for a moderately insulated wall, U = 0.2 W/m²K, the effect of the thermal bridges may result in an increase of U-value by ~15%. The increase of the U-value for a well insulated wall may be >40%.

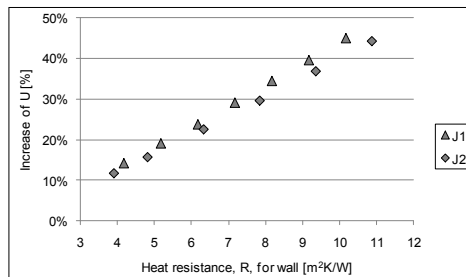


Fig. 6 Increase of U-value when considering the effect of thermal bridges

3.2 Differences in calculated thermal transmittance through thermal bridges based on different measuring methods

The results from the calculations of thermal bridges are shown in Table 4. The junctions where thermal bridges mainly are caused due to partial penetration of the building envelope by material with a different thermal conductivity (J3, J6 and J7), the percentage difference between Ψ_i and Ψ_e is 15-21%. The junctions who show the greatest difference (J10 and J11) between Ψ_i and Ψ_e are junctions with a large difference between internal and external area.

Table 4 Results from analysis of thermal bridges

Junction	Ψ_i [W/mK]	Ψ_{oi} [W/mK]	Ψ_e [W/mK]	Percentage difference between Ψ_i and Ψ_e [%]
J3	0.325	0.325	0.263	21%
J4	0.035	0.035	0.035	0%
J5	0.033	0.033	0.033	0%
J6	0.161	0.135	0.135	18%
J7	0.139	0.120	0.120	15%
J8	0.002	0.002	0.002	0%
J9	0.141	0.141	0.022	146%
J10	0.009	<0.000	<0.000	195%
J11	0.024	0.024	-0.068	422%

3.3 Possible differences in energy needed for space heating, peak load and supply air temperature

The analysis shows that the thermal bridges account for 28 % of the transmission losses when the transmission heat transfer coefficient, H_T , is calculated in scenario 5. This can be compared to the transmission losses due to doors, windows and window doors which accounts for 31 % of the transmission losses. The difference between scenario 1 and scenario 5 is an increase of H_T by 23 % and increased supply air temperature by 11 °C. If an indoor temperature of 21 °C is requested at the design outdoor temperature there will be a need to preheat the supply air to 48°C. See Fig 7 for H_T and needed supply air temperature for all scenarios.

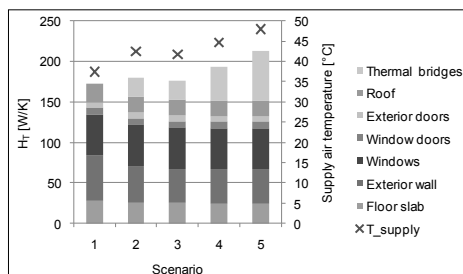


Fig. 7 Transmission heat coefficient, H_T , and required supply air temperature if preheated air is used for space heating, based on different scenarios

As can be seen in Fig 8; the energy demand for space heating varies between 19 and 30 kWh/m²a for the different scenarios and the peak load for space heating varies between 10 and 14 W/m². In other words, the underestimation of energy demand for space heating and peak load for heating in scenario 1 compared to scenario 5 is 37% and 29% respectively.

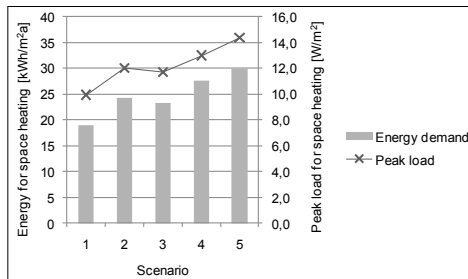


Fig. 8 Annual energy demand, for space heating and peak load for space heating based on different scenarios

4. Discussion and conclusions

The difference between specific values and impact of thermal bridges may be large when comparing thermal bridges based on internal measuring and external measuring. This paper shows that it is not suitable to consider the effect of thermal bridges by increasing the calculated thermal transmission losses due to building elements, the term ΣAU_i , by a fixed percentage or by using default values for specific linear transmittance. It is not suitable due to that:

- The impact of thermal bridges increases when the thermal resistance of the building envelope increases
- The specific values may increase (as shown in Fig 5)

The analysis also elucidates the need for clear communication between consultants in the design phase of a building project. If an architect and a HVAC engineer should collaborate to compile the needed basis for the energy design of a passive house, including energy simulations and the design of the heating system, there may be a risk of misunderstanding leading to:

- Increased annual energy need for space heating
- Undersized heating systems
- High supply air temperature needed (if preheated air is used for space heating)
- Reduced thermal comfort

To minimize this risk of misunderstanding, the subscripts presented in Table 1 should always be used when calculated values for thermal bridges are presented. Correct calculations and communication, with subscripts, should reduce the risk of misunderstandings and performance failure of passive houses and nearly zero-energy houses.

In this study was internal measuring of building elements in combination with Ψ_i used as the correct approach. It is of course possible to apply both external measuring or over all internal measuring to quantify building elements as long as the correct values for thermal bridges are considered in these cases (Ψ_e for external measuring and Ψ_{oi} for over all internal measuring)

In the Swedish building regulations, BBR [11], there are today no references to which measuring method that should be used when quantities of A_i are defined. They do, however, set requirements for maximum allowed average heat transfer coefficient, which is equal to H_T divided by the total surface area of the enclosing parts of the building. This requirement in combination with the lack of clear guidelines regarding which measuring method that should be used makes it possible for unscrupulous builders to interpret the regulations in the way most suitable for them.

In this specific reference building, nine potential thermal bridges were investigated which were considered to be the most relevant in this case. In Sweden, a variety of building systems are used and the thermal transmittance due to thermal bridges varies between different building systems and due to different construction solutions for junctions within the different building systems. This study should therefore not be used as a basis to draw conclusions regarding how much of a building's transmission losses that occur through thermal bridges, but more as an example of how large errors that may occur if you do not understand and apply standards regarding thermal bridges in a correct way.

5. Acknowledgements

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Hygrothermal conditions in exterior walls for passive houses in cold climate considering future climate scenario

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Abstract

Reduction of energy use constitutes as an important measure for climate change mitigation. Buildings today account for 40% of the world's primary energy use and 24% of the greenhouse gas emissions [1]. The concept of passive houses is one of many necessary measures for climate change mitigation. To reach the passive house ambition in cold climates, increased thermal resistance of the building envelope is vital. Increasing the thermal resistance in combination with climate change will result in a different microclimate within the building envelope.

Possible future micro climate in exterior walls are produced by hygrothermal simulations using the numerical software WUFI. The simulations are conducted for four different locations in Sweden, where the main difference is geographically in the respect of latitude, for the year period 1985-2098. Regional climate is based on data from the Swedish Meteorological and Hydrological Institute, using regional climate models developed at the Rosby Centre, RCA3. The RCA3 model covers Europe with a horizontal resolution of 50x50 kilometres. The boundary conditions are from the global climate model ECHAM5.

The increased risk for performance failure due to high humidity levels is conducted by assessing the result from the simulations combining three different evaluation models described in, which mainly differ in respect of the consideration of fluctuating hygrothermal conditions.

The investigations show that the risk of mould growth will increase in the future. However, adding more insulation to the exterior side of a wood frame construction results into more stable hygrothermal conditions. Based on the results from the simulations it is recommended that all constructions with bio gradable materials should be given exterior insulation to decrease the risk of mould growth. Furthermore, building elements must always be designed to have the ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

Introduction

Published in 2007, the fourth assessment report [IPCC 2007] generated considerable attention as it through observations and measurements stated that there is a warming of the climate system. The observed temperature increase is wide spread all over the globe and is higher at northern latitudes. Furthermore, IPCC concludes that further warming is expected, and increases in the amount of precipitation are very likely in high-latitudes. One of the drivers of climate change is Green house Gases, GHG. Buildings today account for 40% of the world's primary energy use and 24% of the GHGs [International Energy Agency (IEA) 2011]. As the world's population and need for buildings are growing; Reduction of energy use and a transition towards use of renewable energy in the building sector is vital.

A common approach to design and build an energy efficient building is to apply the passive house design principle where the first step is to reduce heat losses by constructing a well insulated and air tight building envelope in combination with balanced ventilation with high system heat recovery efficiency [Janson 2010]. Within the building construction industry, robustness and durability of building elements are often based on experience. The experiences are often expressed qualitatively, and not specified in quantitative terms. However, it is very likely that increasing the thermal resistance in combination with climate change will result in different hygrothermal conditions within the building envelope. Built in moisture will take longer time to dry out and the outer parts of building elements will have hygrothermal conditions more similar to the exterior climate. This might give a higher risk for mould growth.

This paper investigates the risk of performance failure due to mould growth, based on possible future climate scenario using three different evaluation models. The paper is a prolongation of a previous study [Berggren and Wall 2012] which will be presented at the 7th International Cold Climate HVAC Conference, hosted by

ASHRAE. One of the conclusions in the previous study was that built in moisture has a considerable effect on the risk of mould growth. To maintain consistency the present study is based on the same case wall constructions. The hypothesis of this study is that built in moisture and adsorbed water due to driving rain may have a great effect on the risk of performance failure.

Method

The case study

An exterior wall construction with standard amounts of insulation, $U_c=0.17 \text{ W/m}^2\text{K}$, was compared to two alternative wall constructions with more insulation, $U_c=0.09 \text{ W/m}^2\text{K}$. The standard case was an insulated wood frame construction, 170 mm, insulated with mineral wool. Exterior to the wood frame construction are; 13 mm wind shield/wind stabilization, 28 mm air gap and wood panel cladding. On the interior side of the wood frame construction are; vapour barrier, 70 mm insulated wood frame construction and 13 mm gypsum plasterboard. The difference between the two alternative wall constructions was where the increased amounts of insulations were mounted. In Alternative 2, the insulation was mounted on the interior side of the wood frame construction. In Alternative 3, the insulation was mounted partly on the exterior side of the wood frame construction, and partly on the interior side of the wood frame construction. The different wall assemblies are presented graphically in Figure 1 below.

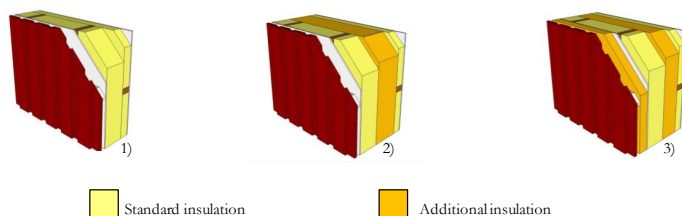


Figure 1 Alternative 1 - Standard wall constructions. Alternative 2 – Additional insulation on the interior side of the wood frame construction. Alternative 3 – Additional insulation on the exterior and interior side of wood frame construction

Investigation of hygrothermal conditions

To generate future climate scenario data for simulations, the imposed offset method was applied. There are different methods to generate future climate data for simulations and estimations of building performance in respect to climate change. Several studies and proposals have been published. These may be divided into four groups, from simple to complex; extrapolating statistical method, the imposed offset method, stochastic weather model and climate models [Guan 2009]. The imposed offset method bases the climate data on a typical year, meteorological – TMY, or reference – TRY. Known parameters that are expected to be affected by climate change are adjusted by offsetting the parameters based on the results from the climate models. This method has been used in many studies and has the benefit that it can be used even if changes of all parameters are not known. The Rossby Centre at the Swedish Meteorological and Hydrological Institute, SMHI, uses three-dimensional regional climate models that mathematically describe the climate system with a rather high resolution. In this case study the RCA3 [Samuelsson, Jones et al. 2011] model was used. The RCA3 model covers Europe with a horizontal resolution of 50x50 kilometers. The boundary conditions are from the global climate model ECHAM5 [Roeckner, Bengtsson et al. 1999]. In the previous study [Berggren and Wall 2012], climate scenario data were obtained for four different locations, based on the scenario A1B, in Sweden with monthly resolution for the period 1985-2098 [Swedish Meteorological and Hydrological Institute (SMHI) 2012]. The locations are given in Figure 2. The study showed that the most unfavourable conditions were location A and B. Hence location C and D are not included in this study.

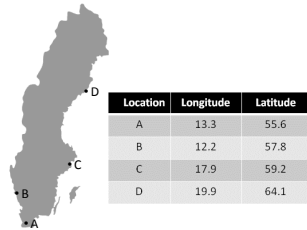


Figure 2 Geographical presentation of locations included in the study

The monthly mean deviation from the reference year, 1961-1990, was calculated for temperature, wind speed and precipitation. To generate input data for detailed simulations, reference years were generated with hourly resolution using Meteonorm 6.1 [Meteotest 2010]. These data were adjusted with the monthly deviation and compiled into longer time series. Adjustments in wind speed and temperature were made in absolute terms, increasing or decreasing the hourly data. Adjustment of precipitation was made by multiplying the hourly data with the monthly deviation in percentage.

Due to limitations in computing power, the investigated period has been divided into time series of three years, i.e. 1985-1987, ..., 2096-2098.

Hygrothermal simulations were conducted using the numerical software WUFI Pro 5.1 1D [Fraunhof-Institut für Bauphysik 2012]. The interior climate was seasonally varied according to EN 15026 [Swedish Standards Institute 2007]. A separate simulation was conducted for each three year period, specific location and wall assembly.

Evaluation models

Initiation of mould growth is difficult to predict. There are climate conditions documented under which mould growth is initiated. Examples may be found in [Viitanen 1997], [Johansson, Samuelson et al. 2005] and [Nilsson 2006]. However, these are usually based on constant hygrothermal conditions. In reality, hygrothermal conditions are fluctuating. In this study three different models are used to assess the risk of mould growth based on temperature and relative humidity (RH).

The Dose model

A performance model has been developed at Lund University in order to quantify the potential for mould growth [Isaksson, Thelandersson et al. 2010]. The model is based on the critical time, t_{ms} , for onset of mould growth, level 1, under different climate conditions (constant time) given by Equation 1, based on [Viitanen 1997].

$$t_{ms} = \exp(-0.74 \ln T - 15.53 \ln RH + 75.736) \quad 1$$

Where T is the temperature in (°C) and RH is the relative humidity (%). The formula is valid for relative humidity in the interval $75 \leq RH \leq 100$ and temperatures $0.1 \leq T \leq 40$. By choosing a reference climate as $T_{ref} = 20^\circ\text{C}$ and $RH_{ref} = 90\%$. Mould is in theory initiated after 38 days. The total mould dose, D , may then be described as in Equation 2 based on Equation 3, Equation 4 and Equation 5. Input data for calculations are daily averages.

$$D_n = \sum_1^n D_{RH}(RH) \cdot D_T(T) \quad 2$$

Where D_n is the dose after n days, $D_{RH}(RH)$ is the dose component based on RH and $D_T(T)$ is the dose component based on temperature. The dose components are defined by derivation of Equation 1.

$$D_{RH} = \exp \left[15.53 \cdot \ln \left(\frac{RH}{90} \right) \right] \quad \text{for} \quad 75 < RH \leq 100 \quad 3a$$

$$D_{RH} = \left(-2.7 + \frac{1.1RH}{30} \right) \quad \text{for} \quad 60 < RH < 75 \quad 3b$$

$$D_{RH} = -0.5 \quad \text{for} \quad RH < 60 \quad 3c$$

$$D_T = \exp \left[0.74 \cdot \ln \left(\frac{T}{20} \right) \right] \quad \text{for} \quad 0.1 \leq T \quad 4$$

$$D_T \cdot D_{RH} = -0.5 \quad \text{for} \quad T < 0.1 \quad 5$$

Negative “doses” are added when conditions for mould growth is unfavourable [Isaksson, Thelandersson et al. 2010]. The accumulated mould dose, D_n , never falls below zero. To calculate the relative dose, the accumulated dose may be divided with the reference climate for which mould in theory is initiated, i.e. in this case 38 days. Mould is in theory initiated when the relative mould dose ≥ 1 . To analyze the risk for mould growth, daily averages of relative humidity and temperature at the interior side of the wind barrier were extracted from WUFI Pro 1D and analyzed, using the “Dose model”. As the mould dose varies within each 3-year simulation, the highest accumulated D, divided by 38, is displayed.

The m-model

The m-model was developed at Skanska Sverige AB to assess and compare different design solutions with respect to the risk of mould growth, also described in [Tengberg and Togerö 2010] and [Togerö, Tengberg et al. 2011]. The m-model is similar to the “Dose Model”. The model also is based on calculating the critical time for when mould in theory is initiated. However, the m-model enables evaluations on shorter time steps, 1-3 hours, and uses six different duration curves for which mould in theory is initiated, as shown in Figure 3.

