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Planning for solar buildings in urban environments

An analysis of the design process, methods and tools

Jouri Kanters

Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2015
Report EBD-T--15/19



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.

Planning for solar buildings in urban environments

An analysis of the design process, methods and tools

Planning for solar buildings in urban environments

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Jouri Kanters

Doctoral Thesis

Keywords

solar energy, design process, design tool, architecture, urban planning, photovoltaics, solar thermal, building integration, density, net zero energy buildings, interviews, parametric studies, action research

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Abstract

Energy use in buildings accounts for a significant proportion of the total energy use in many countries. While past and current buildings have solely been energy consumers, future buildings will, besides using less energy, also need to produce (part of) the required energy on site with renewables. Solar energy is generally very suitable for producing this on-site renewable energy. Although solar technology is widely available, the installed effect is still very low. This is not only due to legislation and solar energy prices, but also because of decisions made throughout the design process for buildings. This research focuses on the decisions taken during the design process and by which player, and also the impact of such decisions, by using a mix of quantitative and qualitative research.

In the first research phase, semi-structured interviews were held with Scandinavian architects who had worked with solar energy during the building design process. The architects identified several crucial points for designing buildings with solar energy – the importance of collaboration and teamwork, the lack of attractive solar products, and that clients are actually not prioritising solar energy. The interviews also showed that architects rarely used any sophisticated tools to quantify solar energy, and that zoning plans can hinder the possibilities for implementing solar energy in buildings.

The next research phase focused on the implementation of solar energy in urban planning. Action research, and analytical and parametric studies were used to examine how decisions in the urban planning process affect the possibilities for implementing solar energy, as well as how these decisions were supported by tools.

Solar maps have become a popular tool for assessing the potential of solar energy in existing buildings, but an analysis of 19 solar maps showed that the underlying assumptions and methodology of such maps varied greatly. The amount of information provided to the user also varied greatly. While solar maps are used to analyse existing buildings, a proper solar assessment of new buildings requires the use of advanced simulation tools. In this research, such tools are used in three cases – an analysis of flat roofs, the

development of a new facade assessment tool, and an analysis of typical Swedish building blocks.

A parametric study was performed to analyse the energy output and financial consequences of varying row distances and inclination angles of a solar system on a flat roof. Results indicated that, in order to maximise energy production, the inclination of the panels should be 0° and rows should be placed directly next to each other.

In the future, facades may become an appropriate place to harvest solar energy. To assess the solar potential of a facade, a tool called FASSADES was developed. This tool consists of four steps: 1) an hourly irradiation analysis, 2) calculation of the photovoltaic/solar thermal output, 3) calculation of the economic value of the energy production, and 4) calculation of the payback time.

Urban planners can create a favourable environment for solar energy by designing a solar-friendly zoning plan. A parametric study examined how design decisions – density, orientation, roof shape and design – taken in the urban planning phase affect the solar potential. Density was found to be the most sensitive parameter and, for higher densities, the study showed that attaining a net zero energy balance is difficult.

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Nomenclature

IDP	Integrated Design Process
BPS	Building Performance Simulation
CAAD	Computer Aided Architectural Design
EDP	Early Design Phase
FSI	Floor Space Index
nZEB	Nearly Zero Energy Building
NZEB	Net Zero Energy Building
PV	Photovoltaic solar cells
ST	Solar Thermal panels
RE	Renewable Energy

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Finally, my wife Lina. Her endless support helped me to get through this period of life so much easier, and she always helps to put things into perspective. Our family extension will make life even better!

1 Introduction

In this section, the background, research questions and objectives are described.

1.1 Background

The effects of global warming on our environment have become clearer and more noticeable in recent decades, with much of the problem caused by human activity. These effects, together with the pressure on available natural resources in the world, have made it clear that we need to reduce our impact on our environment.

The associated greenhouse gas emissions (GHG) from Sweden's total energy use is 7.89 tonnes CO_2e per person (World Research Institute, 2014). In the ambitious *Roadmap for a Sweden without Greenhouse Gas Emissions in 2050*, various scenarios are put forward to successively reduce GHG emissions to zero (Swedish Environmental Protection Agency 2012). One of these scenarios (Figure 1.1) shows that all sectors need to make a substantial contribution to reduction of GHGs.

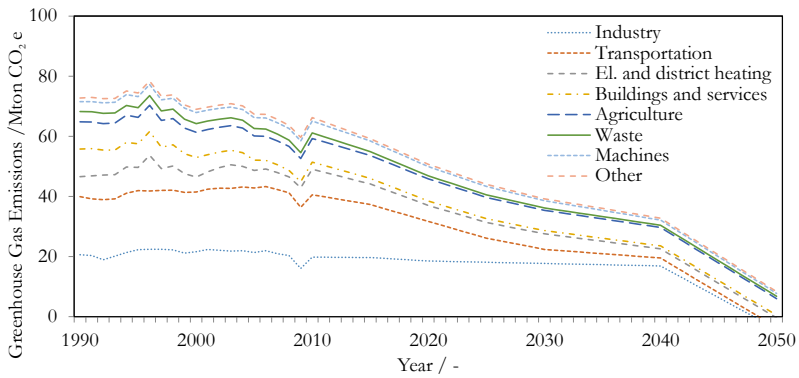


Figure 1.1 *A scenario towards zero GHG emissions in Sweden (after Swedish Environmental Protection Agency 2012)*

With buildings and services accounting for 38% (144 TWh) of Sweden's total energy use (Swedish Energy Agency, 2013), planning and designing future energy-efficient buildings and cities has become a vital feature in the strategy towards a low-energy society. Urban planners and architects are important players in this process, but not only because they shape the form and architecture of buildings. Their actions also result in a certain energy performance of buildings and possible implementation of renewable energy on-site. The urban planning and building design process consists of several stages – political decision phase, urban design phase, building design phase, and implementation phase – and is shown in Figure 1.2.

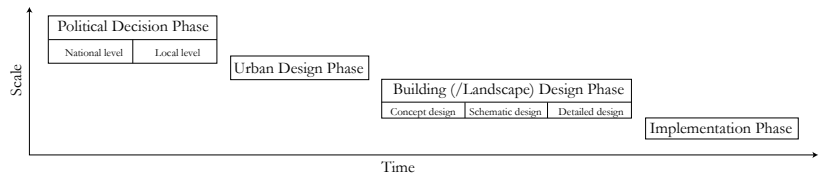


Figure 1.2 The design process and different levels of scale

This scheme with its phases will be used throughout the thesis.

1.1.1 Energy use balance in buildings: energy use and production

Currently, most of the energy used in the building sector provides domestic hot water (DHW) and space heating (60% of total energy use in this sector), although this is likely to decrease due to stricter building regulations that set the maximum level of energy use for new buildings. Electricity used in buildings has been relative steady since 1990 (Figure 1.3) (Swedish Energy Agency, 2013).

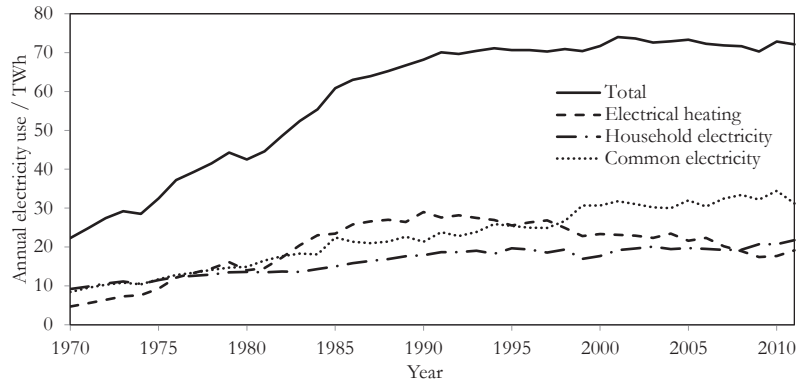


Figure 1.3 Electricity use 1970-2011 in Swedish buildings (Swedish Energy Agency, 2013)

In Sweden, electricity is mainly used for common electricity (pumps, fans, lifts and lighting for common purposes) and household electricity (household devices, TVs, computers, etc., also called plug loads), but also for space heating. The use of electricity for space heating has decreased since the 1990s, but household electricity and common electricity use have increased steadily over the years.

Seen from the traditional energy perspective, buildings have always been energy consumers, although this is likely to change in the future. In order to reduce the impact of buildings on our environment, a two-step shift is needed; first, the amount of energy used in buildings must be reduced and, secondly, the energy needed in buildings must be (partly) produced with renewable energy sources.

Today, there are many different concepts of energy use and energy production in buildings, such as the passive house, a LEED Platinum building or a net zero energy building. Figure 1.4 provides a visualisation of the relationship between the different energy concepts.

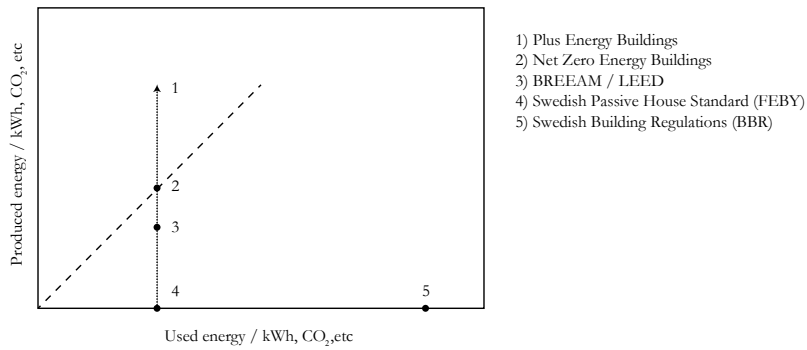


Figure 1.4 Visualisation of different energy concepts

Swedish building regulations are the only legally binding regulations for new buildings in terms of energy use in buildings, while the other concepts are voluntary.

Current Swedish building regulations

The current Swedish building regulations, BBR 20, stipulate requirements on the used energy (defined as bought energy) (Swedish National Board of Housing, 2013a). Due to the large variations in climate, Sweden is divided into three climatic zones, and the three biggest cities of Sweden, Stockholm, Gothenburg and Malmö are in Zone I. Table 1.1 provides an overview of the energy performance of buildings.