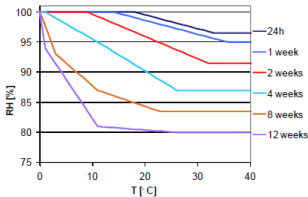


Figure 3 Six critical moisture levels based on [Viitanen 1996] and [Nilsson 2009] from [Togerö, Tengberg et al. 2011]

At each time step, a parameter called m is calculated according to Equation 6. This is calculated for all six critical duration curves.

$$m_{DC} = \frac{RH(t)}{RH_{crit}(T(t))\gamma} \quad 6$$

Where m_{DC} is the *m parameter* for each duration curve, DC, based on the critical relative humidity, RH_{crit} , at the temperature T. This equation also includes a safety factor, γ , in this study 0.99. If $m \geq 1$, conditions for mould growth have occurred in one time step. All time steps where $m \geq 1$ are summarized separately for each DC, and constitute the accumulated risk time. The m-model considers dehydration according to Equation 7.

$$m_{DC, reduced} = \beta \cdot \sum m_{DC} \quad 7$$

Where β is the retardation factor according to Equation 8.

$$\beta_{m_{DC,24h}} = \left(\frac{RH}{RH_{crit}}\right)^{4.5} \quad \text{for } \frac{RH}{RH_{crit}} < 1 \quad >6 \quad 8a$$

h

$$\beta_{m_{DC,1w,2w,3w}} = \left(\frac{RH}{RH_{crit}}\right)^{1.7} \quad \text{for } \frac{RH}{RH_{crit}} < 1 \quad 8b$$

>168 h

$$\beta_{m_{DC,8w,12w}} = \left(\frac{RH}{RH_{crit}}\right)^{1.2} \quad \text{for } \frac{RH}{RH_{crit}} < 1 \quad 8c$$

>168 h

$$\beta_{m_{DC,all}} = 0 \quad \text{for } \frac{RH}{RH_{crit}} < 1 \quad 8d$$

>504 h

Where RH and RH_{crit} is average during the period for unfavorable conditions. The accumulated risk time for each duration curve is divided with the critical risk time. The quota is called critical duration quota, CDQ. Mould will in theory be initiated when $CDQ \geq 1.0$. To analyze the risk for mould growth, hourly values of relative humidity and temperature were extracted from WUFI Pro 1D and analyzed, using the "m-model". The same position for analysis was chosen as the one for the "Dose model". As within analysis using the Dose model, the risk of mould growth, CDQ, varies. The highest CDQ during each evaluated period and for all six calculations is displayed.

WUFI Bio

In addition to the software WUFI Pro, a plug-in to assess the risk of mould growth is available; WUFI Bio. This model differs from models described above. Within the model a hypothetical mold spore is given characteristics of diffusion of water vapour and sorption of water. If the water content within the mold spore exceeds critical levels [Sedlbauer 2001], mould growth is initiated. The pace of mould growth is related to the level water content. The model is described in [Sedlbauer 2001] and [Sedlbauer 2003]. The result of the evaluation is presented on a seven-point scale, presented in Table 1, defined by [Viitanen and Ritschkoff 1991]. The position of analysis was the same as used for the other models. The substrate class chosen was class 1, which corresponds to building products made out of biologically degradable materials.

Index	Description
0	No mould growth
1	Some mould growth, visible under microscope
2	Moderate mould growth, visible under microscope – coverage >10%
3	Growth detected visually, thin hyphae found under microscope
4	Visual coverage of mould growth >10%
5	Visual coverage of mould growth >50%
6	Visual coverage of mould growth 100%

Table 1 Mould index [Viitanen and Ritschkoff 1991]

Test of models and sensitivity analysis

For the three different case wall assemblies, Figure 1, a base case and a simple sensitivity analysis was carried out, focusing on built in moisture and rain penetration. A summary of the different set-ups are presented in Table 2.

Set up	Description	Varied parameters		Parameters not varied
		Built in moisture	Rain penetration	
α	Base case	Gypsum boards; 20 kg/m ³ Insulation; 4 kg/m ³	1 % of driving rain reaches wind shield	Cardinal direction; west Ventilation in air gap; 50 h ⁻¹
β	Minimizing built in moisture	Gypsum boards; 10 kg/m ³ Insulation; 2 kg/m ³	1 % of driving rain reaches wind shield	Indoor climate; EN 15026, normal occupancy
γ	β + increased rain penetration	Gypsum boards; 10 kg/m ³ Insulation; 2 kg/m ³	5 % of driving rain reaches wind shield	Driving rain; (precipitation)x(wind speed)x0.07

Table 2 Summary of different scenarios

Results

Evaluation of hygrothermal conditions are presented in Figure 4, Figure 5 and Figure 6. Numbers represents the studied wall assemblies (1-3 according to Figure 1). Letters represents the geographical position (A & B according to Figure 2).

The “dose model” indicates that location B has much more unfavourable conditions compared to location A. The risk for mould growth for the wall assemblies at location A are relatively constant and not particularly affected by the climate scenarios when studying set-up α and β where the rain penetration was 1% of the driving rain. In these set-ups, wall assembly 2 (increased insulation without exterior insulation), receives the highest calculated relative mould dose. In set up γ , increased rain penetration, the wall assembly 3 (increased insulation with exterior insulation) receives the highest relative mould dose compared to the other set-ups. This is due to the external insulation (on the exterior side of the wind shield) which results in warmer conditions. Hence, this becomes more favourable for mould growth. If the built in moisture is minimized and the rain penetration is 1% (set-up β), all wall assemblies at location A and wall assembly 3 at location B receive a calculated relative mould dose ≤ 1 .

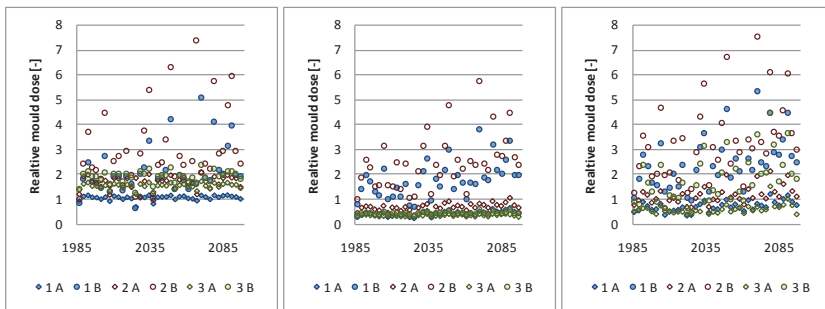


Figure 4 Evaluation of hygrothermal conditions using the “Dose model”. Left; Set-up α . Middle; Set-up β . Right; Set-up γ .

Using the m-model indicates the same results as when the dose model was used. However, there is a clearer trend of increased risks for mould growth due to climate change. Examining set up γ , increased rain penetration, some results show a higher risk of mould growth when exterior insulation is used compared to the other wall assemblies without exterior insulation. This result is not seen in the analysis using the dose model.

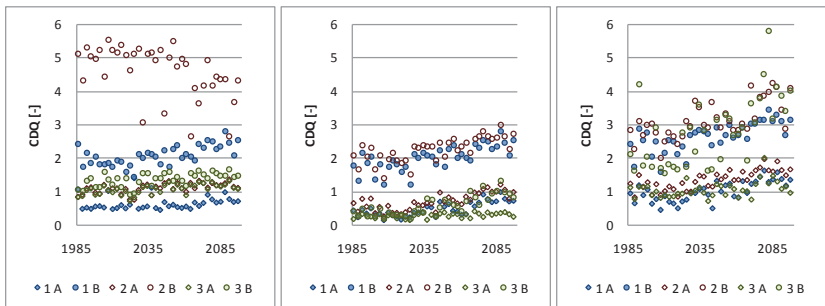


Figure 5 Evaluation of hygrothermal conditions using the “m-model”. Left; Set-up α . Middle; Set-up β . Right; Set-up γ .

In difference compared to all other results, wall assembly 2 at location B and base case set-up, show a decreasing risk for mould growth for future climate scenarios. The reason for this has not been determined.

Using WUFI Bio results in a very clear indication that using external insulation and keeping the built in moisture to a minimum is favourable. Examining the set-up with low built in moisture and location B, wall assembly 3 show a very low mould index compared to wall assembly 1 and 2. WUFI Bio also indicates (as when the m-model was used) that external insulation may result in higher risk for mould growth if the rain penetration is high.

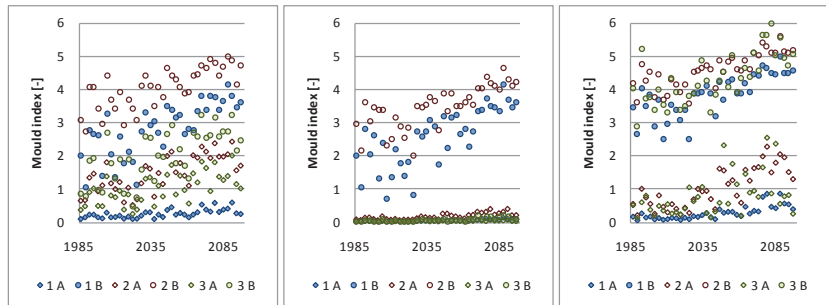


Figure 6 Evaluation of hygrothermal conditions using WUFI Bio. Left; Set-up α . Middle; Set-up β . Right; Set-up γ .

Discussion and conclusions

This study is based on one climate scenario. It is important to stress that climate models are used to simulate and produce climate scenario data. These climate scenarios are not weather forecasts. They are scenarios based on emissions scenarios from IPCC Special Report on Emissions Scenarios, SRES (IPCC 2000). The climate scenarios answer the question; - if the atmosphere is changing in a certain way, how will the climate change? The investigated scenario indicates that the ongoing climate change will most likely increase the risk of mould growth.

From this study, the major conclusions and recommendations are:

- Buildings are expected to have a long life-span. Therefore effects of climate change in the design of buildings and building elements must be considered.
- Construction materials based on bio gradable materials, e.g. wooden studs, should always be given exterior insulation to decrease the risk of mould growth. However poor assembly, i. e. enabling driving rain to penetrate exterior walls, most likely at junctions may actually increase the risk for mould growth.
- Within the construction phase of buildings, there is a need to implement all reasonable measures to decrease the amount of moisture, added in this phase.
- Building elements must be given the ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

Acknowledgements

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Conference paper 11

Moisture Conditions in Exterior Walls for Net Zero Energy Buildings in Cold Climate Considering Future Climate Scenario

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ABSTRACT

An important measure for climate change mitigation is reduction of energy use in buildings worldwide. To decrease the energy use of a building in a Nordic climate, increased thermal resistance of the building envelope is a suitable measure. Adding more insulation in combination with climate change may increase the risk of mold growth within the building envelope. This study evaluates hygrothermal conditions for three different wood frame wall assemblies and four different locations in Sweden. The evaluation is based on simulations where the exterior climate is based on a climate scenario from the Swedish Meteorological and Hydrological Institute. The evaluation of the climate scenarios show a trend of increased precipitation and temperature. Examining the hygrothermal conditions; all evaluations models indicate an increased risk of mold growth over time due to climate change. Adding more insulation to a building envelope will decrease the dehydration of built-in moisture. However, adding more insulation to the exterior side of a wood frame construction results into more stable hygrothermal conditions. Based on the results from the simulations it is recommended that all constructions with bio gradable materials should be given exterior insulation to decrease the risk of mold growth. Furthermore, building elements must always be designed to have the ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

INTRODUCTION

The fourth assessment report (IPCC 2007) presents, through observations and measurements, that there is a warming of the climate system. The increase of temperature is spread all over the globe but higher at northern latitudes. In addition to the warming, increases in the amount of precipitation in high-latitudes are very likely. One of the drivers of climate change is Green house Gases, GHG, where Carbon dioxide, CO₂, is the most important GHG.

Reduction of energy use constitutes as an important measure for climate change mitigation. Buildings today account for 40% of the world's primary energy use and 24% of the GHGs (International Energy Agency (IEA) 2011). Today, the concept of Net Zero Energy Buildings, Net ZEBs, is no longer perceived as a concept that only can be reached in a very distant future. A growing number of projects/buildings in the world, in different climate, show that it is possible to reach Net ZEB balance with technologies available today on the market (SHC Task40/ECBCS Annex52 IEA 2011; U.S. Department of Energy 2011). To reach the Net ZEB balance in cold climates, increased thermal resistance of the building envelope is a fundamental measure. An overview of Net ZEBs worldwide (Musall, Weiss et al. 2010) shows that all investigated projects have applied the measure of increasing the amount of insulation in the building envelope.

Traditionally, durability and robustness of building elements are based on experience and are not specified in quantitative

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terms. However, increasing the thermal resistance in combination with climate change will result in different hygrothermal conditions within the building envelope. For example, in a Nordic climate the outer parts of a wall will have hygrothermal conditions more similar to the exterior climate as the thermal resistance increases and moisture may take longer time to dry out. This might give a higher risk for mold growth.

This paper focuses on investigating the risk of performance failure, due to mold growth, based on possible future climate scenario using four different evaluation models.

METHOD

Climate Scenario

Climate models are used to simulate and produce climate scenario data. Global climate models, GCMs, are representations of physical processes within and between the atmosphere, land surface, oceans and sea ice. GCMs require a lot of computing power. Therefore, the grid in global climate models usually has a sparse resolution and gives little detail on the regional and local scale. Regional climate models, RCMs, can be used to study specific areas in more detail, e.g. Europe. A small area makes it possible to have a denser grid, and consequently more detailed results. The boundary conditions for a RCM are coupled to a GCM. The Rossby Centre at the Swedish Meteorological and Hydrological Institute, SMHI, uses three-dimensional regional climate models that mathematically describe the climate system with a rather high resolution. In this case study the RCA3 (Samuelsson, Jones et al. 2011) model was used. The RCA3 model covers Europe with a horizontal resolution of 50x50 kilometers. The boundary conditions are from the global climate model ECHAM5 (Roeckner, Bengtsson et al. 1999). Climate scenario data were obtained for four different locations, based on the scenario A1B, in Sweden with monthly resolution for the period 1985-2098 (Swedish Meteorological and Hydrological Institute (SMHI) 2012). The locations are named A-D and corresponds to the following locations; A; Lund (55.6°N, 13.3°E), B; Göteborg (57.8°N, 12.2°E), C; Stockholm (59.2°N, 17.9°E) and D; Umeå (64.1°N, 19.9°E).

The monthly mean deviation from the reference year, 1961-1990, was calculated for temperature, wind speed and precipitation. To generate input data for detailed simulations, reference years was generated with hourly resolution using Meteotest 6.1 (Meteotest 2010). These data were adjusted with the monthly deviation and compiled into longer time series. Adjustments in wind speed and temperature were made in absolute terms, increasing or decreasing the hourly data; using the monthly average offset from reference year. Adjustment of precipitation was made by multiplying the hourly data with the monthly deviation in percentage.

Due to limitations in computing power, the investigated period has been divided into time series of three years, i.e. 1985-1987, ..., 2096-2098.

The case study

An exterior wall construction with standard amounts of insulation, $U_e=0.17 \text{ W/m}^2\text{K}$ or $R_{SI}=5.9 \text{ m}^2\text{K/W}$, was compared to two alternative wall constructions with more insulation, $U_e=0.09 \text{ W/m}^2\text{K}$ or $R_{SI}=11.1 \text{ m}^2\text{K/W}$. The standard case was an insulated wood frame construction, 170 mm, insulated with mineral wool. Exterior to the wood frame construction; 13 mm wind shield/wind stabilization, 28 mm air gap and wood panel cladding. On the interior side of the wood frame construction; vapor barrier, 70 mm insulated wood frame construction and 13 mm gypsum plasterboard.

The difference between the two alternative wall constructions was where the increased amounts of insulations were mounted. In Alternative 2, the insulation was mounted on the interior side of the wood frame construction. In Alternative 3, the insulation was mounted partly on the exterior side of the wood frame construction, and partly on the interior side of the wood frame construction. The different wall assemblies are presented graphically in Figure 1 below.

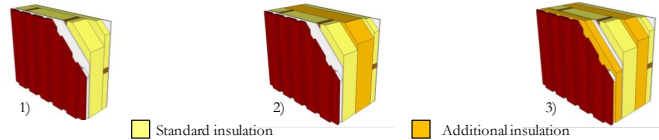


Figure 1 (1) Alternative 1 - Standard wall constructions and (2) Alternative 2 - Additional insulation on the interior side of the wood frame construction (3) Alternative 3 - Additional insulation on exterior and interior side of wood frame construction

Investigation of hygrothermal conditions

Hygrothermal simulations were conducted using the numerical software WUFI Pro 5.1 1D (Fraunhofer-Institut für Bauphysik 2012). The interior climate was seasonally varied according to EN 15026 (Swedish Standards Institute 2007). A separate simulation was conducted for each three-year period, specific location and wall assembly. Relatively high initial moisture content was assumed in the simulations, 20 kg/m^3 for gypsum boards and 4 kg/m^3 for insulation, in order to account for built-in moisture during the construction phase. To enable detailed analysis of the relative temperature distribution within the constructions, all constructions were 3D-modeled in HEAT 3 6.0 (Blöcon Sweden 2011) with a temperature difference of $1^\circ\text{C}/1.8^\circ\text{F}$.

Evaluation models

The Dose Model. At Lund University a performance model has been developed in order to quantify the potential for mold growth (Isaksson, Thelander et al. 2010). The model is based on the critical time, t_{m0} , for onset of mold growth, level 1, under different climate conditions (constant time) based on (Viitanen 1997).

The accumulated mold dose is calculated and divided with the reference climate for which mold in theory is initiated. In this case the reference climate is set to $20^\circ\text{C}/68^\circ\text{F}$ and relative humidity, RH, to 90%. Mold will then in theory be initiated in 38 days. If the relative mold dose ≥ 1 mold is in theory initiated. To analyze the risk for mold growth, daily averages of RH and temperature at the interior side of the wind barrier were extracted from WUFI Pro 1D and analyzed, using the "Dose model". As the mold dose may vary over time, this study examines the risk of mold growth by displaying the highest accumulated D, divided by 38.

The m-model. The m-model was developed at Skanska Sverige AB to assess and compare different design solutions from a mold risk perspective and is further described in (Tengberg and Togerö 2010; Togerö, Tengberg et al. 2011). The m-model is similar to the "Dose Model" since this model also is based on calculating the critical time for when mold in theory is initiated. However, the "m-model" enables evaluations on shorter time steps, 1-3 hours, and uses six different duration curves based on (Viitanen 1996; Nilsson 2009).