Table 1.1 Energy requirements according to the Swedish building regulations (climatic zones I, II, and III)

	With electrical heating	Without electrical heating
Houses	95 / 75 / 55 kWh/m^{2}a	130 / 110 / 90 kWh/m^{2}a
Commercial buildings	95 / 75 / 55 kWh/m^{2}a	120 / 100 / 80 kWh/m^{2}a

The building regulations do not specify what kind of energy sources must be used to fulfil the requirements, thereby providing flexibility for real estate developers and owners to choose a system suitable for their conditions. Energy produced by active solar energy systems in the buildings or on the plot can be deducted from the total amount of bought energy. In some cases, where municipalities sell their own land to real estate developers, stricter energy regulations apply.

Passive house

In Sweden, the Passive House Centre (FEBY) has developed a set of voluntary requirements for passive houses. The following requirements are specified: without electrical heating, a maximum total energy use of 58 / 54 / 50 kWh/m^{2}a; with electrical heating, 29 / 27 / 25 kWh/m^{2}a (when systems are using only one energy source for heating and DHW). These requirements are significantly lower than the Swedish building regulations.

Nearly Zero Energy Buildings

The term nearly zero energy building was introduced in the Directive of the European Parliament on the energy performance of buildings: a "*nearly zero-energy building* means a building that has a very high energy performance and that the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (European Parliament, 2010). It is up to each member state to determine how to quantify 'nearly zero'. In Sweden, the National Board of Housing, Building and Planning (Boverket) has stated that the current building regulations will function as the requirements for 'nearly zero' buildings (Swedish National Board of Housing, 2013b), which implies that only the demand side of the nearly zero energy building will be legally binding, not the production side. This leaves a gap in the Swedish definition of nearly zero energy buildings.

Net Zero Energy Buildings

The net zero energy building can be seen as a concept in line with the nearly zero energy building. Although there is no single agreed definition today, there is a common understanding that *all* the energy used by a building should be compensated by locally produced renewable energy within certain site boundaries. Much of the difficulties of deciding on a common definition for world-wide application are caused by discrepancies in how the energy balance should be calculated (kWh, CO_2 emissions, etc.) and how the site boundary is to be defined.

LEED & BREEAM

Rating new buildings by means of Energy Performance Certificates (EPC) has become very popular in the past decade, especially for commercial properties, e.g. LEED and BREEAM. EPCs use credits or points, and certain levels are to be obtained. On-site renewable energy sources (like PV) are normally awarded with credits/points; the greater the production

on-site the more points are earned if this energy is used on-site as well. In some countries, local authorities even made the attainment of an EPC a requirement (Fuerst & McAllister, 2011). Many property developers see attainment of a certain EPC level as a key to increasing the property value, although several studies have shown that this assumption is not always correct (Bonde & Song, 2013; Fuerst & McAllister, 2011). The effect of EPCs on the energy performance of buildings is also not that straightforward, since several studies have shown different outcomes (Newsham, Mancini, & Birt, 2009; Scofield, 2009, 2013; Shaviv, 2011).

1.1.2 State-of-the-art in solar energy

Solar energy is a technology that could provide energy either in or outside cities and buildings. In the south of Sweden, PV panels with an optimal inclination will receive 1130 kWh/m^{2}a; in Stockholm, 1260 kWh/m^{2}a in Gothenburg, and 1320 kWh/m^{2}a in Malmö (PVGIS, 2006).

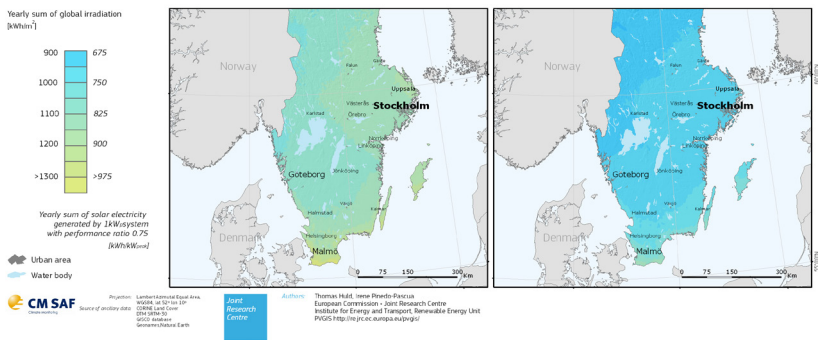


Figure 1.5 *Irradiation on an optimal inclination (left) and on a horizontal plane (right) in southern Sweden (PVGIS, 2006)*

The energy provided by the sun can be divided into two parts, passive and active. Passive solar energy consists of daylight, and passive solar gains penetrate a building. Active solar energy can be defined as the transformation of incoming radiation into heat, cooling or electricity. Systems which deliver electricity are called photovoltaic (PV) systems; those that produce heat are called solar thermal (ST) systems (Figure 1.6).

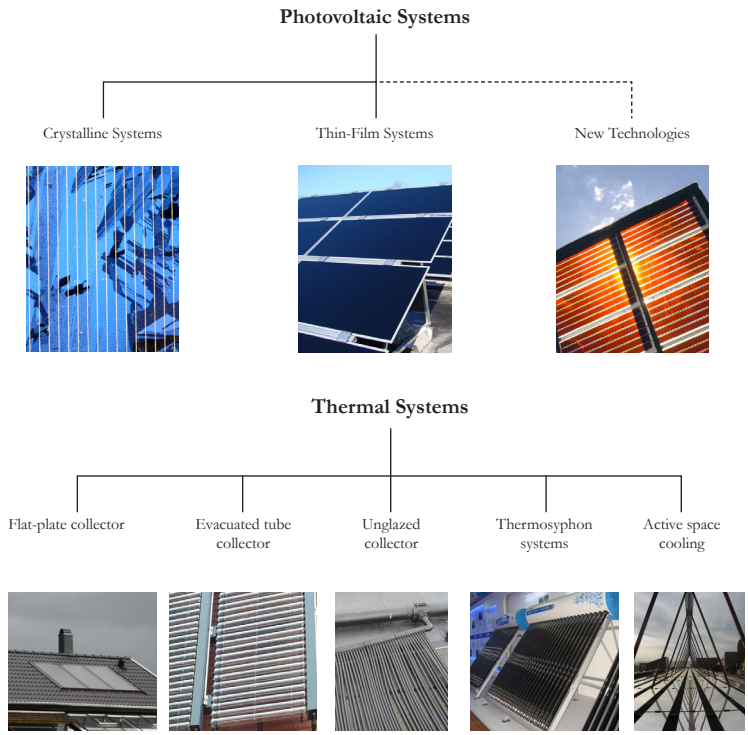


Figure 1.6 *Overview of solar photovoltaic and thermal systems*

PV systems

PV systems can be divided into two major groups: the crystalline silicons and thin-film technology. The appearance of polycrystalline cells is frost-like, while thin-film cells have a uniform appearance with a dark grey-black, red-brown or blue-violet colouring.

PV cells have different efficiencies depending on their type; systems with multi-junction concentrators (modified thin-film systems) are the systems being developed most intensively and whose efficiency is constantly increasing. However, there is a limit to the efficiency of PVs: for a 1-junction system, this is 40.6%, 2-junction systems 55.6%, 3-junction systems 63.6%, and 4-junction systems 68.5% (Razykov et al., 2011). It should be kept in mind that these values are often obtained under perfect laboratory conditions and for prototypes. The efficiency of standard PVs on the market is normally between 10 and 20%. Their lifetime is expected to increase to 35-40 years in the future (Neij, 2008).

Solar thermal systems

Solar thermal systems can be divided into categories: 1) flat-plate glazed collectors, 2) unglazed collectors, 3) evacuated collectors, 4) flat-plate air heating collectors, 5) thermo syphon systems, and 6) solar air-conditioning (Figure 1.6). The efficiency of a ST system is dependent on the temperature difference between the solar panels and the ambient temperature.

Installed effect, legal and financial issues in Sweden

Currently, neither PV nor ST solar systems contribute that much to the Swedish energy mix in terms of effect or annual produced energy (Figure 1.7) (Svensk Energi, 2014). Hydropower and wind power are the renewable energy sources that currently provide a significant contribution.

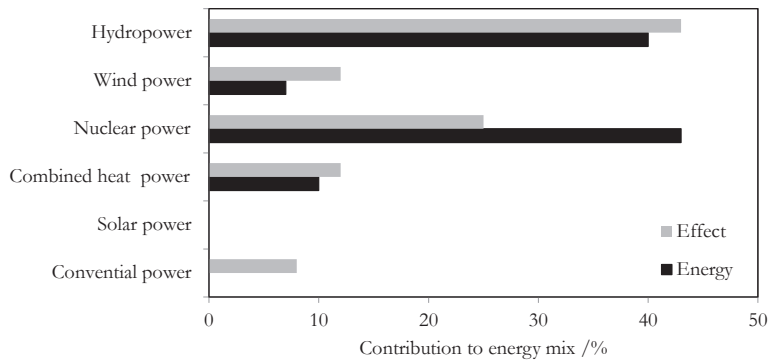


Figure 1.7 *Distribution of installed effect and provided annual energy for different energy sources in 2013 in Sweden*

Under current Swedish regulations, there is no feed-in tariff system in place, nor is there a possibility for net-metering. The counties are distributing subsidies for installing PV systems, but due to the high pressure on the limited financial resources, the system is rather slow and not transparent. A new law proposal involves a tax reduction for smaller systems wanting to feed overproduction into the grid. For ST systems, a subsidy system was in place until the end of 2011, but this system has stopped. There is hardly a market for selling excess heat into the grid. More constructive legal and political conditions would accelerate the employment of active solar energy in Sweden. Even though Sweden already has a high share of renewables in the mix – due to a large installed effect of hydropower – further expansion of solar energy would obviously increase this share.

Some energy companies have started offering to buy electricity produced by PV systems at a price lower than supply price, and under the conditions that the system does not exceed a certain size in terms of effect

and that the owners of such a system remain a net consumer of energy seen over the year.

Although the political framework is not that favourable for solar energy, there has been a sharp rise of installed effect (mainly PV) in the past few years (Figure 1.8).

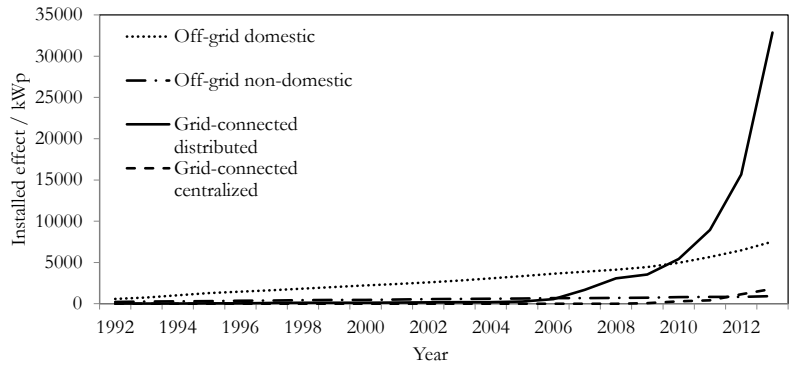


Figure 1.8 Installed effect of PV cells in Sweden since 1992 (IEA, 2014)

This increase in installed effect is mainly due to decreasing PV system prices (Figure 1.9 shows the development of PV prices in Sweden). The differences between the types of solar systems have decreased as well, as it can be seen that prices have dropped significantly over the past five years.

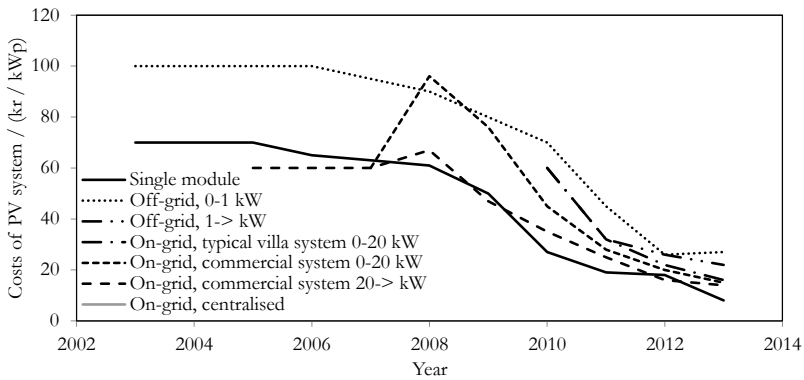


Figure 1.9 Development of PV prices in Sweden (IEA, 2014)

The total installed solar thermal effect in Sweden in 2011 was 312 MW_{th}, with 29% unglazed collectors, 57% flat plate collectors and 14% vacuum-tube collectors (Weiss & Mauthner, 2011). The solar thermal market in Sweden has not been increasing as steadily as the PV market; in fact, after the peak in 2008, the market has slowed (Figure 1.10).

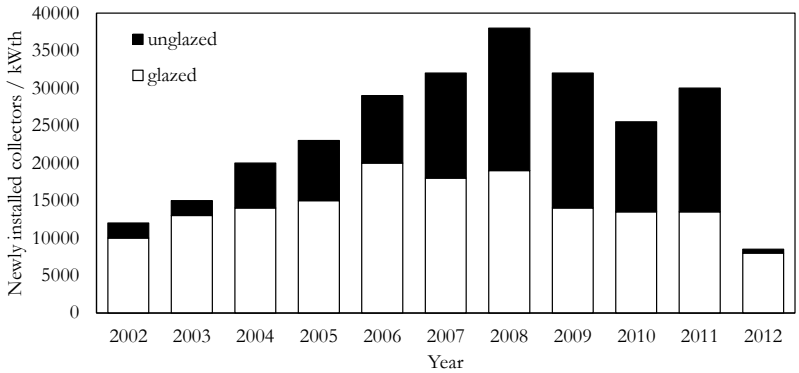


Figure 1.10 Development of ST market in Sweden (IEA, 2014)

Prices of solar thermal systems have been rather stable in recent years. Solar panels cost between SEK 2000 and 5000 per square metre, while other system components cost approximately SEK 5000 (Swedish Solar Energy, 2015).

1.1.3 Working method, research questions, and objectives

The technology is available to significantly reduce our energy demand in buildings and to produce renewable energy on site, but is hardly common practice in the current building industry. For solar energy, which is the focus in this research, this lag is due to several causes (Wall, Windeleff, & Lien, 2009):

1. Economic factors such as investment costs and maintenance costs.
2. Technical knowledge factors such as lack of knowledge amongst decision makers and architects, as well as a general reluctance to adopt 'new' technologies.
3. Architectural (aesthetic) factors: solar technologies for building use have an important impact on the building's architecture.

The first cause has been studied by many authors, and is encountered in many decision making stages in the design process. In this thesis, the focus is mostly on the second and third causes. Since all decisions about the energy balance (demand vs. production) are made in the design process, it seems natural to focus on the impact of such decisions made in the design process.

It was necessary to first obtain information about the decision making process, and barriers and drivers of the implementation of solar energy in the building design phase. This information was obtained by conducting interviews, and is described in **Part A** of this thesis. The results of Part A, combined with a literature review, led to the creation of a theoretical map of the design process as described in Chapter 2. An analysis of this theoretical model, together with input from local urban planners, identified the following knowledge needs regarding the implementation of solar energy in buildings (the core of **Part B**);

1) Under which conditions is solar energy considered to be feasible?
2) How can we quickly consider solar energy in an early design stage in buildings in an urban context?
3) What effects do urban design decisions have on the solar potential of building blocks?

These three questions led to the following research studies:

1) When is solar energy considered to be 'reasonable'? (Chapter 4)
2) Development of a façade assessment tool (Chapter 5)
3) Parametric studies to analyse the effect of design decisions (Chapter 6)

Research questions:

The two parts were based on the following research questions:

- Part A: *What are the barriers and drivers for implementing solar energy in buildings?*
- Part B: *How can we improve the urban planning process to facilitate a better integration of solar energy in urban environments?*

Objectives

1) The objective of Part A was to analyse the implementation of solar energy in current architectural design processes and to identify the barriers

and drivers of solar energy in architectural projects in Denmark, Norway and Sweden.
2) The objective of part B was to support urban planners with implementing solar energy in the design process, by participating and contributing actively in this process.

1.3 Research method

A mixed-method approach has been applied in this research. In part A, a qualitative study involved semi-structured interviews with architects, while in part B, the research form can be described as action research (Figure 1.11). Action research is a research methodology "concerned with introducing change (or 'action'), and critically understanding that change to produce new knowledge ('research'), within a social setting, with the researcher and the indigenous people of that social setting being active participants in the change process under investigation" (Sexton & Lu, 2009). The same authors also identified that action research can be characterised as change orientated, collaboration orientated and process orientated.

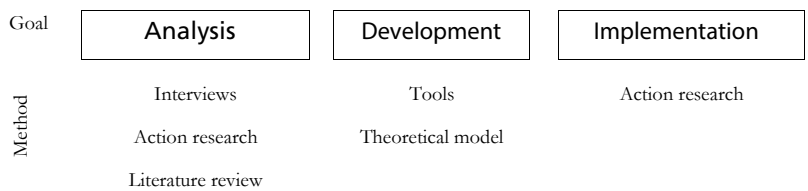


Figure 1.11 Different methods used according to goal

1.4 Limitations

In part A, the focus was on the architects' views on barriers and drivers in the design process, not on other players involved in the design process. In part B, the focus was on new buildings, not on existing buildings. In both parts, the main aspect of study was the active utilisation of solar energy, not the passive utilisation.

1.5 Related articles by the author

At the end of this thesis, all relevant peer-reviewed journal articles (PR), conference papers (CP) and a popular science article (PS) are listed. The articles and papers relate to the different parts of this research.

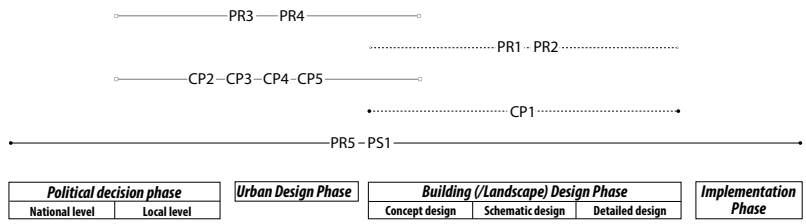


Figure 1.12 Overview of published articles and conference papers

The following articles and papers are connected to part A:

PR1 Kanters, J., Dubois, M.-C. & Wall, M. (2012). Architects' design process in solar-integrated architecture in Sweden. [doi: 10.1080/00038628.2012.681031]. Architectural Science Review, 1-11. doi: 10.1080/00038628.2012.681031

The co-authors helped by discussing the research methodology, the set-up of the interviews and by reviewing the article.

PR2 Kanters, J., Horvat, M. & Dubois, M.-C. (2014). Tools and methods used by architects for solar design. Energy and Buildings, 68, Part C(0), 721-731. doi: http://dx.doi.org/10.1016/j.enbuild.2012.05.031

The co-authors had been responsible for the internet survey in the framework of IEA SHC Task 41. Horvat and Dubois helped analysing the results of the survey and by reviewing the article.

CP1 Kanters, J. & Horvat, M. (2012). The Design Process known as IDP: A Discussion. Energy Procedia, 30(0), 1153-1162. doi: http://dx.doi.org/10.1016/j.egypro.2012.11.128

The co-author helped by providing data from integrated design processes in Canada, as well as by discussing the methodology and by reviewing the article.

The following articles and papers are connected to part B:

PR3 Kanters, J., Wall, M. & Dubois, M.-C. (2014). Development of a Façade Assessment and Design Tool for Solar Energy (FASSADES). Buildings, 4(1), 43-59.

The co-authors helped by discussing the research methodology of the tool and by reviewing the article.

PR4 Kanters, J., & Wall, M. (2014). The impact of urban design decisions on net zero energy solar buildings in Sweden. Urban, Planning and Transport Research, 2(1), 312-332. doi: 10.1080/21650020.2014.939297

The co-author helped by discussing the research methodology of the simulations and by reviewing the article.

PR 5 Kanters, J. & Wall, M. A planning process map for solar buildings in urban environments. Renewable & Sustainable Energy Reviews (submitted in 2015)

The co-author helped by discussing the research methodology of the process map and by reviewing the article.

CP2 Kanters, J. & Davidsson, H. (2014). Mutual Shading of PV Modules on Flat Roofs: A Parametric Study. Energy Procedia, 57(0), 1706-1715. doi: http://dx.doi.org/10.1016/j.egypro.2014.10.160

The co-author helped by discussing the research methodology. Davidsson also helped by analysing the results and by reviewing the article.

CP3 Kanters, J. & Horvat, M. (2012). Solar Energy as a Design Parameter in Urban Planning. Energy Procedia, 30(0), 1143-1152. doi: http://dx.doi.org/10.1016/j.egypro.2012.11.127

The co-author helped by discussing the simulations and by reviewing the article.

CP4 Kanters, J., Wall, M. & Dubois, M.-C. (2014). Typical Values for Active Solar Energy in Urban Planning. Energy Procedia, 48(0), 1607-1616. doi: http://dx.doi.org/10.1016/j.egypro.2014.02.181

The co-authors helped by discussing the methodology and by reviewing the article.