The accumulated risk time for each duration curve is divided with the critical risk time. The quota is called critical duration quota, CDQ. If $\text{CDQ} \geq 1.0$, mold will in theory be initiated. The highest CDQ during the evaluated period and all six calculations is displayed. To analyze the risk for mold growth, hourly values of RH and temperature were extracted from WUFI Pro 1D and analyzed, using the "m-model". The same position for analysis was chosen as the one for the "Dose model".

The Hagentoft model. A simplified method for risk assessment was introduced by C-E Hagentoft at the 3rd Nordic Passive House Conference 2010 (Hagentoft 2010). The model uses a non-dimensional temperature factor, ξ , to calculate the RH at any point in a construction. For each month the calculated RH was divided by RH_{crit} . The highest value within each three-year period, 1985-1987, ..., 2096-2098, is presented. The specific position who was examined was the same as for the analysis conducted with the "Dose model" and the "m-model".

WUFI Bio. In addition to the software WUFI Pro, a plug-in to assess the risk of mold growth is available; WUFI Bio. This model is different from models described above. Within the model a hypothetical mold spore is given characteristics of sorption of water and diffusion of water vapor. If the water content within the mold spore exceeds critical levels (Sedlbauer 2001), mold growth is initiated. The pace of mold growth is related to the level water content. The model is thoroughly described in (Sedlbauer 2001; Sedlbauer 2003). The result of the evaluations is presented on a seven-point scale defined by (Vitanen and Ritschkoff 1991). The position of analysis was the same as used for the other models. The substrate class chosen was class 1, which corresponds to building products made out of biologically degradable materials.

RESULTS

Climate scenarios

Summarized results from the climate scenario for the different locations are presented in Figures 3-5. For each location, the effect on temperature, precipitation and wind is presented based on five different indicators. Comparing the reference year, 1961-1990, to the average year for future climate, 1985-2100, the difference between them is small. The increase of temperature varies between 0.6 and 3.4°C (1.1 and 6.1°F). However, examining the maximum increase or decrease of temperature; the highest increase may be as high as 9°C/16.2°F, and decrease 7°C/12.6°F. The increase in temperature is slightly higher at northern latitudes.

The monthly average wind speed and maximum offset compared to reference year are considerably higher at location A compared to the other examined locations. At all locations the wind speeds are higher in winter compared to summer. A very small increase of average wind speed is expected in the examined climate scenario.

The monthly average precipitation is increasing at all locations. The maximum monthly average is expected in fall at all locations, exceeding 200 mm of precipitation.

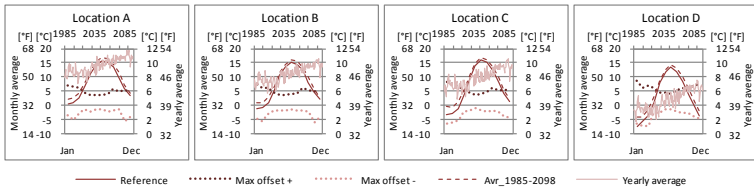


Figure 3 Climate scenario; Temperature. All data, except Yearly average, refer to the bottom x-axis and left y-axis. Yearly average refers to the top x-axis and right y-axis.

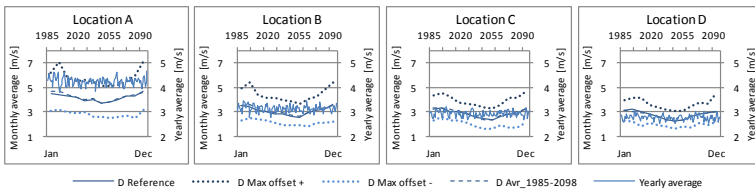


Figure 4 Climate scenario; Wind. All data, except Yearly average, refers to the bottom x-axis and left y-axis. Yearly average refers to the top x-axis and right y-axis.

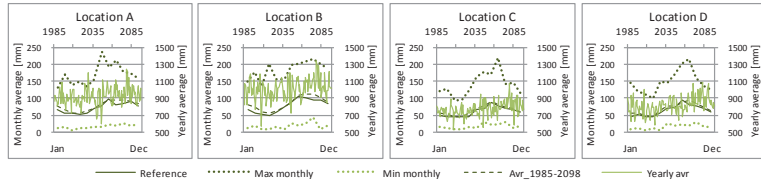


Figure 5 Climate scenario; Precipitation. All data, except Yearly average, refers to the bottom x-axis and left y-axis. Yearly average refers to the top x-axis and right y-axis.

Results from the case study

Evaluations of hygrothermal conditions are presented in Figures 6-9. In these figures, 1A-1D represents the standard wall assembly. 2A-2D represents Alternative 2 where insulation was added on the interior side of the wood frame construction. Furthermore, 3A-3D represents Alternative 3 where insulation was added both on the interior and exterior side of the wood frame construction. For all wall assemblies the suffix A-D represents the specific location.

The highest calculated relative mold dose, D, for each three year period, location and wall assembly is presented in Figure 6. Using the “Dose-model” to analyze the hygrothermal conditions, the conditions for mold growth is increasing over time regardless of location and construction. The increase is somewhat more evident in the wall assembly where more insulation is added to the interior side of the wood frame construction.

When adding more insulation to the exterior side of the wood frame construction, more stable hygrothermal conditions occur. For the worst conditions, location B, the mold dose decreases even though more insulation is used in the construction. For the other locations the mold dose is increasing when more insulation is added. For location A and B, adding insulation to the exterior side of the wood frame construction decrease the mold dose compared to adding insulation to the interior side.

The CDQ, calculated using the m-model, shows a small increased risk of mold growth for the standard wall assembly over time for location A, see Figure 7. However, except for three simulations, $CDQ \leq 1$ for all simulations. For location C and D; the CDQ is low, except for three simulations where $CDQ \geq 1$. For C and D; the CDQ is decreasing over time for the standard wall assembly. For location B, all simulations result in $CDQ \geq 1$ and the increase of CDQ is clear for this location.

Except for location B, adding more insulation results into a clearer trend of increasing CDQ over time. For location A, the CDQ is lower if exterior insulation is used but CDQ exceeds 1 roughly around year 2030. At the more northern latitudes, C and D, CDQ is always below 1 regardless of construction chosen and examined year.

Comparing results based on “Dose-model” and “m-model”, adding insulation to the exterior side of the wood frame construction result in more stable hygrothermal conditions for all locations. For unfavorable climate with high RH, location B, a clear decreased risk of mold growth is also shown.

The highest mold index from WUFI Bio for each simulation is displayed in Figure 8. In this evaluation, the increase of mold is clearer over time compared to previous evaluations, especially when more insulation is added. This evaluation confirms the previous conclusion; adding insulation to the exterior side of the wood frame construction is especially favorable in location B. However, for all locations the mold index is lower in alternative 3 compared to alternative 2. In locations C and D. Mold index is almost always < 1 , regardless of wall assembly.

The Hagentoft model, based on monthly averages, shows increased risk of mold growth over time based on the climate scenarios. Furthermore, it indicates that exterior insulation is preferable in location A but has little effect on other locations.

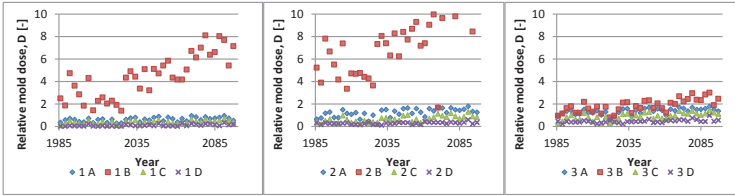


Figure 6 Evaluation of hygrothermal conditions using the "Dose-model".

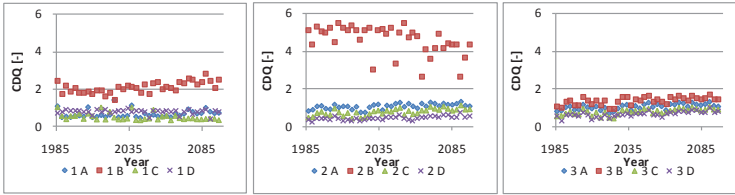


Figure 7 Evaluation of hygrothermal conditions using the "m-model"

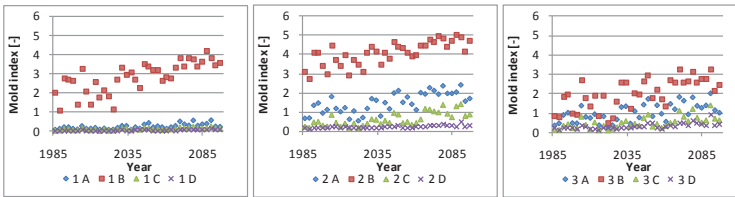


Figure 8 Evaluation of hygrothermal conditions using WUFI Bio

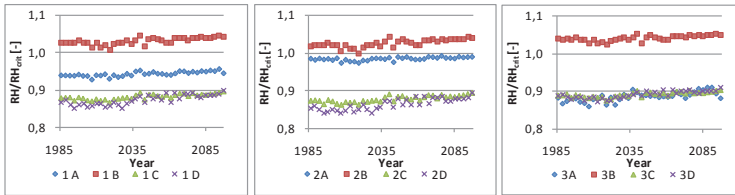


Figure 9 Evaluation based on the Hagantoft model

For location A and B, the risk of mold growth is high, regardless of wall assembly. To investigate the effect of built in moisture, the accumulated mold dose was studied in detail for location A and location B, the most unfavorable locations. The period was chosen to 2048-2050. The accumulated mold dose, D , is presented in Figure 10.

At location A, the built in moisture affects the accumulated mold dose, which rather fast exceeds the critical condition of 38 days. When more insulation is added, the dehydration of the construction takes longer time, resulting in a long period for which the accumulated mold dose exceeds 38 days. However in spring 2050, when unfavorable conditions once more occurs; the wall assembly with exterior insulation gets the lowest accumulated mold dose.

At location B, the exterior climate has a high relative humidity and lower temperature over the period. The built in moisture therefore takes longer time to dry out. The consequence is high accumulated mold dose. However, the wall assembly with exterior insulation, 3B, shows a slowly decreasing mold dose. Furthermore, when the very unfavorable conditions occur in spring 2050, the exterior insulation ensures that accumulated mold will not increase as much as for alternative 1 and alternative 2.

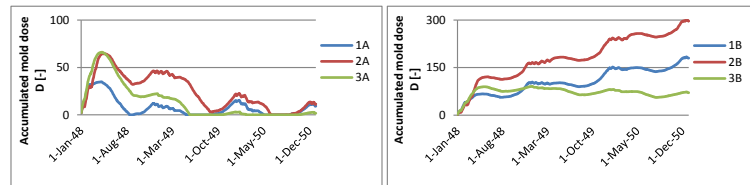


Figure 10 Accumulated mold dose for location A and B, wall assemblies 1, 2 and 3

DISCUSSION AND CONCLUSIONS

This paper is based on one climate scenario. Other climate scenarios may show similar or different results. Furthermore, a climate scenario is not a forecast, i.e. it is not the expected climate conditions, it is a climate scenario. All results in this paper must be interpreted with this in mind. However, some conclusions may still be made.

The investigated scenario indicates that the ongoing climate change will most likely increase the risk of mold growth. Except for two evaluations, 1C and 2B, evaluated with the m-model, all other evaluations indicate increased risks for mold growth due to climate change.

At first a fist glance; the interpretations of the evaluations of different locations, using different evaluation models may be that increased amounts of insulation is equal to higher risks for mold growth. This is due to that values presented in Figures 6 - 9 are maximum values. Examining the hygrothermal conditions in detail, as in Figure 10; it is possible to see that the built in moisture is the major reason for high risks of mold growth. When the built in moisture has dehydrated; the wall assembly with insulation on the exterior side of the wood frame work, is the most robust wall assembly.

From this study, the major conclusions and recommendations are:

- There is a need to consider the effects of climate change in the design of buildings and building elements in cold climate.
- Within the construction phase of buildings, there is a need to implement all reasonable measures to decrease the amount of moisture, added in this phase.
- Construction materials based on bio gradable materials, e.g. wooden studs, should always be given exterior insulation to decrease the risk of mold growth.
- Building elements must be given the ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

Evaluations based on simulations with hourly data showed higher risks and larger spreading of the calculated risks. Therefore, more studies are recommended to gather climate scenario data with higher time resolution and where more parameters are included, e.g. relative humidity, cloud cover etc., suitable for hygrothermal simulations.

ACKNOWLEDGMENTS

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Conference paper 12

EVALUATION AND OPTIMIZATION OF A SWEDISH NET ZEB - USING LOAD MATCHING AND GRID INTERACTION INDICATORS

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ABSTRACT

Net Zero Energy Buildings, Net ZEBs, is one of many necessary measures for climate change mitigation as they may reduce the energy consumption in the building sector. The Net ZEB interacts with a grid infrastructure. It is therefore important to consider the interaction with the grid in the design phase.

This paper reports an evaluation of a proposed design of a Net ZEB in the south of Sweden evaluating load matching and grid interaction using simulated data sets with hourly resolution. The aim was to find a design with as high load matching and as low grid interaction as possible.

The results show difficulties of achieving a high load matching between the building load and on-site generation, due to the Nordic climate and the relatively low loads during daytime, when the availability of solar energy is high. The building is likely to accomplish the goal of a Net ZEB balance. If higher flexibility is sought, a larger energy storage should be considered.

INTRODUCTION

Buildings today account for 40% of the world's primary energy use and 24% of the greenhouse gas emissions (IEA, 2010). The building sector is expanding. Therefore, reduction of energy use and the use of energy from renewable sources in the buildings sector constitute important measures required to reduce energy dependency and greenhouse gas emissions.

Today a number of buildings exist where the design principle has been to construct a Net Zero Energy Building, Net ZEB (IEA, 2012). The definition of a Net ZEB may differ, usually it is referred to as a building that provides as much energy as itself uses but interacts with an energy supply system and can export energy when the building's system generates a surplus and import energy when the building's system not supply the quantities of energy required.

To design and build a well functioning Net ZEB that interacts with an existing grid, it is important to consider the interaction with the grid in the design

phase. One reason for this is that self-consumption of on-site generation is generally more economically favourable than selling the surplus, in the absence of generous feed-in tariffs. Lower overproduction also lowers the load on the grid and increases the so-called hosting capacity of the grid.

The design may be evaluated by using quantitative indicators to describe load matching and grid interaction (LMGI), where load matching refers to how the local energy supply compares with the building load and grid interaction refers to the energy exchange between the building and the grid. The terminologies are further described in (Voss et al., 2010), (Salom et al., 2011) and (Sartori et al., 2012).

One of the most vital features that LMGI indicators may grasp is the flexibility of a building (Salom et al., 2011). The term flexibility here defined as a building's ability to respond to actions from the residents or the grid; adjusting in order to minimize the stress to the grid. This flexibility could be quantified using suitable LMGI indicators, especially those indicators that provide significant differences if a feed-in strategy is used, prioritizing export of energy from a building to the grid, or if the opposite, load matching is prioritized, trying to match the varying need of energy for a building by energy from renewable sources produced on-site or nearby.

(Voss et al., 2010) concludes that a monthly resolution could be an appropriate level on which load matching and grid interaction could be examined in order to characterise differences between projects and solution sets. In a literature review, (Salom et al., 2011) found 14 different LMGI indicators, which they divided into four different categories. The different LMGI indicators were evaluated for a building with and without a battery for storage. The evaluation showed that some indicators are affected by the use of battery storage, but not all. The study concludes that LMGI indicators may add significant value to the output of building performance tools, and give a more complete picture of Net ZEBs.

In the recently published article by (Sartori et al., 2012) the focus is to describe a consistent framework for Net ZEB definitions to make it possible to define

consistent and comparable Net ZEB definitions. Within the framework LMGI indicators are addressed.

In Sweden, Skanska Sverige AB has developed a concept for a Net ZEB. However, the load match and grid interaction has not been considered. Therefore, LMGI are considered in this study. The study does not include so called demand side management, DSM.

In addition to studies mentioned above, there are several other studies investigating the impact of on-site generation. Examples may be found in (Hawkes et al., 2005), (Peacock et al., 2006), (Kelly et al., 2008) and (Widén et al., 2009). However, these do not use the terminology; LMGI indicators. LMGI indicators used in this study are originating from (Voss et al., 2010), (Salom et al., 2011) and (Sartori et al., 2012).

Numerous studies has been done on modelling Net ZEBs and the feasibility of different tools. The feasibility of different tools is not within the scope of this study.

The nomenclature section at the end lists the symbols used in this paper.

SIMULATIONS

The case study

The proposed building is a five dwelling terraced house, situated in the city of Malmö in the south of Sweden. The building has a large roof and facade towards south-southwest with integrated PV modules. On the top of the roof, which is horizontal, solar thermal collectors are mounted. They are not integrated. The characteristics of the building are presented in Figure 1 and Table 1. The building is designed to be connected to the electricity grid and district heating network.

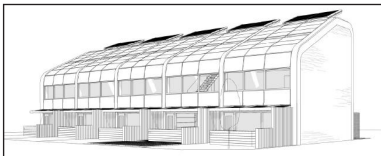


Figure 1 Proposed design of case study building.

Table 1 Characteristics of case study building

CHARACTERISTIC	DATA	UNIT
Orientation of facade and roof with PV (180° = south)	200	°
Slope of roof	20	°
A_c , Conditioned area	703	m ²
$g_{des, PV}$, Installed PV capacity	34	kWp
A_{ST} , Solar thermal collector	108	m ²

In the proposed design, no energy storage is installed in the building; E.g. no battery and no hot water storage tank. Instead, the building relies on the grid and will therefore always export energy when the building's system generates a surplus and import energy when the building's system does not produce the quantities of energy required. However, the district heating network only accepts the building to export heat from the solar thermal collectors when the mean fluid temperature from the solar thermal collector exceeds 75°C. The possibility to export the surplus of the heat to the district heating network has previously been implemented in both residential and non residential buildings in Malmö (City of Malmö, 2007), (Isaksson et al., 2007) and (Eon Energy, 2011).

To investigate LMGI factors, whether it is possible to reduce the building's need for delivered energy and to reduce the peak load, seven different options were examined. The options are described in Table 2. After studying all options, an eighth option was tested, seeking a "best option", based on the results from the previous options. The strategy were to increase load matching, decrease the amounts of exported heat during the summer, due to the low need of heat during summer.

Table 2 Description of investigated options

	DESCRIPTION
1	Instalment of battery, $SC_{battery}$, 50 kWh
2	Instalment of hot water storage tank, $V_{Storage tank}$, 0.75 m ³ /dwelling. The ability to export heat to the district heating network is terminated
3	1+2+ Decrease of A_{ST} 50%, increase of $g_{des, PV}$ 20%
4	Orientation of building -20°
5	Orientation of building -40°
6	Slope of roof and solar thermal collectors +20°
7	Slope of roof and solar thermal collectors +40°

Method

Hourly data sets were generated by simulations, using VIP Energy (Strusoft, 2012). Figure 2 gives an overview of the energy flows and terminology used in this case study.

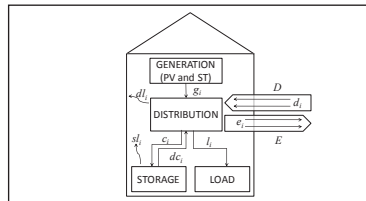


Figure 2 Schematic presentation of energy flows addressed in this study.

To enable analysis in hourly resolution, profiles for electric load for lighting and plug loads, hot water and occupancy were created based on (Bagge, 2011), (Bernardo, 2010) and (SCNH, 2012). The peak load was set to 1.1 kW/dwelling for hot water and 770 W/dwelling for lighting and plug loads. In Figure 3 and Figure 4, the relative load profiles are presented. The maximum internal heat gains from occupancy presence were set to 1.2 W/m² with a daily variation as presented in Figure 5. The occupancy presence is assumed not to have a seasonal variation.

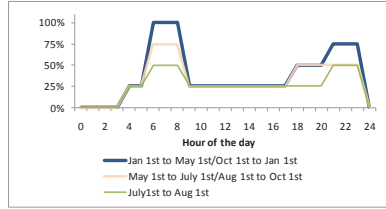


Figure 3 Load profile; hot water.

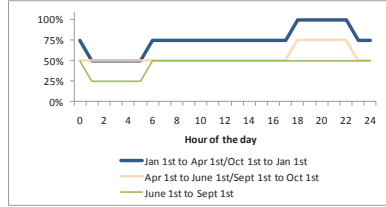


Figure 4 Load profile; lighting and plug loads.

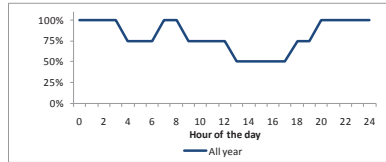


Figure 5 Relative occupancy presence

The chosen software does not include a model for storage losses in batteries. Furthermore, it does not consider distribution losses for heating. These were addressed by applying Equation 1 and Equation 2.

$$s_{electricity} = 0.01s_{electricity}(t) \quad (1)$$

$$d_{heating} = 0.05d_{heating}(t) \quad (2)$$

The yearly import/export balances were calculated as in Equation 3.

$$\sum_i e_i w_i - \sum_i d_i w_i = E - D \quad [\text{kWh/m}^2\text{a}] \quad (3)$$

The yearly load/generation balance were calculated as in Equation 4.

$$\sum_i g_i w_i - \sum_i l_i w_i = G - L \quad [\text{kWh/m}^2\text{a}] \quad (4)$$

Differences between import/export balance and load/generation balance is expected due to the fact that there will be some self-consumption of energy within the building and storage losses. These two facts reduce the amounts of imported and exported energy, compared to load and generation. Weighting factors, w_i , may differ if asymmetric weighting is preferred (Sartori et al., 2012). However, the Swedish definition of a Net ZEB requires symmetric weighting (SCNH, 2012). The applied weighting factors are according to (SCNH, 2012);

- $w_{electricity} = 2.5$
- $w_{heating} = 0.8$

This study includes all delivered and exported energy to the building, as defined in EN 15217 (SIS, 2007), in contradiction to the Swedish definition of a Net ZEB, which excludes plug loads and appliances (SCNH, 2012). The temporal match between load and generation for electricity and heat were investigated using the *load match index*, which describes the ratio of on-site power generation and load. The definition is described in Equation 5. The load match index was calculated both for heat and electricity on three different time intervals; hourly, daily, and by year. When energy is fed into the grid, the load match index is 100%. Regarding the load match index, a high index is preferable if a high on-site coverage of the energy demand is desired.

$$f_{load,i,T} = \min \left[1, \frac{g_i + dc_i - c_i}{l_i} \right] \quad [\%] \quad (5)$$

To assess the interaction between the building and the electricity grid and district heating network the grid interaction was investigated. The grid interaction is based on the ratio between the net metering (e.g. exported - delivered energy) compared to the maximum exported - delivered energy over a given time period, as shown in Equation 6. Three different time intervals are investigated; hourly, daily and monthly.

$$f_{grid,i,T} = \frac{e_i - d_i}{\max|e_i - d_i|} \quad [\%] \quad (6)$$

It may be argued that both numerator and denominator in Equation 6 should be in absolute terms. However, by not using absolute numbers, the quota shows whether the building exports or import energy. A positive value describes a net exporting building. The average stress on the grid was investigated by calculating the *grid interaction index*. This is defined as the standard deviation of the grid interaction over the year, as shown in Equation 7.

Regarding the grid interaction index, low standard deviations are preferable.

$$f_{grid,i,year,T} = STD(f_{grid,i,T}) \quad (7)$$

To quantify the stress on the grid, peak export and import for each energy carrier were calculated as well as the duration of high load as in Equation 8 and Equation 9. Low peak loads are preferable.

$$e_{i>lim} = \frac{time_{e_i>lim}}{8760} \quad [\%] \quad (8)$$

$$d_{i>lim} = \frac{time_{d_i>lim}}{8760} \quad [\%] \quad (9)$$

RESULTS

In Table 4, a summary of all calculations is shown. Based on the studied options, the proposed best option is to:

- Increase the slope of the roof/PV and solar thermal collectors by 20°
- Rotating the building -20°
- Increasing the PV, $g_{des\ PV}$, by 10% + instalment of battery, $SC_{BATTERY}$ 50 kWh
- Reducing solar thermal collectors, A_{ST} , by 50% + instalment of hot water storage tank, $V_{Storage\ tank}$, 0.75 m³/dwelling. The ability to export heat to the district heating network is terminated

Note that the increase of PV, $g_{des\ PV}$, is only increased by 10% compared to previous investigated option 3; 20%. It is assumed that a 10% increase is enough to reach a Net ZEB balance without increasing the peak load for exported electricity, compared to option 3. Hence, the orientation of the building and roof slope is now more favourable.

The import/export balance and load/generation balance is graphically presented in Figure 6 and Figure 7. Note that the scale in Figure 6 is different and the intersection for the axes is at 110 kWh/m²a. The configuration is chosen to enable the possibility to grasp differences between the options. Of the investigated measures, all except measures 2 and 7 meet the basic requirement of a positive load/generation- and import/export balance.

Examining the load match index for electricity, in Table 4, the index does not show significantly different values for the different options investigated. Since it is the minimum value presented for load match, the value is zero or close to zero due to the low availability of solar energy in winter.

A small increase of load match, based on monthly resolutions, is seen when the slope of the roof/PV is increased by 20° and the installed kWp of PV is increased. Introducing a battery does not increase the load match index. However, the grid interaction index based on hourly resolution, peak load for exported electricity and duration of high load for

exported electricity decreases slightly when a battery is used.

The option to terminate the ability to export heat to the district heating network and instead install a hot water storage tank reduces the yearly load match for heat, from 74 % to 25 %, and increases the grid interaction index based on hourly resolution, from 18 % to 23 %. The grid interaction based on daily and monthly resolution decreases from 44 % to 29 % and 70 % to 41 % respectively. Furthermore, as a corollary; peak load for exported heat, and duration of high load for exported heat, drops to zero.

The monthly load distribution, exported energy, load match and grid interaction were investigated further in order to discern differences between the most interesting options; base case, option 1, option 2 and “best option”. The results are presented in Figure 8. The small differences in monthly load match and grid interaction for electricity is not possible to discern in the resolution used in Figure 8.

The instalment of a hot water storage tank in each dwelling and terminating the ability to export heat to the district heating network is clearly shown. The graphic load match profile and grid interaction are similar for option 2 and “best option”, even though A_{ST} is reduced by 50% in the latter option.

In contradiction to the difficulties to distinguish differences in the monthly load match and grid interaction profiles for electricity, examining the monthly load distribution and exported energy shows differences when battery storage was installed. Roughly, the instalment of a battery allows the building not to import electricity during the period May-August. The monthly quantities of exported electricity were also reduced during the period. Comparing the base case and the first option, the reduction is almost 1 MWh/month.

Increasing PV by 10% + instalment of a battery results in roughly the same quantities exported electricity monthly, compared to the base case during the same period. When hot water storage tanks were installed in the dwellings, the need for heat from the district heating network during the summer was significantly reduced. During the period May-August the need was nearly zero, compared to the base case, a reduction of roughly 1 MWh of heat/month. As mentioned earlier exported heat is reduced to zero.

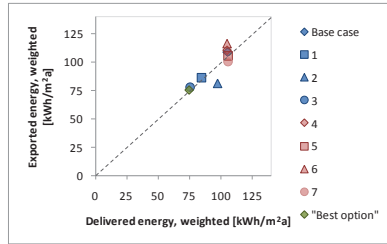


Figure 6 Import/export balance for the investigated options

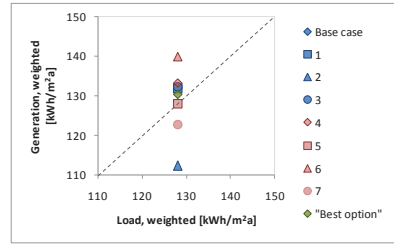


Figure 7 Load/generation balance for the investigated option

Table 4
Summary of energy balance and LMGI indicators for all investigated options

INDICATOR	BASE CASE	OPTIONS							BEST OPTION
		1	2	3	4	5	6	7	
Import/export balance [kWh/m²a, weighted]	4	2	-16	2	5	0	12	-5	1
Load/generation balance [kWh/m²a, weighted]	4	4	-16	4	5	0	12	-5	2
$f_{load, electricity, hourly}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, electricity, daily}$ [%]	1%	1%	1%	1%	1%	1%	1%	1%	1%
$f_{load, electricity, monthly}$ [%]	4%	4%	4%	5%	4%	4%	5%	4%	5%
$f_{load, electricity, yearly}$ [%]	100%	100%	100%	100%	100%	100%	100%	100%	100%
$f_{load, heat, hourly}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, heat, daily}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, heat, monthly}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, heat, yearly}$ [%]	74%	74%	25%	23%	75%	72%	78%	69%	24%
$f_{grid, electricity, year, hourly}$ [%]	22%	19%	22%	20%	22%	22%	22%	22%	20%
$f_{grid, electricity, year, daily}$ [%]	42%	42%	42%	40%	42%	42%	41%	43%	40%
$f_{grid, electricity, year, monthly}$ [%]	65%	65%	65%	60%	65%	66%	63%	68%	60%
$f_{grid, heat, year, hourly}$ [%]	18%	18%	23%	23%	18%	18%	18%	18%	23%
$f_{grid, heat, year, daily}$ [%]	44%	44%	29%	29%	44%	45%	43%	46%	29%
$f_{grid, heat, year, monthly}$ [%]	70%	70%	41%	41%	70%	68%	72%	67%	41%
$e_{max, electricity}$ [kW]	37	36	37	44	37	35	39	34	43
$e_{max, heat}$ [kW]	61	61	0	0	61	59	64	56	0
$d_{max, electricity}$ [kW]	4	4	4	4	4	4	4	4	4
$d_{max, heat}$ [kW]	16	16	16	16	16	16	16	16	16
$e_{electricity > Lim 20 kW}$ [%]	6%	5%	6%	7%	6%	6%	7%	5%	7%
$e_{heat > Lim 20 kW}$ [%]	6%	6%	0%	0%	7%	6%	7%	6%	0%
$d_{electricity > Lim 5 kW}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$d_{heat > Lim 10 kW}$ [%]	5%	5%	5%	5%	5%	5%	5%	5%	5%

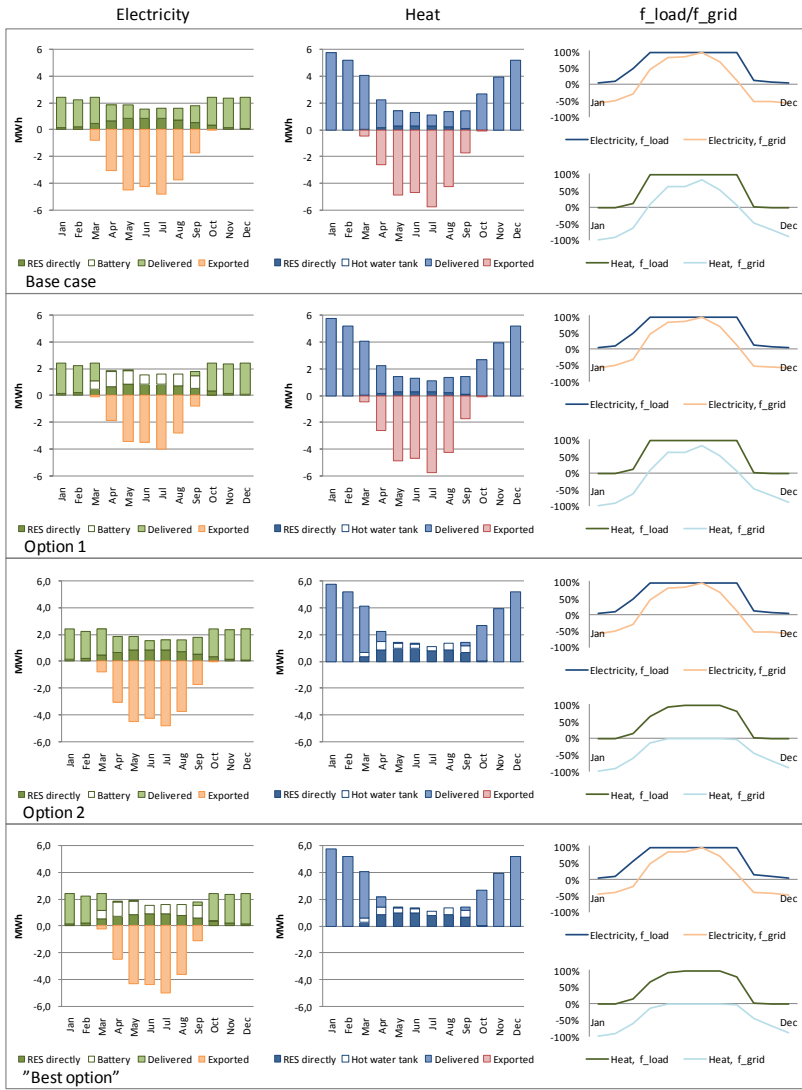


Figure 8 Monthly load distribution and exported energy for electricity (left column) and heat (middle column). Monthly load match and grid interaction for electricity and heat in the right column. Base case, option 1, option 2 and "best option" are presented.

DISCUSSION AND RESULT ANALYSIS

The results show the difficulty of achieving a high load match for the studied building when the evaluated resolution is lower than one year. The cause is mainly due to two aspects. The first aspect is the fact that the building is situated in a Nordic climate where the heating demand is high in winter when the available solar energy is low. The second cause is that the building is designed for dwellings and therefore assumed to have relatively low loads for plug loads, lighting and hot water during daytime, when the availability of solar energy is high.

Introducing small energy storage systems, e.g. hot water tanks or batteries, results in small effects on load match and grid interaction. This indicates a need for larger energy storages in a Nordic climate if a higher flexibility of buildings is desired. Architectural changes (e.g. slope of roof) and adjustment to the location (e.g. orienting the building towards south) shows small or no effect on the building's flexibility (e.g. LMGI indicators). However, it affects the Net ZEB balance.

The used indicator for load matching presents the minimum load match over a period. If an average (e.g. arithmetic mean) load match had been calculated, there might have been greater difference between the options. However, an average load match would not grasp the flexibility of a building. It would rather show an indication of a load match, possible to achieve if the ability to store energy within the building would have been sufficient.

If the goal is that the building should not export heat to the district heating network and still achieve Net ZEB balance, this is possible by redesigning the building as described in the "best option". However, if heat and electricity would have the same weighting factors, the PV yield would not be enough.

(Salom et al, 2011) concludes that a higher resolution is needed, probably less than ten minutes, to capture a dynamic behaviour of a building, especially regarding peak load and generation. Other studies, mentioned in the introduction (Hawkes et al., 2005), (Peacock et al., 2006) and (Kelly et al., 2008), shows that load and generation fluctuates at a much higher resolution than one hour.