CP5 Kanters, J., Wall, M. & Kjellsson, E. (2014). The Solar Map as a Knowledge Base for Solar Energy Use. Energy Procedia, 48(0), 1597-1606. doi: http://dx.doi.org/10.1016/j.egypro.2014.02.180

The co-authors helped by discussing the methodology, analysing part of the results and by reviewing the article.

PS1 Dahblerg, J., Kanters, J.,Lundgren, M. & Wall, M. (2014). Solar energy on the urban scale (solenergi i stadsbyggnadsskalan). PLAN. Nr.6 Energi.

All co-authors contributed to the article by discussing the content and by reviewing the article.

At the beginning of each relevant section, it is stated which article or paper that is connected to the specific section.

2 Theoretical framework: Solar energy in buildings and cities

This following article relates to this section:

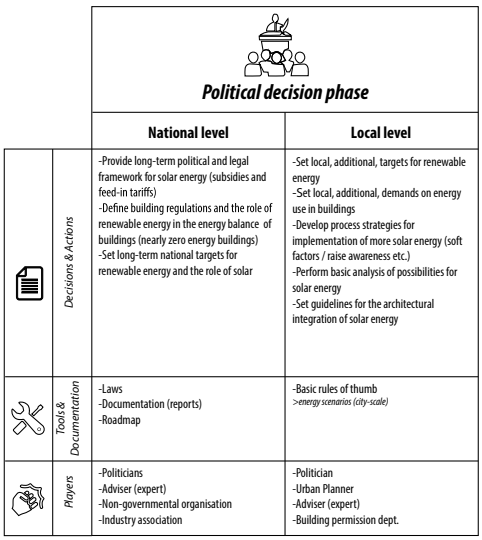
PR 5 Kanters, J., & Wall, M. (2015). A planning process map for solar buildings in urban environments. Renewable & Sustainable Energy Reviews (submitted)

Decisions made by players during the planning process all have impact on how well the integration of solar energy in buildings succeeds. To understand the coherence of the different scale levels and the decisions taken during the planning process, a theoretical model was constructed after studying relevant literature. The planning process map for solar buildings in urban environments is shown in Figure 2.1.

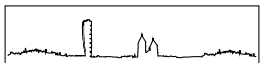
The planning and design process is divided into the following phases:

a) Political decisions phase: this is the phase where decisions are made regarding the political context of solar energy on a large scale (administrations on European Union, national and local level). This also implies indirect consequences of political decisions, e.g. the lack of political decisions.
b) Urban design phase: in this phase, proposals for new urban districts take shape, and/or the possibilities for integrating solar energy into existing urban districts are explored.
c) Building design phase: the design of a building is developed, as well as the architectural integration of solar energy.
d) Renovation phase: decisions are taken on how to implement solar energy in existing buildings.
e) Implementation phase: here, the active solar system is installed and used.

The renovation phase is parallel to the building process phase, since renovation projects do not have the same priorities and possibilities as new buildings. Decisions and actions, used tools, documentation and methods are described according to the phases of the planning and design process. The planning process map itself does not indicate that some parts are of greater priority than others. Decisions taken in all stages of the planning process are important; while political decisions might have a bigger impact in general, a non-attractive integrated solar energy system might lead to less acceptance of solar energy.



		Political decision phase	
		National level	**Local level**
	Decisions & Actions	-Provide long-term political and legal framework for solar energy (subsidies and feed-in tariffs) -Define building regulations and the role of renewable energy in the energy balance of buildings (nearly zero energy buildings) -Set long-term national targets for renewable energy and the role of solar	-Set local, additional, targets for renewable energy -Set local, additional, demands on energy use in buildings -Develop process strategies for implementation of more solar energy (soft factors / raise awareness etc.) -Perform basic analysis of possibilities for solar energy -Set guidelines for the architectural integration of solar energy
	Tools & Documentation	-Laws -Documentation (reports) -Roadmap	-Basic rules of thumb *>energy scenarios (city-scale)*
	Players	-Politicians -Adviser (expert) -Non-governmental organisation -Industry association	-Politician -Urban Planner -Adviser (expert) -Building permission dept.



	Urban Design Phase
Decisions & Actions	-Develop an urban master plan / zoning plan *>Building mass, Orientation, Heights, Density, Functions* -Perform an assessment of the active solar energy potential *>Suitable area (m²), Production (kWh), shading* -Map and define visiblity issues (sensitivity analysis) -Optimise zoning / urban plan based on the previous assessments
Tools & Dcoumentation	-Building Performance Tools for analysis of *>shading patterns, active solar energy potential*
Players	-Urban planner -Real estate developer -Architect -Engineer -Energy planner





Building (/Landscape) Design Phase

	Concept design	Schematic design	Detailed design
Decisions & Actions	-Develop architectural design *> Orientation, Height, Fenestration, Material, Dimensions of the building / Which solar products* -Develop technical systems *>HVAC, DHW* -Prepare budget for renewable energy / payback period -Plan energy demand -Assess the active solar energy potential *>Suitable area (m²), Production (kWh)* -Assess the PV /ST ratio -Assess shading patterns -Asses daylight and passive solar energy measures -Assess the best suitable location for PV/ST -Search suitable products for architectural integration -Determine rough system size	-Develop detailed architectural design >Outer walls, solar products, dimensions, colour, rhythm, texture, roof material -Develop structural design -Prepare budget for renewable energy (detailed) -Provide annual energy use charts for baseline vs. proposed -Propose detailed layout of the system *>strings, series / parallel* -Define exact dimensions of system and system components (tanks etc) -Develop detailed layout of joints and materials -Perform detailed financial evaluation -Assess mutual shading of rows PV / ST	-Provide construction details for the installation of the solar products -Final design model -Final documents for code compliance -Prepare for building permission
Tools & Docu.	-Building Performance Tools for analysis of: *> solar irradiation, energy demand, shading patterns, load matching*	-Detailed simulation software for solar energy systems *>irradiation, output ST/PV, mutual shading, shading*	-Detailed simulation software for solar energy systems *>irradiation, output ST/PV, mutual shading, shading*
Players	-Architect -Engineer -Real estate developer -Product developer	-Architect -Engineer -Real estate developer -Product developer	-Architect -Engineer -Real estate developer -Product developer



Renovation phase / exisiting buildings

Decisions & Actions	-Map the active solar potential of exisiting buildings (solar map) -Map and define integration issues of solar energy in exisiting buildings *>sensitivity (heritage), material, colour, reflections* -Prepare for building permission
Tools & Documentation	-GIS based solar map tool -Database with heritage restrictions (preferably GIS based) -Documents on the building permission procedures for solar energy
Players	-Real estate owner -Architect -Urban plannner -Energy planner -GIS / solar map expert



Implementation phase

Decisions & Actions	-Install the solar energy system on the building *>actual jointing, installation* -Follow-up of system performance
Tools	-Construction documents -Manual
Players	-Installer -Architect -Engineer

Figure 2.1 The process map

2.1 Political decision phase

Political decisions can be made at different levels. The two most important are the national level and the local level.

2.1.1 National level

The ratification of the Kyoto Protocol was the first global step towards a cut in CO_2 emissions (United Nations, 1998). However, recent re-negotiation of the protocol has not extended it. On European level, member states agreed on common environmental goals, which is partly enforced through directives, such as the European Directive on the Energy Performance of Buildings (European Parliament, 2010). This agreement provides a framework on a European level, leaving space for each member state to concretise these goals into national energy decisions, thereby taking into account the energy availability (like hydropower, solar, and wind) and other geographic constraints (land use, available land). The national plans are important means for reaching the national goals. Since solar energy is clearly a significant source of renewable energy, it is important to shape the political context to accelerate the implementation of solar energy.

Decisions and actions

Political decisions taken at national level shape a political climate for solar energy, which may be either beneficial or disadvantageous. The main political instruments defining the political climate for solar energy are:

- Feed-in tariffs
- Subsidies
- Building regulations

Feed-in tariffs

The feed-in tariff system, an obligation for utilities to purchase electricity generated by any renewable source at a set price, is in place in many European countries. In Germany, this system has led to a significant increase in market demand, leading to reductions in the Balance of System (BOS) (Neij, 2008). Other advantages and disadvantages of the feed-in tariff system were identified by Rowlands (2005):

Advantages
1. Effectively promotes the expansion of renewable energy capacity.
2. Use of installed capacity is encouraged by its payment structure.
3. More geographical locations can benefit from the system.
4. Can encourage technological learning.
5. Flexible, fast and easy to set up.

Disadvantages
1. Hardly any competition between generators of renewable electricity.
2. Prices of renewable energy systems are higher in countries with feed-in tariff systems than in countries without.
3. Setting an optimal tariff for every renewable technology was found to be very difficult.

Subsidies

Another way to accelerate the generation of renewables is by providing subsidies for installing renewable capacity. Sandén (2005) identified the following conditions for providing subsidies:

1. Subsidies should promote a self-sustained growth, driven by dynamic learning and scale effects.
2. The subsidised technology should meet the needs of the future market.

If the two conditions are met, the subsidies should decrease over time. Palm (2015) identified that the PV market in Sweden has been restricted by the subsidies, and that the market has trouble growing beyond this cap.

Building regulations

In many countries, building regulations set requirements for indoor climate, functionality and, often, energy use. However, these requirements often focus on energy demand, not energy production. Future building regulations will most probably include such demands, making it legally binding for new buildings to produce renewable energy on-site (I. Sartori et al., 2010; Igor Sartori, Napolitano, & Voss, 2012).

Targets

What are realistic targets on a national level, what are the advantages and disadvantages of setting up these targets, and how can solar energy play a role in these targets?

Delucchi and Jacobson (2011) studied the possibility of producing all global energy by wind, water, and solar power, at the same level of costs for energy as current costs. They identified that the barriers to a 100%

conversion to wind, water, and solar power are primarily social and political, not technological or even economic. It would be very beneficial if every country, region or city analysed which renewable energy sources were available and feasible given the context of that country. An example of such an analysis was carried out for New York State by Jacobson et al. (2013). Their proposal was to reduce the power demand, followed by installing renewable energy sources, of which a significant part was provided by active solar energy (Jacobson et al., 2013). Another example is the proposal for a Zero Carbon Britain (Centre for Alternative Technology, 2011) which is a national action plan to first 'power down' and then 'power up'. From such national and/or regional analyses, national, realistic, targets for both PV/ST can be extracted.