A recent study compared simulations based on one-minute resolution and one-hour resolution for PV yield in combination with electric load profile for a residential house (Widén et al, 2010). This study shows that the differences in matched, exported and imported electricity only give overall differences in order of a few percent, when the resolution is improved from one-hour to one-minute. (Widén et al, 2010) concludes that the difference would have an insignificant impact on the calculations conducted within their study.

Based on the previous studies it may be concluded that hourly resolution is sufficient to grasp the load

match for solar energy in the design phase. However, to thoroughly study peak loads and on site generation, a higher time resolution is needed. Especially if micro-combined heat-and-power systems are included.

One-hour resolution may be sufficient when a proposed building is in the concept design stage. A higher resolution should be used, when the building design is defined more in detail. Furthermore, the proposed best solution should be subject to a sensitivity analysis before final decisions, regarding the design of the building and on site generation, are made.

CONCLUSIONS

This work presents the Net ZEB balance and flexibility of a Net ZEB residential building designed to be built in Sweden. The building is likely to achieve a Net ZEB balance. However, the proposed "best option" may be a more suitable design, reaching the Net ZEB balance without exporting heat to the district heating network in summer.

If a higher flexibility is required, a larger energy storage should be considered. Energy storage has previously been determined to have the best potential of achieving a better match between load and production in terms of solar fraction, i.e. load match (Widén et al, 2009).

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NOMENCLATURE

<i>A</i>	Area
<i>c</i>	Charging energy to storage
<i>d</i>	Delivered energy
<i>D</i>	Delivered energy, weighted
<i>dl</i>	Distributions losses
<i>dc</i>	Discharge energy from storage
<i>e</i>	Exported energy
<i>E</i>	Exported energy, weighted
<i>f_{grid}</i>	Load match index
<i>f_{load}</i>	Grid interaction index
<i>g</i>	Generated energy
<i>G</i>	Generated energy, weighted
<i>i</i>	Energy carrier
<i>l</i>	Load
<i>L</i>	Load, weighted
<i>lim</i>	Desirable limit
<i>PV</i>	Photovoltaic

<i>S</i>	Stored energy
<i>SC</i>	Storage capacity
<i>sl</i>	Storage losses
<i>ST</i>	Solar thermal
<i>t</i>	Time step, 1 hour
<i>T</i>	Evaluation period, hourly, daily, etc
<i>V</i>	Volume
<i>w</i>	Weighting factor

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Conference paper 13

Profitable Net ZEBs – How to break the traditional LCC analysis

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Abstract

Global warming and an increasing population needing more buildings are important issues ahead. Hence, Net ZEBs and green buildings is one of many necessary measures for climate change mitigation. Some studies indicate that improved energy and/or green performance in these buildings may not be profitable. However, a short time perspective and narrow concept for evaluation may be wrong. This study presents two different built Net ZEBs in Sweden, with verified plus energy performance in user phase. Furthermore, it presents an economic analysis, based on life cycle costing (LCC), where additional green values are included in the analysis. The study shows that the, discounted, cumulative annual cost reductions due to green values exceed the initial extra cost after roughly five years. More research should be carried out in order to develop the methods and equations presented here and to gain more knowledge regarding reduced employee turnover, reduced sick absence, increased productivity, etc. in green buildings.

Keywords: Net Zero Energy Building; Life Cycle Costing; Net ZEB; LCC

1. Introduction

The IPCCs first working group, states unambiguously through observations and measurements that there is a warming of the climate system [1]. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

Energy use in buildings accounts for 24 % of the generation of greenhouse gases and 40 % of the primary energy use [2]. The population, and the need for buildings, on the planet is increasing. Hence, Net Zero Energy Buildings, Net ZEBs, is one of many necessary measures for climate change mitigation as they may reduce the fossil energy use in the building sector. The number of low-energy buildings and Net ZEBs has increased significantly over the past years in Sweden [3].

Net ZEBs are usually also “green buildings”, which here are referred to as buildings with high performance within the aspects of energy, thermal comfort, indoor air quality, building materials etc.

Despite that construction of Net ZEBs and other low-energy and/or green buildings has been proven possible; it was, by the Swedish government, suggested to forbid the possibility for municipalities in Sweden to set tougher energy requirements for new construction, than the requirements in the national building regulations in 2013 [4]. The suggestion was based on a Swedish

Government Official Report, “Byggrävsutredningen” [5], stating that calculated incurring additional costs, 10-15 %, are unprofitable. Based on this, the Swedish law: Planning and Building Act (2010:900) were changed in 2015, prohibiting municipalities in Sweden to set tougher energy requirements than the requirements in the national building regulations.

To design and construct buildings with additional insulation, more energy efficient HVAC-systems etc. are usually coupled to increased investment costs. However, several other studies and evaluations estimates the additional costs to 0-10 % [6-8], to design and construct buildings with significantly better energy performance than in the mentioned official report [5].

The energy tariffs in Sweden are relatively low today. Hence, it is usually difficult to justify decisions such as investing in more insulation and energy-efficient HVAC-systems if the measures need to be profitable based on a short time perspective. Furthermore, it may be hard to value other aspects that may be included in green buildings.

A short time perspective and a narrow concept for evaluating profit, only focusing on increased investment costs and decreased energy costs, may be wrong. This may be wrong not only from a socio economic perspective, but also from a strict business perspective. By broadening boundary conditions for the traditional economic framework, the economic conclusion may be completely different compared to the Swedish Government Official Report [5].

This paper presents two green Net ZEBs in Sweden and cost analyses, showing a slightly different way to evaluate the

profitability of investment. This study does not claim to verify green value in these buildings. Rather, it shows how these values may be quantified.

2. Added value in green buildings

Quantifying added value in green buildings in monetary terms, except for energy savings, may be complex. Nevertheless, attempts to include increased productivity, reduced turnover and reduced absenteeism has been carried out, for example by James Scott Brew [9]. The calculation procedure in itself may not be complex, but the research on green buildings and environmental and green benefits is still in its early stage. I.e. well proven statistic-based input data for the calculations are not always easy to find. However, studies do exist that may be used as a basis [10-14].

An American study showed that 19 % of 534 tenants/companies in green buildings reported lower employee turnover [10]. Furthermore, roughly 20-25 % of the tenants/companies also reported higher employee morale, easier to recruit employees and more effective client meetings.

Regarding productivity in green buildings, studies show that employees in green buildings perceive a positive effect of their work environment and productivity in green buildings [11-13]. Furthermore, reduced absenteeism has also been found [12, 13]. However, a recent study highlights that social factors are significantly more important from a monetary perspective, than environmental factors [14].

Three additional “values” are worth mentioning. Firstly, it is “publicity for free”. The value of a positive news article about a specific building or a specific project should be comparable to advertising costs in the specific source, in which the article is published. Secondly, in Sweden, green incentives may be given from municipalities for projects with high green ambitions, such as the possibility to buy land for development, reduced land prices, reduction of administration costs for building permits and shortened process time for building permits. A recent study [15] found that 40 % of the municipalities in Sweden applies promotion measures in order to increase the share of green buildings and 13 % applies green incentives in monetary terms.

3. Introduction to the case studies

Two Net ZEB case studies are included in this study; one office building and one residential building. The Net ZEB balance is based on the Swedish building regulations, excluding energy use for plug loads and lighting.

The office building is located in the south of Sweden, Väla Gärd, see Fig 1. The building consists of two main buildings with double pitched roofs, connected by a smaller building with a flat roof. The smaller building serves as an entrance and reception. The building is designed according to the passive house design principle with an airtight and well-insulated building envelope and balanced mechanical ventilation with

heat recovery and variable air volume, based on temperature and CO2. Heat is supplied via a ground source heat pump, GSHP, connected to bore holes. During summer, the boreholes are used as a natural heat sink, free cooling is extracted by circulating the working fluid for the heat pump in the bore holes. Roof sides facing south-west are equipped with PV panels. A summary of the design is presented in Table 1. In addition to the Net ZEB performance, the building is also certified as LEED platinum [16], which includes high focus in indoor environment quality. The projects also had tough green goals for construction materials and waste such as 100 % recycling/reuse of waste from the building site, and 100 % non-hazardous chemicals and building materials. More technical information and results from measurements and verification may also be found in other publications [17-20].



Fig. 1 Väla Gärd, Office building in the south of Sweden

Table 1 Summary of technical description, Väla Gärd

Technical description	Data
Conditioned floor area	1 670 m ²
U-average, building envelope	U=0.26 W/m ² K
Air tightness, assumed (q ₅₀ /n ₅₀)	0.3 l/s, m ² / 1.0 h ⁻¹
Ventilation heat recovery	82 %
COP (heating/cooling)	3/20
PV-panels (area/kWp)	455 m ² /67.5 kWp

The office building, Väla Gärd, was taken into use in 2012 and the energy performance has been monitored, see Table 2. The measurements have not been normalized for deviating boundary conditions (e.g. external climate).

Table 2 Summarized energy performance, Väla Gärd (Sim = Simulated results, Meas. = Measured results)

Energy use	kWh/m ² a	
	Sim.	Meas.
Heating, cooling & auxiliary energy	19	14
Plug loads and lighting	29	26
PV-panels	38	41
Imported electricity	29	23
Exported electricity	19	24

The residential building is also located in the south of Sweden, see Fig 2. The building is one out of seven one-storey

terraced houses within the neighbourhood. All buildings are designed according to the passive house design principle with an airtight and well-insulated building envelope and balanced mechanical ventilation with heat recovery. The ventilation system has the capacity to double the air flow, which may be done manually or programmed to do based on relative humidity or temperature. Heat is supplied via a GSHP connected to bore holes. During summer, the boreholes are used as a natural heat sink, free cooling is extracted by circulating the working fluid for the heat pump in the bore holes. Each building was designed with 40 PV-panels mounted on the roof. A summary of the design is presented in Table 3. More technical information and results from measurements and verification may also be found in other publications [20-22].

In addition to the Net ZEB performance, the building is also certified as a "Svanen building" [23], which includes high focus on indoor environment quality, healthy construction materials and 100 % recycling/reuse of construction waste.



Fig. 2 Solallén, Residential building in the south of Sweden

Table 3 Summary of technical description, Solallén

Technical description	Data
Conditioned floor area	258 m ²
U-average, building envelope	U=0.17 W/m ² K
Air tightness, measured (q ₅₀ /n ₅₀)	0.21 l/s, m ² / 0.84 h ⁻¹
Ventilation heat recovery	90 %
COP (heating/cooling)	3/20
PV-panels (area/kWp)	66 m ² /10 kWp

The residential building, at Solallén, was taken into use in 2015 and the energy performance has been monitored, see Table 4. The measured results have not been normalized for deviating boundary conditions (e.g. external climate).

Table 4 Summary energy performance, Solallén (Sim = Simulated results, Meas. = Measured results)

Energy use	kWh/m ² a	
	Sim.	Meas.
Heating, cooling and auxiliary energy	30	28
Plug loads and lighting	30	22
PV-panels	31	36
Imported electricity	45	38
Exported electricity	16	24

4. Methodology

The profitability of the increased costs related to increased energy efficiency and green values related to the building were evaluated. The increased costs for production were compared to the value of energy efficiency and other green values, quantified as described in this chapter.

The value of reduced energy use and exported energy is described in Eq. 1 which summarizes reduced energy costs (REC). Future value of imported and exported energy is discounted into a net present value. REC is usually evaluated towards the capital expenditures related to the energy measure or measures. Within this model, costs for maintenance and replacement are not included.

$$REC = \sum \frac{EI \cdot \alpha + EE \cdot \beta}{\left(1 + \frac{r - i - \gamma}{1 + \gamma}\right)^t} \quad (1)$$

where *EI* is the reduced imported energy, α is its energy tariff, *EE* is the increased exported energy, β is its energy tariff, *r* is the nominal discount rate, *i* is the inflation rate and γ is the increase in energy tariffs.

In order to widen the economic concept, the net present value of five additional values may be quantified according to Eq. 2-6; reduced employee turnover costs (RETC), reduced sickness absence costs (RSAC), increased productivity value (IPV), public publicity value (PPV), reduced sickness absence salary (RSAS). Equation 1 and 6 may be used for a stakeholder who will invest in a residence building to live in. Equations 1-5 may be used for a stakeholder who will invest in a non-residential buildings for its own staff.

$$RETC = \sum \frac{\varepsilon \cdot Emp(RC + IC + RPC + LI + DC)}{(1 + R)^t} \quad (2)$$

where ε is the reduced employee turnover, *Emp* is the quantity of employees, *RC* is the recruitment cost per employee, *IC* is the introduction course for new employee, *RPC* is the reduced productivity cost (new employee and supervisor), *LI* is the lost income during vacancy, *DC* is the decommissioning cost and *R* is the discount rate, as presented in Eq. 7.

$$RSAC = \sum \frac{Emp \cdot 0.8SC \cdot \phi \cdot \kappa}{(1 + R)^t} \quad (3)$$

Where *SC* is the average salary costs per employee, ϕ is the average sickness absence, κ is the reduced sickness absence.

The reason for the reduction of the salary in Eq 3 is due to that wageworkers in Sweden usually get 80 % of their salary when they are on sick leave [24].

$$IPV = \sum \frac{Emp \cdot SC \cdot IP}{(1 + R)^t} \quad (4)$$

where *IP* is the increased productivity per employee.

$$PPV = \sum AIP \cdot AC \quad (5)$$

where *AIP* is article in press and *AC* is the advertising costs in the specific source (paper, internet, etc.).

$$RSAS = \sum \frac{WW \cdot 0.2S \cdot \phi \cdot \kappa}{(1 + R)^t} \quad (6)$$

where *WW* is the quantity of wageworkers in the household and *S* is the salary.

The reason for the reduction of the salary in Eq 6 is due to that wageworkers in Sweden usually get 80 % of their salary when they are on sick leave [24].

$$R = \frac{r - i}{1 + i} \quad (7)$$

Furthermore, as mentioned in the previous chapter, the value of lowered land price may also be included in an evaluation. As this usually occurs during the initial phase of a building process, there is no need to discount these values. I.e. no need for an equation to express the net present value.

Våla Gärd, the office building, were evaluated by quantifying REC, RETC, RSAC, IPV and PPV. Furthermore, the increased investment costs coupled to these savings were quantified.

Sollällén, the residential building, were evaluated by quantifying REC, RSAS and lowered land price (which was the case in this project). Furthermore, the increased investment costs coupled to these savings were quantified.

In Sollällén and Våla Gärd, productivity, sickness absence etc. were not measured. In order to enable quantification of green values, input data regarding reduced employee turnover, reduced sickness absence and increased productivity were based on previous studies [10-14]. Increased costs for the case studies, to achieve their green and Net ZEB targets, were gathered from the project managers in each project. Other data is gathered from Swedish literature and databases. The input data and results are presented in the next section. For all input data, except investments and energy performance, a base case data set is defined and presented together with an interval for sensitivity analysis.

5. Results and discussions

Boundary conditions regarding nominal discount rate, inflation, energy tariffs, changes in energy tariffs and period of analysis are presented in Table 5. Regarding nominal discount rate, governmental and municipal organizations usually have rather low requirements, 4-6 % [25]. However, private actors may have higher requirements. In this study we have chosen to set 7 % as the baseline.

The inflation is constantly changing. In Sweden, the national target is 2 % [26]. Hence, 2 % is chosen as a baseline.

Regarding energy tariffs, data show that the increase of energy prices over time in Sweden has been almost 4 %, not adjusted for inflation [27]. I.e. a lower value, 2 % is chosen. Energy tariffs are set to reflect Swedish conditions.

Table 5 Boundary conditions

Boundary condition		Input
Nominal discount rate, <i>r</i>	[%]	7 ±2
Inflation, <i>i</i>	[%]	2 ±1
Tariff for imported energy, <i>α</i>	[€/kWh]	0.12 ±0.02
Tariff for exported energy, <i>β</i>	[€/kWh]	0.10 ±0.02
Increase in energy tariff, <i>γ</i>	[%]	2 ±1

The office building, Våla Gärd, reported increased costs amounting to almost 450 000 € or 268 €/m², roughly an increase of 11 % of costs compared to if the office would have been a “normal office”. Increased production costs, consultants and certifications costs are included. The GSHP-system is not included in the increased costs, as it would have been required regardless of whether the building was to be green or not. Regarding investment costs, a state grant were given for the PV-panels, amounting to roughly 82 000 € or 49 €/m².

The residential building, Sollällén, reported increased costs amounting to almost 300 000 €. However, these costs represent increased costs for all seven buildings in the project. The increased cost per building were roughly 42 000 € or 164 €/m², roughly an increase of 8 % of costs compared to if it would have been a “normal residential building”. The same costs are included as in the costs for Våla Gärd. No state grants for PV-panels were given in this case. However, a municipal discount on land was given for projects who were designed as passive houses or better. In this case the discount amounted to 165 000 € for all seven houses or 92 €/m².

Reduced energy costs are based on measured values and calculated according to input data in Table 5.

Salary, *S*, and salary costs, *SC*, is based on average salaries in Sweden [28], which is roughly 3 765 €/month. Including costs for employers, the salary costs amounts to 6 325 €/month. No differences in salary for managers and other employees have been included. In total 70 persons are employed to work at Våla Gärd and 5 wage workers are expected to live in Sollällén.

Regarding reduced costs related to employee turnover for Våla Gärd, data is summarised in Table 6.

The average employee turnover in Sweden is 3.5 % [29]. Based on previous findings in reduced employee turnover [10], we assume that a reduced employee turnover of 0.5 % to 3.0 % is reasonable.