Tools and documentation

Although political decisions are taken by politicians, external players (e.g. industry and non-governmental organisations) could still exert an influence. They do not have that many official instruments at their disposal to affect political decisions, but an example of an important instrument in the political design phase is the technology roadmap, a long-term planning tool to "forecast the direction of future markets and developments in technology and help make strategic decisions providing a critical link between technology investment decisions and business planning and providing a structured approach for mapping the evolution and development of complex systems" (Jeffrey, Sedgwick, & Robinson, 2013).

An example is the roadmap for PV developed by the International Energy Agency (2010). Besides an overview of the latest figures and facts about the PV market (e.g. installed effect, price trends), it also pinpoints the key actions for the following years: a) policies should support long-term investment in solar energy, removing any uncertainties for investors by creating favourable political conditions; b) grid operators, utilities and the PV industry have to develop strategies for how to integrate large amounts of PV electricity into the grid; c) research and development needs to be increased to reduce costs of PV, as well as international collaboration to accelerate the learning process; d) more should be invested in rural electrification in emerging countries; and e) national and/or local governments should try to remove any non-economic barriers like planning delays, lack of coordination between different authorities, and long permission granting time (International Energy Agency, 2010).

2.1.2 Local level

National targets for solar energy and the potential of a city set a framework for the city administrations to apply them on the local level. A specific environmental analysis of the city's possibilities would provide a foundation for how to comply with the national targets.

Decisions and actions

There are two main important factors that need to be considered at city level:

- Translation of national goals into local (and possible additional) targets for renewable energy.
- Local, additional, demands relating to energy use in buildings.

As on all levels, it is important to look at energy reducing measures as well as local, renewable energy production, and to define a strategy to reach reasonable goals. A study by Grewal and Grewal (2013) examined the energy future of Cleveland (USA). Different scenarios and their costs were presented to facilitate the choice of the right future scenario; the presentation of such scenarios provides cities with tangible, quantifiable data on which decisions could be based. Besides the potential for renewables, the existence of energy grids and energy production and/or planning of new energy networks (urban district heating, smart electricity grid) is seen as an important factor in the analysis.

Urban planners and city administrations currently have limited opportunities to legally enforce solar energy. Azevedoa, Delarueb and Meeusa (2013) described different instruments for pursuing goals. There are policy mechanisms known as *tambourines* "whose main objective is to raise awareness among city authorities on what is expected from them and how they can achieve it"; *carrots* are policy mechanisms that "enable different stakeholders to act by providing incentives"; and finally *sticks* which are about "regulating the performance of stakeholders, as well as sanctioning the lack of it" (Azevedo et al., 2013). Right now, the possibility to use the stick might be limited as a way to 'force' real estate developers to implement solar energy in their buildings. What is left are *tambourines* and *carrots*. Urban planners might be limited – at least in Sweden – to the *tambourine* principle.

Tools and documentation

City administrations require simple tools to see the impact of decisions on future climate goals. On the one hand, different parameters for reducing

energy will need to be studied; on the other, different options for generating renewable energy need to be studied.

2.2 Urban design phase

Decisions and actions

In this study, the term *urban design* is interpreted as "place-making; creating a vision for an area and then deploying the skills and resources to realise that vision" (Llewelyn Davies Yeang, 2009). The urban design phase mainly consists of the development of a zoning plan for either new or existing urban districts. Zoning is one of several tools urban planners use to control "the physical characteristics of developing landscapes by imposing restrictions on variables such as maximum building height and density, extent of impervious surface and open space, and land use types and activities" (Wilson, Clay, Martin, Stuckey, & Vedder-Risch, 2003). In most cases, the zoning plan is designed and developed by the local planning authorities; sometimes it is first subject to a competition and later transformed into a zoning plan, making it legally binding.

Urban design can affect the energy use and energy production in cities. Denser settlements reduce the amount of energy used for transportation (Hestnes, 1999), while data shows that savings in energy cost of 20-50% are possible through integrated planning with carefully considered site orientation and passive strategies (Lehmann, 2008). However, some authors identified that the urban scale has been neglected in the debate on energy consumption and climate change (Lehmann, 2008; Ratti, Baker, & Steemers, 2005). Although limited in numbers, there are studies which have focused on the layout of the zoning plan and the urban canyon. Those studies have shown that the zoning plan has a considerable impact on energy use in buildings, daylight penetration, and available solar radiation (Cheng, Steemers, Montavon, & Compagnon, 2006; Compagnon, 2004; Montavon, 2010; Strømann-Andersen & Sattrup, 2011; van Esch, Looman, & de Bruin-Hordijk, 2012).

Okeil (2010) developed a model to evaluate the relationship between urban built form and energy efficiency. A new urban building block design was developed, and results showed that this new model allowed the maximum potential of passive utilisation of solar energy in buildings, and combined this high solar exposure with the functional, spatial, social and visual advantages.

In a PhD thesis entitled 'Optimisation of Urban Form by the Evaluation of the Solar Potential', Montavon (2010) compared actual and theoretical

urban forms in order to explore the diverse effect of daylighting and solar potential on dense sites. In this study, sites in Switzerland and Brazil were analysed, as well as Le Corbusier's Contemporary City of Three Million Inhabitants. Simulations were performed with Radiance and PPF, and thresholds were specified to compute the potential contribution to solar energy, based on threshold values set by Compagnon (2004). Important factors that influence the implementation of solar energy into urban planning were found to be financial aspects, environmental aspects, energy-efficiency of buildings, comfort, ambience, and protection. Other findings in the thesis were that implementing PV panels on facades in a dense urban area might not be feasible, and that reorganising the layout of building blocks (without reducing the usable floor area) allows more favourable conditions for solar energy utilisation.

Van Esch et al. (2012) discussed the effects of urban and building design parameters on solar access and solar heat gains. Buildings with three different roof shapes and two different orientations were simulated in order to see the effect on solar access and solar heat gains. The results showed that street width had a significant influence on the global radiation of the canyon: the wider the street, the higher the global radiation yield. Increasing the street width was also preferable from the point of view of maximising the solar gain of dwellings in the winter, although decreasing the street width would result in limiting overheating in summer as well as increasing density in cities. Maximising solar exposure of the building envelope in the winter can best be done in the east-west street direction, since the radiation yield of dwellings in east-west canyons is larger in winter compared with north-south streets. For canyons in an east-west direction, single-pitched roofs produced the highest yield. Increasing the amount of transparent facade openings will not always improve the solar performance of the dwelling and will often lead to overheating in summer.

Kanters & Wall (2014) assessed the effect of design decisions – form, density, orientation and roof type – on the solar potential of building blocks typically used in Swedish urban planning. Results showed that density was the most influential parameter, while the effect of orientation was not that clear. In the framework of this study, the website www.solarplanning.org was launched, where urban planners can compare the performance of different building blocks.

Implementing solar energy systems in new and existing buildings also requires an approach for how well these systems should be architecturally integrated. One method was proposed by Munari Probst and Roecker (2011), who defined sensitivity (the quality of the architectural environment) and visibility (close and remote visibility of the proposed system). Together with the socio-political context, different levels of integration quality of solar systems were specified.

In the process map, the following parameters were specified as influencing the solar energy potential and/or the passive use of solar energy (daylight):

- Building dimensions
  - Orientation
  - Heights
- Number of inhabitants, business, industry
- Functions

During the design of a zoning plan, it is preferable that a first solar energy potential quantification of the developed zoning plan is conducted, producing the active solar energy potential (suitable area in m^2 and production in kWh), and shading patterns to identify those places on the building envelope that experience shade. Preferably, different design alternatives should be simulated, optimised and re-simulated in an iterative way.

Furthermore, it should be clearly defined how active solar energy systems should be architecturally integrated into buildings, both for existing buildings and for new buildings.

Tools and documentation

Several types of tools are used for the design tasks within the urban design phase: reports, written guidelines for the zoning plan, Computer Aided Architectural Design (CAAD) programs, physical models, and Geographic Information System (GIS) tools. As regards solar energy, Gadsden (2003) pointed out the lack of tools for helping city planners to make informed decisions. In the past, assessment of the solar potential in urban conditions has been difficult because of the complexity of modelling the 3D urban geometry due to the need for computer power (Ratti et al., 2005).

One prominent solar energy tool used in urban planning is the solar map. A GIS system provides the annual solar irradiation on building surfaces, mostly accompanied by information regarding the output of solar thermal or photovoltaic systems. There are several ways to produce a solar map. The most common method was described by Lukač et al. (2013). First, LiDAR data and a digital elevation model is obtained, then the data is prepared. The next step involves calculating irradiance on all surfaces as well as shading. In the final step, a filter is used to place surfaces in different categories, e.g. reasonable, good and very good. A growing number of cities are obtaining LiDAR data, making it in theory possible for these cities to produce a solar map.

One important method in producing a solar map is the calculation method, both for the solar irradiation and the output of the solar tech-

nology (PV/ST). Jakubiec & Reinhart (2013) noted that "limited attention has been paid to the assumptions and calculation methods underlying solar maps". In their analysis of North American solar maps, they found that the most commonly used calculation method was the constant irradiation level method, which predicts that every point on the rooftop receives the same irradiation. Since this assumption decreases accuracy in many cases, Jakubiec & Reinhart used Radiance and Daysim as calculation method.

Kanters, Kjellsson and Wall (2014) analysed 19 different solar maps. They concluded that solar maps can be classified in three categories; basic, medium and advanced. The *basic* solar map is one with basic information about the irradiation level. Preferably, irradiation levels are also categorised (e.g. 'reasonable', 'good' and very 'good'). Such a solar map is the base for the *medium* and *advanced* solar maps, whose features are all based on the analysis of annual solar irradiation of surfaces. The *medium* solar map provides the energy output of the suitable areas as PV/ST. The most advanced solar map not only provides quantitative data, but also provides information about how to proceed when people want to install PV or ST.

Although solar maps give architects and urban designers valuable information about the suitability of existing buildings to harvest solar energy, they are not yet developed for use as a design tool. One important design, non-computerised, tool for solar urban planning was developed by Knowles (2003), and is called the 'solar envelope'. The solar envelope is a 3D surface on a given site that does not obstruct more than *n* hours of sun onto the adjacent site (Morello & Ratti, 2009) and which is visualised as a 3D volume (Figure 2.2).