Based on an estimation of roughly two days of work, per recruited employee, and costs for advertising for new staff, the recruitment cost is summarised to 6 500 € per new employee. Furthermore an introduction course for each employee is expected to cost 2 000 €.

In order to summarise reduced productivity cost, a reduced productivity of 20% for two persons is expected for 6 months.

One person is the new employee the other person is one experienced co-worker who helps and guides the new employee.

Lost income during vacancy is based on a vacancy of 3 months, salary costs and nominal discount rate.

The decommissioning cost is based on an assumption of reduced productivity of the employee by 50 % after the person resigns for the remaining time of the employment.

Table 6 Basis for quantification of employee turnover costs

Data	Input
Reduced employee turnover, ε [%]	0.5 ±0.1
Recruitment cost, RC [$\text{€}\times 10^3/\text{p}$]	6.5 ±1.5
Introduction course, IC [$\text{€}\times 10^3/\text{p}$]	2.0 ±0.5
Reduced productivity cost, RPC [$\text{€}\times 10^3/\text{p}$]	15.1 ±5.0
Lost income during vacancy, LI [$\text{€}\times 10^3/\text{p}$]	1.3 ±0.3
Decommissioning cost, DC [$\text{€}\times 10^3/\text{p}$]	9.5 ±1.5

Average sick absences in Sweden were six days per year in Sweden 2016 [30]. Based on previous findings of reductions of absenteeism [12, 13], we assume a reduced sickness absence of 10%, both for Väla Gärd and Solallén.

Table 7 Basis for quantification of sick absence costs

Data	Input
Average sickness absence, ϕ [d]	6.0
Reduced sickness absence, κ [%]	10 ±2.5

The quantification of increased productivity is based on the reduction of share of time were an employee does not perform value creating work. I.e. increased productivity. Based on previous findings [11-13], we estimate that the productivity may increase by 0.5 %, see Table 8.

Table 8 Basis for quantification of increased productivity

Data	Input
Increased productivity, IP [%]	0.5 ±0.25

Numerous articles were published about Väla Gärd. In total, ten publications about Väla Gärd were considered to have such a positive value that it could be considered to be equal to advertising. The corresponding cost were estimated to 3 500 € per article.

Based on the input data presented, the recurring cost reductions for Väla Gärd (REC, RETC, RSAC and IPV) amounts to roughly 69 000 €/year or 42 €/m²a. Regarding Solallén, the recurring cost reductions (REC and RSAS) amount to roughly 2 730 €/year or 11 €/m²a. The distribution of the summarised green values for the first ten years are presented in Fig 3. As can be seen, the cost reductions (CR) amount to a significant *relative share* in Solallén compared to Väla Gärd. This is mainly due to additional values in RETC, IPV and PPV for Väla Gärd which is not included in Solallén.

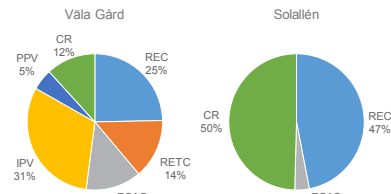


Fig. 3 Distribution of summarised green values for ten years. Väla Gärd (left) and Solallén (right)

The accumulated discounted value for the cost reductions in Väla Gärd and Solallén, normalised by conditioned area, is presented in Fig 4. For both buildings, a base case is presented together with a best case and a worst case. The accumulated value starts on a negative value which is due to the increased costs for green investments.

The accumulated green values, in the base cases, exceed the initial costs after roughly four and seven years for Väla Gärd and Solallén respectively.

The initial green investments, normalised by conditioned area, were roughly 60 % higher for Väla Gärd compared to Solallén. When the grants given by the state and the municipality are considered the difference increases to roughly 300%.

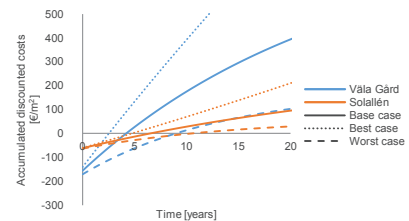


Fig. 4 Accumulated costs for investments and for green values in Väla Gärd and Solallén.

Since green values for increased productivity etc. are not included in Solallén, it takes a little longer time for the “payback”. Furthermore, one may argue that the cost reduction on the land given by the municipality is very important in this case. However, it would be possible to quantify more green values, which are not included here. E.g. increased value of building, less costs moving/changing homes (if one is satisfied with its home, one should stay there for a longer time) etc.

Previous studies exist for which co-incurring additional costs amounts to 0-15 % [5-8]. Here, the corresponding value is 8-11 %.

Results showing increased costs of 0 % are unlikely to be, due to the lack of investment to achieve "green performance". Probably, these projects have prioritized "green investment" and saved money in other parts of the project. Thus, the projects have not become more costly than expected.

Reduced employee turnover, reduced sick absence and increased productivity in this study is based on assumptions, i.e. should not be mistaken for verified results.

6. Conclusions

In this study we showed examples of how green values could be quantified in monetary terms. The study shows that it may be very profitable to build green buildings if one accounts for green values. Furthermore, it may be easier to find it profitable in non-residential buildings.

However, more research should be done in order to further develop these methods and to gain more knowledge regarding reduced employee turnover, reduced sick absence, increased productivity, etc. in green buildings.

Abbreviations

<i>AC</i>	Advertising cost
<i>AIP</i>	Article in press
<i>DC</i>	Decommissioning cost
<i>EE</i>	Exported energy
<i>EI</i>	Imported energy
<i>Emp</i>	Quantity of employees
<i>i</i>	Inflation
<i>IC</i>	Introduction course for new employee
<i>IP</i>	Increased productivity
<i>IPV</i>	Increased productivity value
<i>LI</i>	Lost income during vacancy
<i>PPV</i>	Public publicity value
<i>r</i>	Nominal discount rate
<i>R</i>	Discount rate
<i>RC</i>	Recruitment cost per employee
<i>REC</i>	Reduced energy costs
<i>RETC</i>	Reduced employee turnover costs
<i>RPC</i>	Reduced productivity cost
<i>RSAC</i>	Reduced sickness absence costs
<i>RSAS</i>	Reduced sickness absence salary
<i>SC</i>	Salary costs
<i>t</i>	Period of analysis
<i>WW</i>	Quantity of wage workers
α	Tariff for imported energy
β	Tariff for exported energy
γ	Increase in energy tariff
ϵ	Reduced employee turnover
κ	Reduced sickness absence
ϕ	Sickness absence

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Conference paper 14

A Net ZEB case study – Experiences from freezing in ventilation heat exchanger and measured energy performance

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Abstract. Net Zero Energy Buildings constitute one measure to reduce energy use and increase use of energy from renewable sources. Hence, it is important share knowledge and experiences from completed projects. This case study show that it is possible to build Net Zero Energy Buildings with existing techniques. However, a common strategy to prevent or limit the build-up of ice and frost in ventilation heat exchangers, Supply fan shut off, were not suitable this project, since it is air tight buildings. After occurring problems in the first winter, ventilation pre-heater were installed to prevent the build-up of ice and frost. Thanks to placement of temperature sensor after the pre-heater, the increased energy use for pre-heater may be expected to be low, roughly 1 kWh/m²a.

Keywords: Net ZEB, Energy use, Freezing, Ventilation.

1 Introduction

Buildings account for over 40 % of the primary energy use worldwide and 24 % of its greenhouse gas emissions [1]. The world's population is growing and also the need for buildings. Hence, reduction of energy use and increased use of energy from renewable sources are important measures for climate change mitigation.

Many studies identify a performance gap between predicted energy use and actual measured energy use once buildings are in user phase [2-10]. Hence, it is important that energy use in user phase is measured and verified to enable dissemination of knowledge. Especially in high performance buildings such as Net Zero Energy buildings (NetZEBs).

This study presents a Net ZEB neighbourhood in the south of Sweden with verified plus energy performance. The technical solutions used and measured energy performance is presented. Experiences from the user phase is shared, with focus on problems related to freezing in the ventilation heat exchanger.

2

2 The case study

The case study consists of seven one-storey terraced houses (three dwellings in each house), built in the southern part of Sweden, see Figure 1.

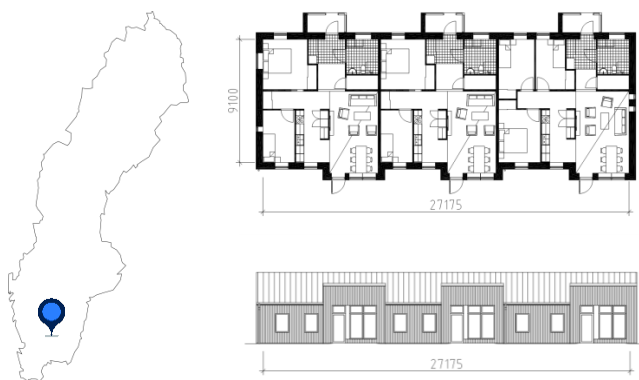


Fig. 1. Left: Location of case study in Sweden. Top right: Layout of terraced house. Bottom left: Facade facing south

The Net ZEB balance were reached in three steps:

1. Reduction of thermal losses by designing the buildings with an air tight and well insulated building envelope and using balanced mechanical ventilation with high heat recovery, heat recovery ventilation (HRV). The occupants has the possibility to increase the ventilation, manually or set point based. One HRV unit per dwelling.
2. Reduction of need for import of energy by choosing a ground source heat pump (GSHP) to cover space heating, via underfloor heating, and heating of water. During summer, free cooling is taken from the bore holes for the GSHP. Cooling is supplied via the ventilation system. One GSHP per building.
3. Generation of electricity by installing photovoltaic panels (PV-panels), on the roof facing south.

Simulations were conducted with VIP Energy [11], validated with ASHRAE 140 [12]. A summary of a technical description is given in Table 1 and results from simulations are presented in Table 2.

It shall be noted that weighting factors should be used in the Swedish NetZEB bal-

Table 1. Summary of technical description of case study. All values are design values except for air tightness.

Type of data/description	Value
Conditioned area	258 m ²
Enclosing area/conditioned area	2.88
Mean U-value for building envelope ¹	0.17 W/m ² K
Air tightness, measured (q ₅₀ & n ₅₀)	0.21 l/s, m ² & 0.84 h ⁻¹
HRV (heat recovery & specific fan power)	90 % & 1.5 kW/m ³ s
Ventilation rate	92 l/s & 0.5 h ⁻¹
GSHP, Seasonal coefficient of performance (SCOP)	3.0
Photovoltaic panels (area/power)	66 m ² /10 kWp

Table 2. Results from simulations for the case study

Energy use	kWh/year	kWh/m ² a
Fans	1 546	6.0
Pumps (including cooling)	934	3.6
GSHP (space heating and hot water)	5 214	13.6
Total energy demand, excluding plug loads and lighting (disregarding PV-panels)	7 694	29.8
Plug loads and lighting	7 766	30.1
Electricity from PV-panels, direct use	-3 832	-14.9
Electricity from PV-panels, exported	-4 053	-15.7

3 Failure description

During the first winter, some residents complained about low indoor temperature when the outdoor temperature dropped below somewhere in-between -5°C and -10°C. They also complained regarding the supply air temperature, which they said were much too low.

After some investigation the reason for the problem were discovered; the condensing extract air were forming ice and blocking the heat exchanger.

This subject is not new, and HRV manufactures have developed different strategies to prevent or limit the build-up of ice and frost in heat exchangers, which has been highlighted and discussed before [14-16]. Common strategies may be Recirculation, Supply fan shut off and Supply air preheating.

In these ventilation units, the defrost strategy was supply fan shut off. This strategy means that the supply air fan stops, while extract air fan continues to run. I.e. the warm extract air defrosts the heat exchanger.

¹ Including thermal bridges, windows and doors

This strategy assumes, when the supply fan stops, that supply air partly finds its way into the dwelling through imperfections in the building envelope, see Figure 2. However, in this case, the building envelope were very airtight (see Table 1).

Since the building envelope were air tight, the supply air mainly came via the supply air ducts and inlet, even though the supply air fan were shut off.

This resulted in build-up of frost and ice in the heat exchanger and low supply air temperature. The consequence of the low supply air temperature were initially limited discomfort, due to low supply air temperature. However, in this project, the HVAC design engineer had assumed that the supply air would not drop below $+15^{\circ}\text{C}$. When the supply air fell to low temperatures, roughly under $+10^{\circ}\text{C}$, the underfloor heating system were not able to compensate for the low supply air temperature, and the temperature in the dwellings dropped, causing high discomfort for the residents.

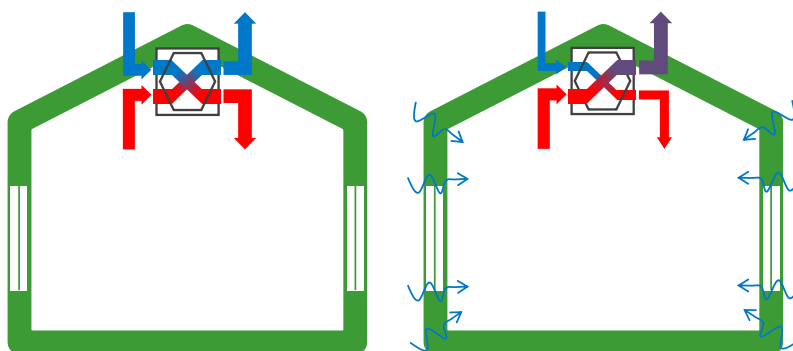


Fig. 2. Schematic description of assumed air flows. Left: Normal use, balanced ventilation. Right: Defrosting mode, Supply fan shut off.

4 Action and evaluation

4.1 Chosen technical solution

When the problems occurred. The subcontractor of ventilation and heating (the same subcontractor) were contacted and ask to suggest a technical solution to overcome the problem. Hence, the subcontractor were bound to ensure $>+21^{\circ}\text{C}$ indoor temperature, at -15°C outdoor temperature.

The subcontractor contacted the supplier and asked for a solution. Initially the supplier suggested to pre-heat the outdoor/fresh air, with an electric pre-heater (1 kW), to ensure no frosting- and freezing problems. However, in the initial suggested solution, the activation of the preheater would be based on the temperature of the outdoor/fresh air (Left in Figure 4) and start heating when the temperature dropped under -1°C . Based on the outdoor temperature a normal year (See Figure 3) and the suggested installed power. This solution were expected to increase the yearly energy use by 1 000 – 2 000 kWh/ventilation unit, and therefore rejected.

After some discussion, the subcontractor found out that the initial given information were wrong/misunderstood. The temperature sensor were actually placed after the preheater unit (Right in Figure 4). This would mean that the preheater would shut off as soon as the temperature after the preheater exceeded -1°C . This was expected to vastly reduce the energy consumption, and the decision was made to test the solution. The pre-heaters were mounted and measurement and evaluation started in March.

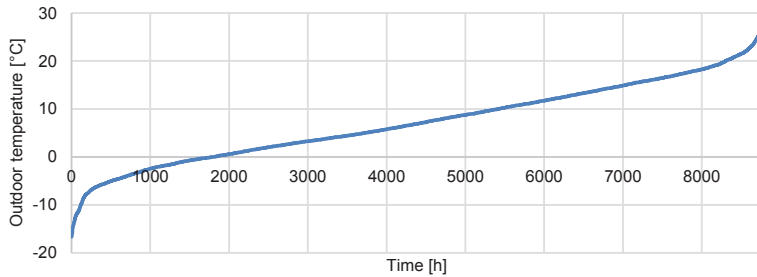


Fig. 3. Duration diagram of outdoor air a Typical Metrological Year (TMY)

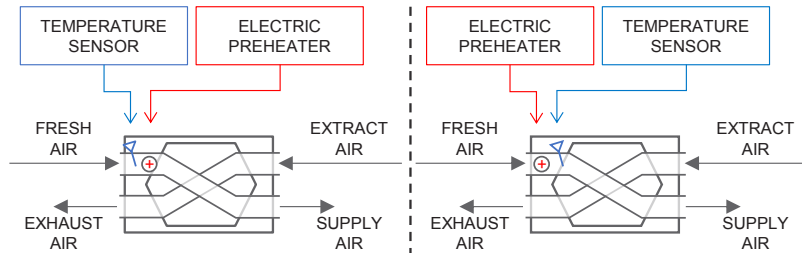


Fig. 4. Schematic description regarding position of temperature sensor and electric preheater. Left: First suggestion given by the manufacturer. Right: The installed and evaluated solution.

4.2 Evaluation of increased energy use for pre-heaters

Already before problems occurred, total electricity use were measured in each dwelling. However, including plug loads, lighting and electricity for ventilation units. Evaluation of increased energy use due to installed pre-heaters were decided to be carried out in two different ways:

1. Total electricity use in six of seven houses, between 3 A.M. and 5 A.M. were analysed, as it was assumed that the total electricity use in each dwelling during that time would be rather stabile, except when the pre-heater would be needed.
2. New electricity meters were mounted on two of ventilation units, to get detailed results.

6

4.3 Evaluation of energy use

One of the houses which did not have problems with the ventilation were monitored in detail. Starting in March 2015, energy use and energy generation were measured and is still ongoing.

5 Results from measurements

5.1 Pre heating

The results from measurements of total energy use is presented in Figure 5. Based on the average energy use in all dwellings. It was concluded that the energy use for fans, refrigerators, stand-by for TVs, etc. (I.e. when there were no active use of ovens, computers, etc.) were 165 kWh/h, dwelling between 3 A.M. and 5 A.M. This is roughly equal to 1.9 W/m², conditioned area.

Based on energy use before the pre-heaters were mounted (left in Figure 5) it was possible to investigate increased energy use related to outdoor temperature. The average increase of energy use between 3 A.M. and 5 A.M. were gathered (right in Figure 5). Based on the equation for the interpolation (right in Figure 5) and TMY for the location (Figure 3), the increased energy use (due to pre-heaters) were calculated to 1.2 kWh/m²a.

The standard error (SE) for the equation (right in Figure 5) is 0.047 kWh/h, dwelling. Using the maximum and minimum values for standard error the uncertainty is calculated to ± 0.6 kWh/m²a, or 50 %.

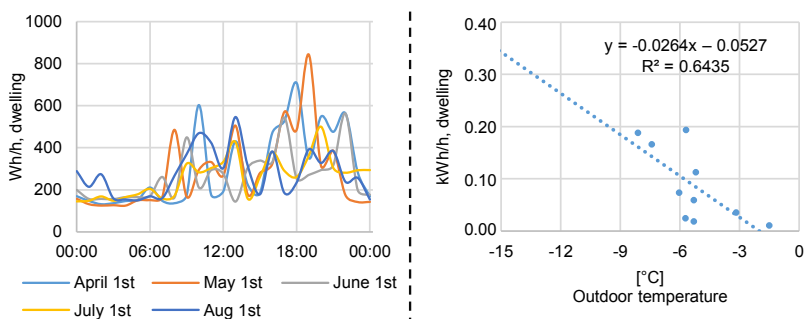


Fig. 5. Left: Average electricity use per dwelling in Solallén, before pre-heaters. Right: Average increased energy use in relation to outdoor temperature, between 3 A.M. and 5 A.M.

The results from the detailed measurements from one of the ventilation unit is presented in Figure 6. Also here, only data between 3 A.M. and 5 A.M. is included. Hourly data is presented. Energy use at outdoor temperatures below -2°C is separated from energy use at outdoor temperatures above -2°C. The mean energy use for the ventilation unit at outdoor temperatures above -2°C were 0.036 kWh/h. Which corresponds to a specific

fan power of $1.2 \text{ kW/m}^3\text{s}$ (This ventilation unit had a ventilation rate of $0.03 \text{ m}^3/\text{s}$) or 0.4 W/m^2 , conditioned area. Based on the equation for the interpolation (Figure 6) and TMY for the location (Figure 3), the increased energy use (due to pre-heaters) were calculated to $0.8 \text{ kWh/m}^2\text{a}$.

The standard error (SE) for the equation (in Figure 6) is 0.022 kWh/h , dwelling. Using the maximum and minimum values for standard error the uncertainty is calculated to $\pm 0.2 \text{ kWh/m}^2\text{a}$, or 25 %.

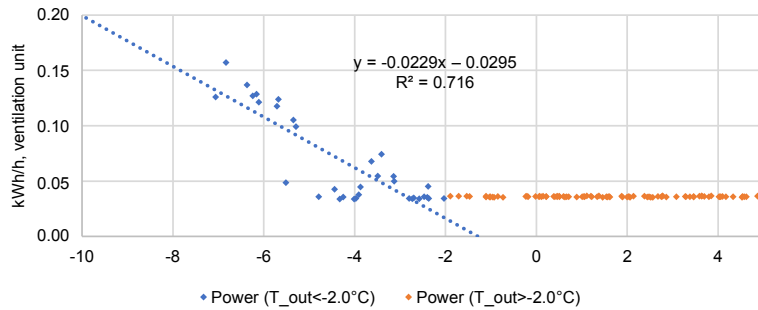


Fig. 6. Energy use for ventilation unit after mounting of pre-heater in relation to outdoor temperature.

5.2 Energy performance

In Figure 7, results from simulations and measurements is presented. Energy use for GSHP were $3 \text{ kWh/m}^2\text{a}$ higher compared to simulations. However, the main reason for higher energy use were lower inter heat loads due to plug loads and lighting, which were $8 \text{ kWh/m}^2\text{a}$ lower compared to simulations. Electricity generation from PV-panels were $5 \text{ kWh/m}^2\text{a}$ higher compared to simulations. The main reason for the higher energy generation were higher solar radiation, 10 % higher compared to TMY. Energy use for fans were almost $2 \text{ kWh/m}^2\text{a}$ lower compared to simulation. The main reason for the lower energy use were more efficient fans compared to procurement/design requirements.

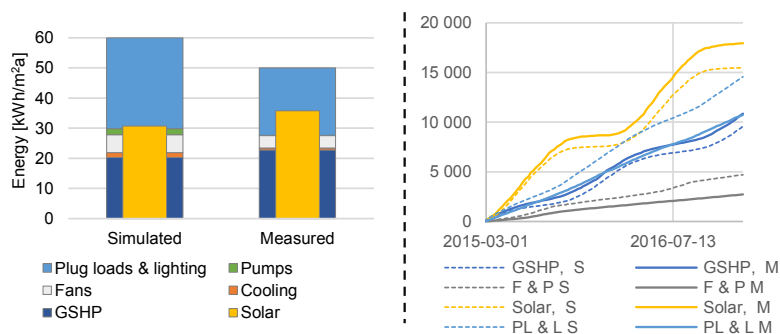


Fig. 7. Left: Comparison of annual energy use and solar energy generation simulated and measured. Right: Comparison of accumulated energy, generation and simulation. GSHP = Ground source heat pump, F&P = Fans and pumps, P&L = Plug loads and lighting.

6 Discussion and conclusions

The case study clearly shows that it is possible to build Net ZEB with existing technologies. However, it also shows that a previously proven working defrosting strategy, “supply fan shut off”, does not work. Hence, it highlights the importance of considering the secondary effects which may occur striving towards Net ZEBs. It is not always suitable to follow “rules of thumb”.

Based on measuring of total energy use, the installed pre-heaters may be expected to increase the energy use in this project, by 1.2 ± 0.6 kWh/m²a. Based on detailed measurements from one of the ventilation unit, the installed pre-heaters may be expected to increase the energy use in this project, by 0.8 ± 0.2 kWh/m²a. In relative terms, the deviation/uncertainty is rather high 50 % and 25 % respectively. However, even in a worst case scenario, the increased energy use is lower than the surplus from energy generation and energy use. I.e. the Net ZEB balance is still reached.

The measurements were conducted in the end of the Swedish winter. I.e. the chosen solution has not been evaluated for outdoor temperatures below -10°C. However, based on the installed capacity of the pre-heaters (1 kW) and air flow 30 l/s, the chosen technical solution is expected to ensure good indoor comfort when temperature is dropping below -10°C. The pre-heater should enable a temperature increase of the outdoor air, before it reaches the heat exchanger, of roughly 25 °C, preventing frost down to outdoor temperatures of -25°C (which is not normal in this part of Sweden).

Secondary effects are hard to predict and investigate. More research is needed and more time is needed in the design phase of building projects, especially in Net ZEB projects.

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Conference paper 15

Normalisation of measured energy use in buildings – need for a review of the Swedish regulations

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Abstract. Normalisation of measured energy use in buildings is important in order to verify their performance in user phase. Two methods for normalisation have been presented in Sweden, static and dynamic normalisation. The static normalisation considers deviating hot water use, indoor temperature, internal loads and external climate. The dynamic normalisation is based on repeated simulation, meaning that the initial simulation, carried out during the design phase, is repeated with updated conditions regarding actual use of the building and exterior climate. The ratio between the first and second simulation is used as a factor for normalisation. A pre-study has been initiated in Sweden to enable further development of the two methods. This paper presents the two methods, the initiated pre-study, and some early findings. The early findings show that there is need for further development of the methods presented.

Keywords: Normalisation, Energy use, Swedish regulations.

1 Introduction

While pushing boundaries of energy efficiency in buildings, it is of growing importance that predicted energy performance is actually achieved during user phase.

Performance gaps have been identified in earlier studies [1-15], showing that predicted energy use is often not achieved during user phase. Some of the studies show a very large performance gap [3-5, 11], some show a lower performance gap [6, 8].

One way to overcome and to identify actual performance gaps is to normalise the measured energy use. Indeed, in the cited works, a smaller performance gap is generally found when measured energy use is normalised.

Some studies normalise the measured energy use due to either internal or external deviating boundary conditions [6, 8], the latter being investigated and discussed in other studies [1, 2, 9, 14], which however do not attempt to normalise the measured energy use. A Swedish study investigated the uncertainty of different methods for normalizing energy use for deviating external boundary conditions and found that different methods may have a major impact. Furthermore, they concluded that the tested methods need to be further developed, especially in order to be suitable for low-energy buildings [16].

2

However, none of the studies [1-16] attempts to normalise measured energy use for both internal and external deviating boundary conditions.

Normalisation of energy use allows comparison and verification of energy use in buildings, clarifying if a deviation is generated by different conditions of use or by an actual performance failure.

The Swedish Board of Housing, Building and Planning (Boverket) recently published regulations regarding verification of energy performance of buildings [17]. These regulations introduce two different methods for normalisation, where it is possible to choose one of these.

The first method is a static approach where the normalisation is carried out in four steps. The second method is a dynamic approach using a simulation tool. These methods have not been evaluated and may both have strengths and weaknesses.

To increase the knowledge on normalisation methods for the measured energy use in buildings a pre-study has been initiated, founded by the Swedish construction industry's organisation for research and development, SBUF [18].

It should be noted that the pre-study is still ongoing. The main purpose of this paper is to present the methods introduced by Boverket, the initiated pre-study, and some early findings.

Boverket has presented two methods to standardise normalisation of measured energy use. However, more work may be needed to improve the methods. The initiated pre-study may be an important first step.

2 Methods for normalisation from Boverket

2.1 Static normalisation

The static normalisation is carried out in four steps, including effect of hot water use, deviating indoor temperature, deviating internal loads and deviating external climate. The static normalisation is graphically summarised in Figure 1 and it follows Equation 1.

$$E_{norm} = E_{meas,DHW} - E_{corr,DHW} + \frac{E_{meas,SH} \cdot TAF + E_{meas,C} - E_{corr,IL}}{OCD} + E_{aux} \quad (1)$$

where E_{norm} is normalised energy performance based on static normalisation, $E_{meas,DHW}$ is the measured energy use for domestic hot water (excluding energy losses for hot water circulation), $E_{corr,DHW}$ is used to normalise energy use for domestic hot water (Equation 2), $E_{meas,SH}$ is measured energy use for space heating, TAF is used to normalise energy use due to deviating indoor temperature (Equation 4), $E_{meas,C}$ is the measured energy use for cooling, $E_{corr,IL}$ is used to normalise energy use due to deviating internal loads from plug loads and lighting (Equation 5), OCD is used to normalise energy use due to deviating outdoor climate (Equation 6), and E_{aux} is auxiliary energy used, e.g. fans, pumps, elevators [19].

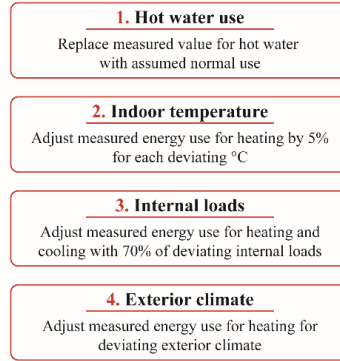


Fig. 1. Summary of static normalisation according to the Swedish national board of planning and housing (Boverket)

Hot water use

The first step of static normalisation is related to hot water use, see Equation 2.

$$E_{corr,DHW} = E_{\alpha,DHW} - E_{meas,DHW} \quad (2)$$

where $E_{\alpha,DHW}$ is the normal energy use for domestic hot water and $E_{meas,DHW}$ is the measured energy use for domestic hot water.

If $E_{meas,DHW}$ is measured including energy losses for hot water circulation, Boverket requires that 25% of the energy use for domestic hot water heating should be assumed to be energy losses due to hot water circulation. These energy losses are expected to heat the building and should therefore be included in space heating energy.

If domestic hot water is measured by volume; $E_{meas,DHW}$ may be calculated according to Equation 3.

$$E_{meas,DHW} = \frac{(V_{DHW} \times 55)}{SCOP_{DHW}} \quad (3)$$

where V_{DHW} is the measured annual volume of domestic hot water (m^3) and $SCOP_{DHW}$ is the seasonal coefficient of performance (SCOP) for the heat source. The equation is based on an assumption that incoming cold water from the municipality on average needs to be heated $47^\circ C$, from $8^\circ C$ to $55^\circ C$.

Indoor temperature (Temperature Adjustment Factor)

The second step of static normalisation is related to indoor temperature, see Equation 4.

$$TAF = 1 + (T_{\alpha} - T_{meas}) \times 0.05 \quad (4)$$

Where T_{α} is the normal indoor temperature during heating season and T_{meas} is the measured indoor temperature during heating season.

4

Internal loads

The third step of static normalisation is related to internal loads, see Equation 5.

$$E_{corr,IL} = \frac{(E_{\alpha,IL} - E_{meas,IL}) \times I_h}{SCOP_{heating/cooling}} \quad (5)$$

where $E_{\alpha,IL}$ is the normal energy demand for plug loads and lighting, $E_{meas,IL}$ is the measured energy use for plug loads and lighting, I_h is the share of internal loads assumed to affect the heating or cooling and $SCOP_{heating/cooling}$ is the SCOP for space heating or cooling. According to Boverket, $E_{corr,IL}$ is applied/used if energy for plug loads and lighting deviates more than 3 kWh/m²a. Furthermore, they recommend that I_h may be assumed to be 70 % when adjusting energy use for heating. No recommendation is given for adjustment of cooling.

Outdoor climate (Outdoor Climate Divisor)

The last and fourth step relates to deviating exterior climate. Boverket recommends normalisation by using the energy index [20] from SMHI [21]. The energy index, OCD_{EI} gives a weighted adjustment divisor based on outdoor temperature, solar radiation and wind.

$$OCD_{EI} = \frac{EI_{meas}}{EI_{\alpha}} \quad (6)$$

where EI_{meas} is the measured heating degree days adjusted for solar radiation and wind and EI_{α} is the normal heating degree days adjusted for solar radiation and wind.

2.2 Dynamic normalisation

It is also allowed to normalise the measured energy use based on repeated simulation. This means that the initial simulation, carried out during the design phase, is repeated with updated conditions regarding actual use of the building and exterior climate. The ratio between the first and second simulation is used as a factor for normalisation. Boverket states that the initial simulation and the repeated simulation has to be carried out in the same way. Furthermore, they clarify that technical parameters, such as quantities of insulation etc., must not be changed and this method of normalisation is only allowed when actual use (plug loads, lighting etc.) is verified.

3 The pre-study

The purpose of the pre-study is to create a knowledge basis for further work. This is done by examining different methods for normalisation and highlighting areas which could benefit from further development. The work is carried out in three phases, see Figure 2.



Fig. 2. Pre-study phases.

3.1 Literature review

The literature review will examine previous studies focusing on identification of important boundary conditions and parameters which may affect buildings' energy use during user phase and how deviating conditions may be accounted for by normalisation. If possible; the identified conditions/parameters will be ranked based on their impact on energy use.

3.2 Stakeholders' engagement

Public seminars will be carried out with consultants, practitioners and experts within the field. The purpose of the seminars is to gather input regarding important parameters which should be considered for normalisation of measured energy use.

3.3 Dissemination

The results from the literature review and seminars will be gathered in a report to highlight important areas for further work. The results will also be presented in a Swedish technical journal.

4 Early findings, review of methods for normalisation

4.1 Static normalisation

In Table 1, early findings regarding different energy use and aspects which are included/excluded in the static normalisation from Boverket are summarised. As can be seen, there is a large number of aspects influencing the energy use that are not included.

Based on Table 1, the static normalisation method by Boverket has the following limitations with respect to different use of energy:

- Heating; aspects such as deviating hot water use, increased/decreased ventilation, occupancy, and system losses are excluded.

- Cooling; aspects such as exterior climate, indoor temperature, hot water use, increased/decreased ventilation, occupancy presence and system losses are not included.
- Hot water; aspects such as system losses, indoor temperature and set points are not included in the normalisation.
- Ventilation, lighting, plug loads, auxiliary energy and renewable energy production; no aspects are included, there is no method for normalisation.

There are also examples where the factors used in the static normalisation lacks scientific basis. One example is the factor for deviating indoor temperature (5% per deviating °C). Previous studies have shown that deviating indoor temperature has a greater effect than the stipulated 5% per °C [5, 8, 14].

Table 1. Summary of early findings regarding energy use and aspects of normalisation which are included/excluded in the Boverket static method for normalisation.

Energy use	Aspects included in Swedish normalisation	Aspects excluded in Swedish normalisation
Heating	Exterior climate Set points/Indoor temperature Plug loads Lighting	Hot water Ventilation Auxiliary Occupancy System losses
Cooling	Plug loads Lighting	Exterior climate Set points/Indoor temperature Hot water Ventilation Auxiliary Occupancy System losses
Hot water	Hot water use	Set points/Indoor temperature System losses
Ventilation		Exterior climate Set points/Indoor temperature Plug loads Lighting Occupancy
Lighting		Exterior climate Occupancy
Plug loads		Occupancy
Auxiliary energy		Occupancy
Renewable energy		Exterior climate

4.2 Dynamic normalisation

Regarding dynamic normalisation there are no instructions regarding parameters which may be included or excluded when the initial “design simulation” should be repeated for the actual conditions regarding use of the building. E.g. is there a need to take into account relative humidity in outdoor air? – If so, it would also mean that it needs to be measured.

5 Discussion and conclusions

The static normalisation from Boverket tries, and succeeds to some extent, to include both deviating internal and external boundary conditions. The method is simple and straight forward but most likely at the expense of accuracy.