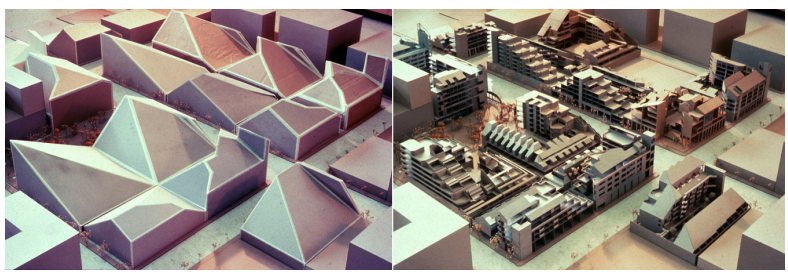


Figure 2.2 *Knowles' solar envelope applied to an urban plan*

Later, Knowles' idea was extended into *solar rights envelopes* and *solar collection envelopes* by Morelli and Ratti (2009). The solar rights envelope is the same as the solar envelope, while the solar collection envelope is defined as a 3D volume examining the total number of sun-hours collected. These envelopes facilitate the calculations of solar envelopes over complex urban sites, providing the actual irradiation and illumination. Jakubiec and Reinhart (2011) incorporated the solar envelope into the 3D CAAD environment of designers [41].

Compagnon (2004) developed a method for quantifying the potential for passive solar utilisation, PV electricity production, and daylighting of facades and roofs located in urban areas. The simulation engine used in this study was Radiance. The output of the simulations provided the proportion of the total facade or roof area that are suitable for various kinds of solar energy technologies. A very important aspect of this study was the setup of threshold values for daylight and active solar systems (Table 2.1), which have served as a basis for many later studies.

Table 2.1 Threshold value used in the study by Compagnon (2004)

Technology	Threshold value / facades	Threshold value / roofs
Passive thermal heating	216 kWh/m^2 during heating seasons	Same as for facades
PV systems	800 kWh/m^{2}a	1000 kWh/m^{2}a
Daylight systems	10 klx mean daylight illuminance during office hours (8-18h)	Same as for facades
ST systems	400 kWh/m^{2}a	600 kWh/m^{2}a

Compagnon's method enables urban planners and architects to assess and compare different design alternatives quantifying passive and active solar potential.

In search of other ways of calculating energy aspects in urban environments, Ratti et al. (2005) used digital elevation models (DEM), a 2D matrix of elevation values storing 3D information. The DEMs make it possible to predict the annual heating, lighting, ventilating and cooling energy use, also by taking into account the impact of overshadowing by surrounding buildings. An interesting aspect in this study is the use of the obstruction sky view (OSV) angle, which is used to quantify the luminance of obstructing facades as a function of their view of the sky. Instead of the Obstruction Sky View angle, Cheng et al. (2006) used the Sky View Factor (SVF), which defines the openness of a surface: a SVF of 1 means an unobstructed view of the sky and a SVF of 0 means a completely obstructed view of the sky. The SVF facilitated the examination of the relationship between built forms, density and solar potential by means of three design criteria: openness at ground level, daylight factor on the building façade, and the PV potential on the building envelope using Compagnon's method (2004).

2.3 Building design phase

The building design phase is the phase where the design of a building is developed, and consists mainly of three phases: concept design, schematic design, and detailed design.

The process of designing, constructing and managing a building is fragmented and involves many participants interacting in complex ways over a longer period of time (Kalay, Khemlani, & Choi, 1998).

This is also true for designing solar buildings, where many different available technologies require different areas of expertise to be involved (Andresen, 2000).

The design process is different for every building, although a general course of the design process can be identified. The majority of architects follow what is called a traditional design process (IEA, 2003), in which the following stages can be distinguished: briefing, pre-conceptual design, conceptual design, preliminary design, detailed design, and design documentation (Jones, 1992). This linear process has proved its value in the past decades, but it has often led to undesirable design features such as limited exploitation of the potential advantages offered by solar gain during the heating season, possible exposure of the building to high cooling loads during the summer, non-utilisation of a building's daylighting potential, exposure of occupants to severe discomfort, and a lack of computer simulations of predicted energy performance (IEA, 2003).

In order to ease the constraints of the traditional design process, the Integrated Design Process (IDP) was developed; a process which considers and optimises the building as an entire system, including its technical equipment and surroundings and for the whole lifespan. It has proven to be more effective in producing high-performance and environmentally-friendly buildings (IEA, 2003), and buildings were found to perform better and more cost-effectively compared with the ones designed according to a traditional design process (Lewis, 2004). In general, the IDP will have the following sequence (IEA, 2003):

1. Establish performance targets for a broad range of parameters, and then develop preliminary strategies to achieve these targets.
2. Minimise heating and cooling loads and maximise daylighting potential through orientation, building configuration, an efficient building envelope, and careful consideration of amount, type and location of fenestration.
3. Meet these loads by an optimum use of solar and renewable technologies and by using efficient HVAC systems, while maintaining

performance targets for indoor air quality, thermal comfort, illumination levels and noise control.

4. Iterate the process to produce at least two, and preferably three, conceptual design alternatives, using energy simulations as a test of progress, and then select the most promising of these for further development.

The most notable difference compared with the traditional design process is that the design becomes a collaborative effort by the design team (Kalay et al., 1998). The American Institute of Architects (2012) produced an architect's guide to integrating energy modelling in the design process. The report says that all architects should be "leaders in energy modelling for the building industry, taking responsibility as designers for assuring that buildings perform to high standards". The report also provides a guideline on how to integrate energy modelling in the design process, for instance by defining which decisions need to be taken.

All stakeholders have a crucial role to play in altering the way the built environment performs in term of energy performance (Feige, Wallbaum, & Krank, 2011). Not only the architects and engineers involved play an important role, but also clients. Nässén, Sprei, and Holmberg (2008) carried out an interview study where most of the interviewees identified clients as the most important players to drive change in the building sector.

Feige et al. (2011) identified key stakeholders and their main concerns in the design process (Table 2.2). Different main concerns might lead to issues in reaching a common goal. This was also confirmed by Lützkendorf, Fan, and Lorenz (2011), who looked at the role of the financial sector in energy-efficient real estate. By engaging in sustainable property development, financial stakeholders are exposed to moderate risks but gain on their image building.

Table 2.2 Stakeholders involved, and their main concerns (after Feige et al., 2001)

Key stakeholders (internal)	Investor	Manufacturer /supplier	Banks/financial institutions	Contractors	Planners /designers	End user/owner	Public authorities
Main concerns	Return of investment, economic feasibility, corporate social responsibility, regulation, personal belief, company image	Energy supply, availability of natural resources, economic feasibility, regulation, personal belief, company image	Return of investment, company image	Materials and energy supply, economic feasibility, cost-efficiency, workforce, corporate social responsibility, regulation, personal belief, company image	Knowledge, creative and efficient application of technologies, cost-efficiency, corporate social responsibility, regulation, personal belief, company image	Well-being, economic feasibility, lifestyle, personal belief, company image	Regulations and control, well-being

Key stakeholders (external)	Non-governmental organisations	Research and education	Media	Environment	Future generations
Main concerns	Social equity, access to information, well-being	Technology and knowledge	Democratic share of information	Permanent degradation	Social equity, well-being

2.3.1 Concept design phase

In this phase, the architectural design starts and is developed. The main aspects of the building are under design. As regards the conditions for implementation of solar energy in buildings, the following aspects are crucial:
Orientation of the building

- Height
- Fenestration
- Material
- Dimensions
- Choice of solar products

Integrating solar energy into buildings needs to be considered from the first design phase. Hestnes (1999) described several case studies where solar systems became part of the general building design. Eight buildings were discussed, with special focus on the integration of solar systems into the building; place, size, problems of integration, colour and material of solar systems and their architectural features were evaluated. It was found that designers of these buildings should have a good and common understanding of how to design buildings where energy systems are an integral part of the whole, which Hestnes called the holistic approach.

Designers needed help when applying this approach in choosing the right solar system. If solar elements replaced other building elements, their architectural integration improved: they served dual functions and thereby reduced total costs. Architects have discovered that solar elements can be used to enhance the aesthetic appeal of a building, and their clients have discovered the positive effect of advertising their use of solar energy. In most cases, the key to success in solar building projects was the use by architects of the approach of aesthetic compatibility rather than of invisibility.

Lundgren and Torstensson (2004) analysed the architectural integration of solar energy in buildings in Scandinavia and the Netherlands through cases studies. All the architects involved found PV interesting as a building material. In some case study buildings, PV was introduced late in the process, resulting in a less attractive integration compared with those buildings where PVs were integrated from the start. Furthermore, architects experienced the financial factors as limiting.

Henemann (2008) described building integrated photovoltaics (BiPV) as an important product that can change the perception of solar energy, since they are more attractive and adaptable than regular systems. Some of the advantages mentioned were that the modules can be integrated into non-ventilated facades of new buildings, and in ventilated facades to increase the appeal of old buildings. They replace other building materials,

can be used as balustrades, and function as a screen against noise, wind, sun, etc.

Kosoric et al. (2011) described the building integration of PV on a demonstration site in Singapore. In the design process, which was divided into three phases, eight design alternatives were produced which all had to be innovative, functional, successfully integrated into the architecture and demonstrate good performance in relation to both costs and energy output. In design phase 1, suitable places for the PV were selected. In phase 2, design alternatives were generated and optimised and, in phase 3, the eight design alternatives were assessed by multi-criteria decision-making (MCDM) in order to pick the best alternative. The use of such a MCDM method was seen as successful since it reduced subjectivity, but special attention should be devoted to the determination of weighting coefficients.

Quesada et al. (2012) performed a detailed literature review of solar facades, with a special focus on opaque solar facades. The review concluded that BiST is a relatively simple technology, but not yet fully optimised and understood, and that BiPV have many advantages, since they not only produce energy but can also reduce cooling loads when the air flow behind the panels is utilised efficiently. Hybrid ST/PV systems were seen as improving the economic return of the system by combining the two technologies. The most developed system is the thermal storage wall or Trombe wall, which can reduce the heating load by about 40-50%.

Munari Probst and Roecker (2007) conducted a survey on the perception of the integration quality of Building Integrated Solar Thermal (BIST) systems. The target groups of the web-based survey were architects, engineers and facade manufacturers from different climatic European areas. Results showed a clear ranking of BISTs by architects, and a different ranking by engineers. Architects agreed on the value of the integration quality of the objects, while engineers and facade manufacturers were generally less demanding regarding integration quality. It was found that some specific system characteristics had a significant impact on the integration quality: size and position of the collector field, shape and size of the modules, type of joining, collector material and surface texture, and absorber colour.

One of the client's main priorities is to perform a financial study of the costs and benefits of solar energy. Clients should define a budget for renewable energy in this phase. In order to make well-founded decisions, clients should be aware of the latest prices for solar products, latest energy prices, and support system (feed-in tariffs and/or subsidies). It might also be useful to be aware of the latest business models for renewable energy. To support the financial study, the following actions should be executed:

- Assessment of the active solar energy potential
  - Suitable area (m^2)
  - Possible production on suitable area (kWh)
- Assessment of ratio PV/ST
- Assessment of shading patterns
- Assessment of most suitable location for PV/ST
- Search for suitable products for best architectural integration
- Estimation of a rough system size

Tools and documentation

Most architects and engineers use CAAD programs for their daily work. CAAD programs have evolved from replacing much of the drawing by hand into a working platform by the introduction of the so-called Building Information Model programs (BIM): a digital building environment containing form, behaviour and relations of parts and assemblies (Eastman, 1999). Architects and engineers can work together on a 3D building model and can exchange information about the building and building components. When assessing the building's energy performance, Building Performance Simulation (BPS) tools are used in the design process. Such tools are whole-building energy simulation programs, providing key performance indicators such as energy demand (and/or production), temperature, and humidity (Crawley, Hand, Kummert, & Griffith, 2008).

Over the past 50 years, hundreds of building energy programs have been developed. Because of the large number of BPS tools, it is hard for architects and engineers to know which program is most suitable for their working method. Another complicating factor is the fact that developers of simulation programs all use their own language when describing their products, which makes it harder for architects to choose (Crawley et al., 2008).

Attia et al. (2009) conducted a survey amongst architects in order to compare several BPS tools for their architect-friendliness. The authors pointed out that most of the current users of those BPS tools were researchers and experts, not architects. An analysis of the different tools showed that only three of the tools were classified as architect-friendly.

Holm (1993) wrote that the designer's approach, working from the whole towards the detail, contrasts with the way analytical models are typically structured. This led to the development of a number of simulation tools which overlook the real needs of the industry. Schlueter and Thesseling (2009) argued that there were still no tools that could seamlessly integrate performance assessment into the design process or support the design and decision-making of the architect or building designer. However, Hensen and Augenbroe (2004) concluded that, over the previous

two decades, the building simulation discipline had matured into a field that offers better methods and tools for building performance evaluation.

Several CAAD embedded plug-ins were launched recently, integrating energy simulation tools into the everyday drawing environment of the architect. Another trend amongst architects and researchers in architecture is called parametric design; the use of parameters to define a form (Monedero, 1997). In order to analyse the performance of several design alternatives, the user needs to produce a script that makes this possible. Including BPS tools in the scripting environment makes energy simulations more easily accessible.

Most BPS tools focus on the consumed energy of buildings and on indoor comfort, and solar energy is not always part of such tools. Dubois and Horvat (2010) provided an overview of the available digital tools used for solar design, dividing the tools into three categories: 1) CAAD (computer-aided architectural design), 2) visualisation, and 3) simulation tools. It was found that most tools were more suitable for later (detailed) design phases than for the EDP. Horvat et al. (2011) also carried out an international survey of digital tools used by architects for solar design within the framework of IEA SHC Task 41 Solar Energy and Architecture. The web-based survey focused on identifying current barriers preventing architects from using existing methods and tools for solar building design, and on identifying important needs and criteria for new or adapted methods and tools to support architectural design and integration of solar components in the EDP. Results showed that architects did not rate their skills at using digital tools as being very advanced (Figure 2.3).

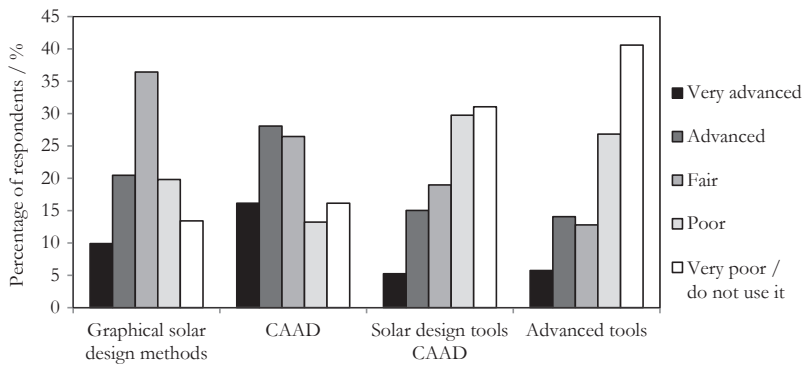


Figure 2.3 *Current skills of architects regarding digital tools (Horvat et al. 2011)*

Results also showed that architects have different needs for tools in each design stage.

Ibara and Reinhart (2011) compared six commonly used distribution methods for solar irradiation. The six methods were: 1) Daysim DS, 2) Daysim DDS-s, 3) GenCumulativeSky, 4) Ecotect tiles, 5) Ecotect Points, and 6) a manual method in Excel. Two test cases were compared; in one case, measured data was compared with the six different methods, while the second case represented a tower in a complex surrounding urban fabric. In case 1, where the measured data was taken as a reference, the biggest relative errors were made on the north side, using the manual calculation in Excel and with Ecotect Points. In case 2, the Daysim program was taken as a reference. Compared with Daysim, the biggest relative errors were seen, on average, with the Ecotect Tiles method. The results in this study have shown that Radiance-based programs made the smallest relative errors under these conditions. Furthermore, the authors demonstrated that differences in results between the different methods significantly influence the design recommendations.

Kanters, Wall and Dubois (2014) developed a tool that can be used to assess the solar potential of facades in complex environments. Besides providing the energy output of PV/ST on an hourly basis, it is also possible to obtain the economic value of this energy production.

2.3.2 Schematic design

When the relevant players agree on the concept design, the next stage starts. In practice, this transition might hardly be noticeable. In the schematic design phase, the layout of the building becomes more detailed.

Decisions and actions

In this phase, the following architectural design decisions have an influence on the conditions for solar energy:

- Detailed architectural design
  - Outer walls
  - Characteristics of solar products
    - Dimensions
    - Colour
    - Rhythm
    - Texture
  - Roof material
    - Dimensions
    - Colour
- Structural design decisions

A proper architecturally integrated system is "the result of a controlled and coherent integration of the solar collectors simultaneously from all points of view: functional, constructive, and formal (aesthetic)" (Farkas et al., 2013). In this design phase, the following actions should be taken to assure a good (architectural) integration of solar energy:

- Detailed layout of the system (strings, series / parallel)
- Exact dimensions of system and system components (tanks, etc.)
- Detailed layout of joints and materials
- Detailed financial evaluation
- Mutual shading of rows PV / ST
- Rough baseline energy model
- Provide annual energy use charts for baseline vs. proposed
- Detailed budget for renewable energy (detailed) / payback

Although the architectural integration of solar technology should be present from the very beginning, this phase is crucial since the integration concept becomes tangible. In the report *Solar Energy Systems in Architecture* developed within the IEA SHC Task 41, different levels of integration put forward are: added technical element, added technical element with double function, free-standing structure, part of surface composition, complete façade / roof surface, and form optimised for solar energy (Farkas et al., 2013). (Figures 2.4 and 2.5).

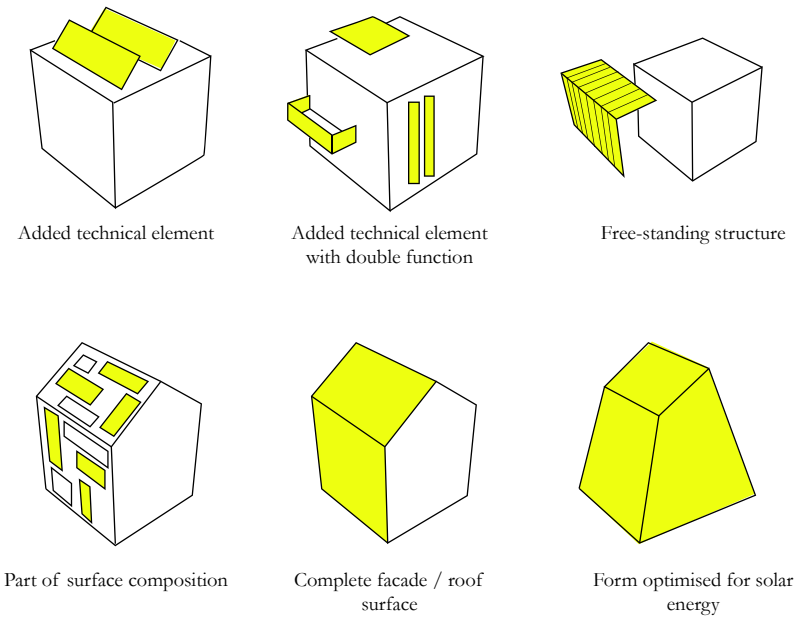


Figure 2.4 Categories of integration (adapted after Farkas et al., 2013)

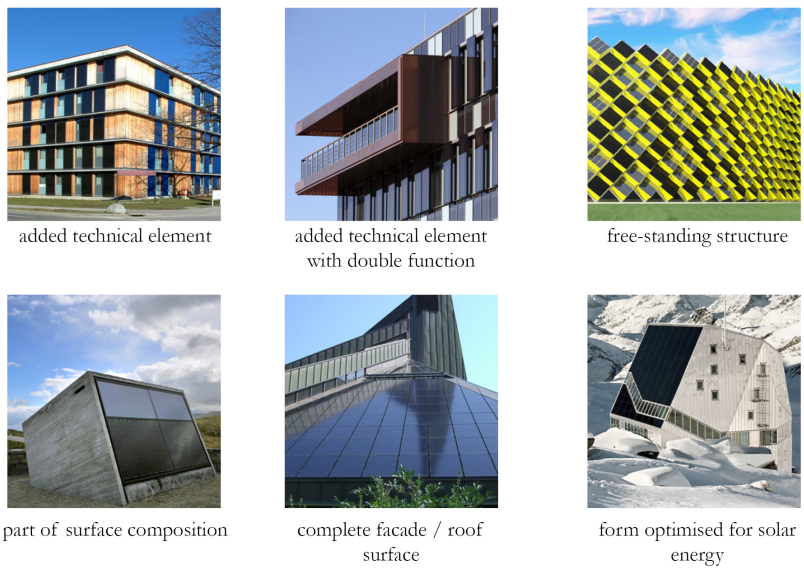


Figure 2.5 Examples of buildings per category (Kappel et al., 2014)

Compared to a traditional facade and roof design, a well-integrated solar system might require more design work. On the other hand, new solutions and architectural elements can be found, and it may also result in better aesthetics and lower costs compared to a later installation when the building is already constructed.