Many important aspects, such as occupancy, are not included in the normalisation. Furthermore, the terms and factors used need to be further developed and clarified. One example may be that the share of internal load that affects the heating or cooling most likely varies in relation to the energy-efficiency of the building. A second example is the normalisation due to deviating external climate; the energy index from SMHI may be applied using one divisor for a whole year, month by month or in a higher resolution, and Boverket does not stipulate which resolution should be used.

Regarding dynamic normalisation, there is much work needed to clarify this method. If the method is allowed to be vague, there is a big risk that different stakeholders will apply and use the method differently.

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Conference paper 16

LCC ANALYSIS OF A SWEDISH NET ZERO ENERGY BUILDING – INCLUDING CO-BENEFITS

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SUMMARY

An increasing population with the need of new buildings in combination with global warming is important issues ahead. Hence, for defining a clear path towards a low and zero-emission building stock in the EU by 2050, as recently stated by the new EPBD recast, Nearly Zero Energy Buildings are one of many necessary measures for climate change mitigation. Finding cost optimal solutions are important, where a short time perspective and narrow concept for evaluation may be wrong. This study presents a Net Zero Energy Building in Sweden, with verified plus energy performance in the operation phase.

Furthermore, it presents an economic analysis, based on life cycle costing (LCC), where additional co-benefits are included. The study shows that the discounted, cumulative annual cost reductions due to energy savings may exceed the initial extra costs after more than 20 years. However, when including additional green values and increased property value, breakeven may occur already after roughly five years.

Key words: Net Zero Energy Building; Life Cycle Costing; Net ZEB, LCC

INTRODUCTION

Buildings account for over 40% of the primary energy use worldwide and almost 25% of its greenhouse gas emissions (International Energy Agency (IEA), 2013). The world's population and need for buildings is growing. Hence, for defining a clear path towards a low and zero-emission building stock in the EU by 2050, as recently stated by the new EPBD recast (European Parliament, 2018), Nearly Zero Energy Buildings (nZEBs) are one of many necessary measures for climate change mitigation. Net Zero Energy Buildings (Net ZEBs) and Nearly Zero Energy Buildings (nZEBs) are usually also defined as “green buildings”, which here are referred to as buildings with high performance within the aspects of energy, thermal comfort, indoor air quality, building materials etc. A NetZEB, is a building with zero net energy consumption, where the weighted energy demand is equal or less than the weighted energy supply (Sartori, Napolitano & Voss, 2012). Another concept approved and implemented by the European Union is nearly Zero Energy Building (nZEB), with the goal of having all buildings in the member states of the European Union reaching nZEB standards by 2020 (European Parliament, 2010). The wording ‘nearly’ underlines the fact that this concept is less ambitious compared to the NetZEB ones.

Cost optimal solutions using concepts as Net NEBs and nZEBs will be major drivers in the construction sector in the next few years, as all new buildings in the EU from 2021 onwards are expected to be nZEBs (European Parliament, 2010).

In Sweden, energy tariffs are relatively low today and it may be difficult to justify investments in NetZEBs and/or nZEBs solely based on cost savings related to energy savings. A narrow concept and a short time perspective for evaluating profit, only focusing on increased investment costs and decreased energy costs, may be wrong. Both from a strict business perspective and from a socio economic perspective.

This paper presents a verified NetZEB in Sweden including LCC analysis when other values in “green buildings” are taken into account, such as increased productivity, improved health, publicity value, etc. The estimation of the Life Cycle Costs is based on the LCC as adopted within the H2020 project CRAVEZero, aimed at identifying and reducing extra-costs of nZEBs during the whole life cycle.

ADDED VALUE IN GREEN BUILDINGS

It is important to quantify added value in green buildings in monetary terms, communicating and presenting business opportunities in a business language that potential investors are familiar with, as technical performance is less likely to attract their interest (Bleyl et al., 2017). I.e. co-benefits such as increased productivity, improved health, publicity value, etc. need to be quantified. The calculation procedures may not be complex; the challenge is to gather well proven input data for the calculations. However, examples exist where increased productivity, higher revenue, reduced employee turnover, reduced absenteeism, etc. have been quantified (Bleyl et al., 2017; Brew, 2017). Furthermore, studies do exist which may be used as a basis for analysing added values.

Studies show that employees in green buildings perceive a positive effect of their work environment and productivity (Bleyl et al., 2017; Hedge, Miller & Dorsey, 2014; Singh, Syal, Grady & Korkmaz, 2010; Thatcher & Milner, 2014). In one case, a 10 000 m2 office building, an increased productivity of 0.3 % percent were reported, equal to 8 €/m2a.

An American study showed that roughly 20-25 % of 534 tenants/companies reported higher employee morale, more effective client meetings and easier to recruit employees (Miller, Pogue, Gough & Davis, 2009). Furthermore, 19 % reported lower employee turnover.

In two studies, reduced absenteeism was also found (Singh et al., 2010; Thatcher & Milner, 2014). However, in relation to green buildings and productivity and wellbeing, a recent study pointed out that social factors may have a greater impact, in monetary terms, compared to environmental factors (Hugh & Eziaku Onyeizu, 2016).

In addition to well-being and productivity, higher revenues from rent or sales may be expected. Bleyl et al reviewed previous studies and concluded that higher rent income may range roughly in between 5 % and 20 %. Furthermore, higher market valuations may range from below 10 % to up to 30 % (Bleyl et al., 2017).

The value of a positive news article about a specific building or a specific project could also be comparable to advertising costs in the specific source, in which the article is published (Berggren, Wall & Togerö, 2017).

One way to discuss the importance to investigate different co-benefits may be to rank them as presented in Figure 1. The classification is a subjective judgement, highlighting the relevance and the difficulty to value the co-benefits discussed above.

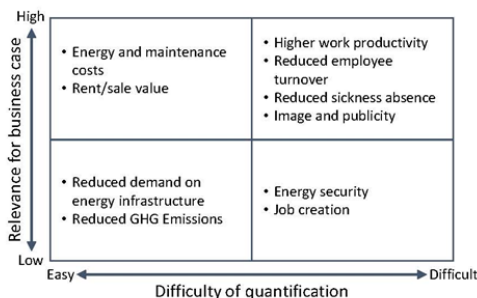


Figure 1 Co-benefits classifications, based on (Bleyl et al., 2017).

METHOD

The case study and costs related to the building construction and operation is presented and analysed including co-benefits expressed in monetary terms. The focus is on benefits with high relevance for a business case as classified in Figure 1.

Reduced energy use and exported energy, reduced energy costs (REC) is valued according to Eq. 1.

$$REC = (\Sigma EI \cdot \alpha + EE \cdot \beta) / (1 + (r - i - \gamma) / (1 + i + \gamma))^t \quad (\text{Eq. 1})$$

where EI is the reduced imported energy, α is its energy tariff, EE is the increased exported energy, β is its energy tariff, r is the nominal discount rate, i is the inflation rate, γ is the increase in energy tariffs and t is time.

Increased productivity value (IPV) is valued according to Eq. 2.

$$IPV = \Sigma (Emp \cdot SC \cdot IP) / (1 + R)^t \quad (\text{Eq. 2})$$

where Emp is the quantity of employees, SC is the average salary costs per employee, IP is the increased productivity per employee and R is the discount rate as presented in Eq. 6.

Reduced employee turnover costs (RETC) is valued according to Eq. 3.

$$RETC = \Sigma (\varepsilon \cdot Emp (RC + IC + RPC + LI + DC)) / (1 + R)^t \quad (\text{Eq. 3})$$

where ε is the reduced employee turnover, RC is the recruitment cost per employee, IC is the introduction course for new employee, RPC is the reduced productivity cost (new employee and supervisor), LI is the lost income during vacancy and DC is the decommissioning cost.

Reduced sickness absence salary (RSAC) is valued according to Eq. 4.

$$RSAC = \Sigma (Emp \cdot 0.8 \cdot SC \cdot \phi \cdot \kappa) / (1 + R)^t \quad (\text{Eq. 4})$$

where ϕ is the average sickness absence and κ is the reduced sickness absence.

Public publicity value (PPV) is valued according to Eq. 5.

$$PPV = \Sigma AIP \cdot AC \quad (\text{Eq. 5})$$

where AIP is article in press and AC is the advertising costs in the specific source (paper, internet, etc.).

$$R = (r - i) / (1 + i) \quad (\text{Eq. 6})$$

The considered time interval for the LCC calculation is 40 years in order to include in the analysis the maintenance occurrence of most of the building components. The calculation is based on the technical standard EN ISO 15686 (International Organization for Standardization, 2011).

THE CASE STUDY

The case study is located in the south of Sweden, see Figure 2. The building is a Net ZEB office building completed in 2012, with verified plus energy performance in the user phase (Kempe, 2014). The building is designed according to the passive house design principles; an airtight and well-insulated building envelope and balanced mechanical ventilation with heat recovery. Heat is supplied via a ground source heat pump, GSHP, connected to boreholes. During summer, the boreholes are used as a natural heat sink, free cooling is extracted by circulating the working fluid for the heat pump in the boreholes. The building's roof sides facing south-west are equipped with PV panels. A summary of technical description is given in Table 1. More technical information and results from measurements and verification may also be found in other publications (Berggren, Dokka & Lassen, 2015; Berggren, Kempe & Togerö, 2014; Berggren, Wall, Flodberg & Sandberg, 2012; Kempe, 2014).



Figure 2 Left: Location of the case study in Sweden. Right: Photo of the case study

The building was taken into use in 2012 and the energy performance has been monitored, see Table 2. The measurements have not been normalized for deviating boundary conditions (e.g. external climate, deviating use of building, etc.).

Table 1 Summary of technical description, Väla Gård

Technical description	Data
Conditioned floor area	1 670 m ²
U-average, building envelope	U=0.26 W/m ² K
Air tightness, assumed (q _{50/n50})	0.3 l/s, m ² / 1.0 h ⁻¹
Ventilation heat recovery	82 %
COP (heating/cooling)	3/20
PV-panels (area/kWp)	455 m ² /67.5 kWp

Table 2 Summarized energy performance, Väla Gård
(Sim = Simulated results, Meas. = Measured results)

Energy use	kWh/m ² a	
	Sim.	Meas.
Heating, cooling & auxiliary energy	19	14
Plug loads and lighting	29	26
PV-panels	38	41
Imported electricity	29	23
Exported electricity	19	24

RESULTS AND DISCUSSION

Boundary conditions regarding nominal discount rate, inflation, energy tariffs, changes in energy tariffs and period of analysis are presented in Table 3. Regarding nominal discount rate, governmental and municipal organizations usually have rather low requirements, 4-6 % (Offentliga fastigheter, 2017). However, private actors may have higher requirements. In this study, we have chosen to set 7 % as the baseline. The inflation is constantly changing. In Sweden, the national target is 2 % (Swedish monetary department, 2017). Hence, 2 % is chosen as a baseline. Regarding energy tariffs, data show that the increase of energy prices over time in Sweden has been almost 4 %, not adjusted for inflation (Nils Holgersson Gruppen, 2016). I.e. a lower value, 2 % is chosen. Energy tariffs are set to reflect Swedish conditions.

Table 3 Boundary conditions

Boundary condition		Input
Nominal discount rate, r	[%]	7
Inflation, i	[%]	2
Tariff for imported energy, α	[€/kWh]	0.12
Tariff for exported energy, β	[€/kWh]	0.10
Increase in energy tariff, γ	[%]	2
Period of analysis	[years]	40

Accounting for 40 years, the LCC for Väla Gård accounts for almost 4 000 000 €, corresponding to 2 352 €/m² and 59 €/m², year). All costs excluding VAT. In the LCC, cost for land, site enabling and planning fees are excluded.

The main impacting phase is the construction phase (including cost of materials and labour), which accounts for 74 % of the LCC. The operation- and maintenance costs are 18 %, while the design is around 8 %.

It is important to point out that the energy consumed, considering the balance with the production of the RES installed, impacts for 0.3 % of the overall LCC, while the impact of maintenance, calculated by adopting the estimations proposed by the standard UNI EN 15459, is roughly 17 %. Figure 3 reports the breakdown of LCC cost for each phase (design, construction and labour, maintenance), also distinguishing the costs for envelope and services.

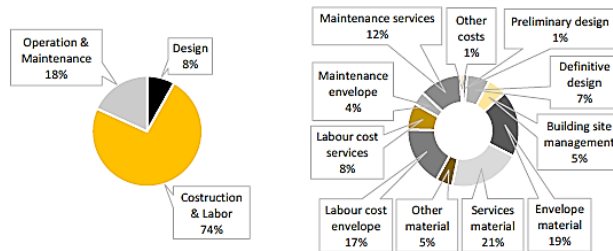


Figure 3 Left: Overall breakdown of LCC. Right: Detailed breakdown of LCC

Väla Gård reported increased costs amounting to almost 450 000 € or 268 €/m² compared to if the office would have been a “normal office”. Increased production costs, consultants and certifications costs are included. Regarding investment costs, a state grant was given for the PV-panels, amounting to roughly 82 000 € or 49 €/m².

The profitability of the increased costs related to increased energy efficiency and green values of the building are based on Eq 1-6. Reduced energy costs are based on measured values (Table 2) and boundary conditions given in Table 3.

Salary costs, *SC*, are based on average salaries in Sweden (Statistiska centralbyrån, 2017c), which is roughly 3 765 €/month. Including costs for employers, the salary costs amount to 6 325 €/month. No differences in salary for managers and other employees have been included. In total 70 persons are employed to work at Väla Gård.

Basis for calculation of reduced employee turnover costs are given in Table 4. The average employee turnover in Sweden is 3.5 % (Statistiska centralbyrån, 2017b). Based on previous findings in reduced employee turnover (Miller et al., 2009), we assume that a reduced employee turnover of 0.5 % to 3.0 % is reasonable.

Based on an estimation of roughly two days of work, per recruited employee, and costs for advertising for new staff; the recruitment cost is summarised to 6 500 € per new employee. Furthermore an introduction course for each employee is expected to cost 2 000 €.

In order to summarise reduced productivity cost, a reduced productivity of 20% for two persons is expected for 6 months. One person is the new employee the other person is one experienced co-worker who helps and guides the new employee.

Lost income during vacancy is based on a vacancy of 3 months, salary costs and nominal discount rate.

The decommissioning cost is based on an assumption of reduced productivity of the employee by 50 % after the person resigns for the remaining time of the employment.

Table 4 Basis for quantification of employee turnover costs

Data	Input
Reduced employee turnover, ϵ [%]	0.5
Recruitment cost, <i>RC</i> [€x10 ³ /p]	6.5
Introduction course, <i>IC</i> [€x10 ³ /p]	2.0
Reduced productivity cost, <i>RPC</i> [€x10 ³ /p]	15.1
Lost income during vacancy, <i>LI</i> [€x10 ³ /p]	1.3
Decommissioning cost, <i>DC</i> [€x10 ³ /p]	9.5

Average sick absences in Sweden were six days per year in Sweden 2016 (Statistiska centralbyrån, 2017a). Based on previous findings of reductions of absenteeism (Singh et al., 2010; Thatcher & Milner, 2014), we assume a reduced sickness absence of 10%, see Table 5.

Table 5 Basis for quantification of sick absence costs

Data	Input
Average sickness absence, ϕ [d]	6.0
Reduced sickness absence, κ [%]	10

The quantification of increased productivity is based on the reduction of share of time were an employee does not perform value creating work. I.e. increased productivity. Based on previous findings (Hedge et al., 2014; Singh et al., 2010; Thatcher & Milner, 2014), we estimate that the productivity may increase by 0.5 %.

Numerous articles were published about Väla Gård. In total, ten publications about Väla Gård were considered to have such a positive value that it could be considered to be equal to advertising. The corresponding cost were estimated to 3 500 € per article.

Based on the input data presented, the recurring cost reductions for Väla Gård (REC, RETC, RSAC and IPV) amount to roughly 69 000 €/year or 42 €/m²a.

The distribution of the summarised green values for the first ten years and the accumulated discounted value for the cost reductions, normalised by conditioned area, are presented in Figure 4. As can be seen, the value of energy savings, compared to the performances that the building would have reached if built according to current energy requirements in building regulations, amounts to 25 % of the total

green values for the first ten years. The assumed increased productivity has the largest relative impact. Hence, these effects should be prioritized in future research. The accumulated green values exceed the initial costs after roughly four years for Väla Gärd. If only reduced costs due to energy use and PV grant would be considered, the breaking point is after 26 years.

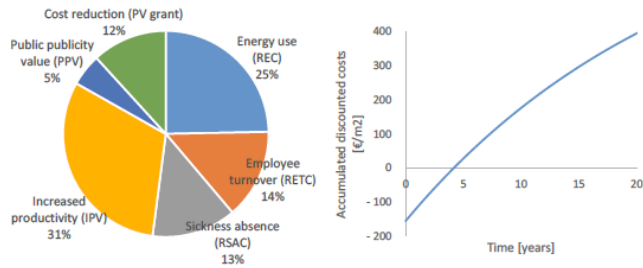


Figure 4 Left: Distribution of summarised green values for ten years.
Right: Accumulated costs for investments and for green values

CONCLUSIONS

In this study we show how green values could be quantified in monetary terms. The study shows that it may be very profitable to build green buildings if one accounts for green values. In fact, the business plan is significantly affected by further values than energy savings, which that cannot balance the initial extra-investment for reaching the target nZEB or Net ZEB if a short time perspective for evaluating profit is applied.

However, more research should be done in order to further develop these methods and to gain more knowledge regarding reduced employee turnover, reduced sick absence, increased productivity, etc. in green buildings, in order to provide more reliable results to be applied in the design phase, for defining an effective business plan.

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