Tools and documentation

Simulation software helps the relevant players perform a full assessment of the technical and financial issues, as is shown in earlier studies (Chikh, Mahrane, & Bouachri, 2011; Davidsson, Perers, & Karlsson, 2012; Kornelakis & Marinakis, 2010). Common output of such tools is the annual, monthly and even hourly output, the size of the system components (mostly inverters), and an estimation of losses. Both mutual shading and shading due to surroundings have often been missing in the simulation software, but newer versions often allow assessment of shading. Tools supporting the architectural integration of solar systems are very scarce. One example is a CAD object tool which uses a library containing common PV cells and enables users to visualise the solar energy system (SUPSI/ISAAC, 2013).

Players

The main players involved in the concept design phase are the architect, engineer, real estate developer, and the product developer.

2.3.3 Construction documents

In the last phase of the design process, final details of the building and the embedded solar energy system are designed and documented.

Decisions and actions

In this phase, the construction details of the integration of solar products will be designed and documented. It is important to get the right details of solar products from the manufacturers for optimal integration of the products. Furthermore, the final design model has to be prepared, as well as the final documents for code compliance.

Tools and documentation

In this phase, detailed simulation software for solar energy systems is used, similar to those used in the previous phase.

2.4 Renovation phase

To reach targets on renewable energy production, it is crucial to not only focus on new buildings, but also on existing buildings. Real estate owners might either choose to renovate the building and implement solar energy while renovating or they might chose to add solar energy on top of the existing building envelope, resulting in a non-integrated solar energy system.

Voss (2000) described fourteen demonstration projects initiated in IEA SHC TASK 20 Solar Energy in Building Renovation, focusing on the technical, economic, and building physics issues of solar collectors, glazed balconies, and solar walls. The case studies showed that when buildings undergo renovation, solar energy can play an important role in helping to reduce energy use and in producing energy if it is considered at an early phase. However, solar concepts were rarely discussed in renovation strategies. Solar concepts in renovation can increase comfort and save energy, but were still considered as being too expensive.

Decisions and actions

The following decisions and actions have to be taken in the renovation phase – some of them overlap with the schematic design phase:

- Map the active solar potential of existing buildings (solar map)
  - Map and define integration issues in existing buildings
  - Sensitivity (heritage), material, colour, reflections
- Prepare for building permissions
- Detailed layout of the system (strings, series / parallel)
- Exact dimensions of system and system components (tanks, etc)
- Detailed layout of joints and materials
- Detailed financial evaluation

Tools and documentation

The mapping of the active solar potential can be done by means of solar maps as described earlier. For the detailed technical evaluation, the same detailed simulation software as for the schematic design phase can be used.

One important tool in the process is construction documents, where the architects and engineers determine how solar energy is implemented and how the constructor and installer should prepare the existing building for the next phase: the implementation phase.

2.5 Implementation phase

In this phase, the actual solar energy system is installed. The final installation of the system could affect the performance of a system. With good preparation and experience, installations flaws could be avoided.

Decisions and actions

- Install the solar energy system on the building
  - Actual jointing, installation
- Follow-up of system performance

Tools and documentation

Construction documents are the main tools used in this phase. They also assure a transfer of knowledge from one player to another. Preferably, the performance of an installed solar systems should be assessed as well as recorded.

2.6 Summary

In this chapter, a process map for implementing solar energy in the urban planning and building design process has been presented. The process map is based on a literature review and ongoing research within the framework of IEA SHC Task 51. Instead of focusing on the technical, social, political and financial aspect of solar energy, this process map focuses on the chronological aspect within the planning process, as well as on the players taking the major decisions regarding solar energy.

The process map distinguishes the following phases of the design process: political decision phase, urban design phase, building design phase, renovation phase, and implementation phase. Within these phases, the following aspects were discussed: decisions and actions, tools and documentation and players.

The presented process map underlines that every player in the design process has the power to influence the final decision to install solar energy on buildings either directly or indirectly, although the respective power of each player differs.

The process map highlights some critical points in the design process:

1) Having the right information on which to base decisions. Decision-makers might take decisions based on their own experience even

though their knowledge might be incomplete and/or outdated. This is especially true for real estate developers, whose decisions are often based on return-on-investment calculations; not taking into account the latest prices and developments on the energy market might lead to a wrong picture of solar energy.

2) The legal framework for solar energy is very much dependent on the political context in a country, which might change considerably in each political term. A long-term political will to create favourable conditions for solar energy will decrease uncertainties for investors in solar energy, thereby encouraging them to invest.

3) All players need to take responsibility to increase the uptake of solar energy. The design process is long, extending over years, and many players are involved. Until now, there has been no clear way for how solar energy should be considered in the design process. Often, the final decision to install solar energy is driven by personal belief or financial benefit (or both). This position could influence all relevant players.

4) Tools play an important role for decision-making during the design process. Different levels of detail in tools are necessary to provide useful information. The level of detail needed in the described phases increases as the design process progresses.



Part A: Integrating solar energy in the architectural design process

Architects can contribute significantly to a more energy-efficient built environment, since they make key decisions early in the design process (Wall, Windeleff, & Lien, 2009). However, it is unclear how architects make design decisions regarding energy and on what grounds these decisions are made. To gain insight into the design process used in architectural offices for solar integrated projects, and to identify the barriers and drivers of solar energy in architectural projects in Denmark, Norway and Sweden, semi-structured interviews were conducted with architects in these countries.

Part A was published as a licentiate thesis:

Kanters, J. (2012). Solar integrated architecture in Scandinavia : an analysis of the design process / Jouri Kanters: Lund : Lund University, Lund Institute of Technology, Department of Architecture and Built Environment, Division of Energy and Building Design, 2012.

3 Qualitative interviews with Scandinavian architects

3.1 Interview results

The following articles relate to this section:

PR1 Kanters, J., Dubois, M.-C., & Wall, M. (2012). Architects' design process in solar-integrated architecture in Sweden. [doi: 10.1080/00038628.2012.681031]. Architectural Science Review, 1-11. doi: 10.1080/00038628.2012.681031

PR2 Kanters, J., Horvat, M., & Dubois, M.-C. (2012). Tools and methods used by architects for solar design. [doi: 10.1016/j.enbuild.2012.05.031]. Energy and Buildings.

The qualitative research method involving interviews was chosen, because qualitative research can be used to acquire more knowledge about things about which little is known, to gain new perspectives on things about

which much is already known, or to gain more in-depth information that may be difficult to gather in a quantitative way (Corbin & Strauss, 1990). Interviews can also register a process and were therefore chosen as the most practical method of collecting data for this research, and also because interviews were used earlier in similar studies (Brunsgaard, Knudstrup, & Heiselberg, 2011; Petersen & Knudstrup, 2010; Portillo & Dohr, 1994; Saeema, 2005; Tomes, Oates, & Armstrong, 1998).

Three types of qualitative interviews can be identified: 1) the informal conversational interview, 2) interviews with interview guide (semi-structured), and 3) the standardised, open-ended interview (Patton, 1990). In this research, the semi-structured interview was chosen because it gives interviewees a certain freedom to express their ideas, and responses can be analysed in greater depth (Horton, Macve, & Struyven, 2004).

The interviews were structured according to an interview guide (Figure 3.1), which is a list of questions that the interviewer wants to explore during each interview. The interview guide was developed in cooperation with members of the IEA SHC Task 41: Solar Energy and Architecture.

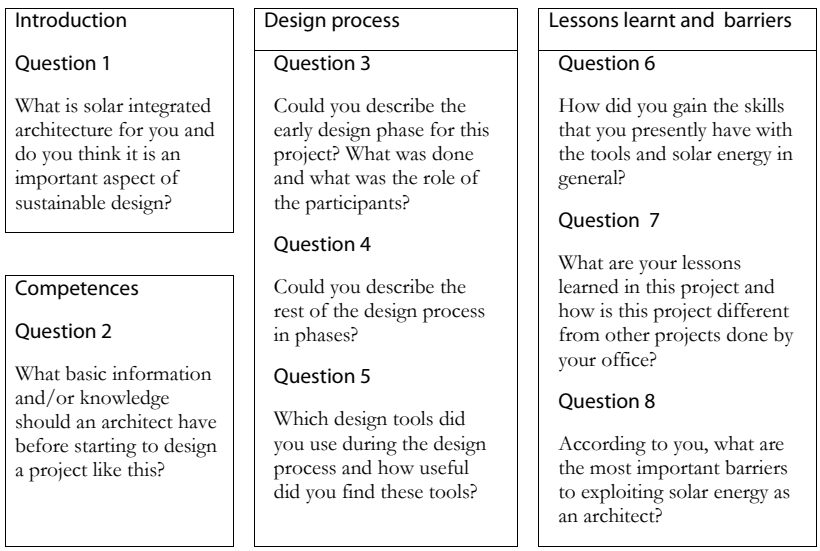


Figure 3.1 Interview guide for architects

A pilot interview was conducted to test the interview guide, which was deemed appropriate for its purpose.

In total, 23 interviews were held, between December 2010 and November 2011, with architects and urban planners in Denmark, Norway

and Sweden who had been involved in implementing solar energy in buildings. The interview guide was sent prior to the interview. In general, interviews lasted between 30-60 minutes and were tape-recorded. In Sweden, the interviews were held in Swedish, while in Denmark and Norway, the interviews were held in English. After the interviews, the content was transcribed and, if necessary, translated. The data was analysed using the steps of the grounded theory (Bryman, 2008). The program NVivo (QSR-International, 2006) was used to analyse and code the data of the interviews.

Results of the interviews can be divided into the following categories:

- Concept of solar integrated architecture
- Architects' skills
- Design process of the projects
- Barriers and drivers for solar energy

3.2 Concept of solar integrated architecture

Interviewees were asked to express how they define solar integrated architecture. In Denmark, architects mainly mentioned the passive use of solar energy (daylight / thermal mass / overheating / solar protection), while in Sweden it was mainly the active use of solar energy (PV/ST) that was mentioned.

With stricter regulations in all three countries, indoor comfort in buildings is becoming an important aspect when designing buildings. Many interviewees said that a risk of overheating was significant with current insulation levels and when the solar access is not considered. Consequently, the amount of fenestration and proper solar protection needs to be determined in the early stages of the design.

Interviewees also reported an increasing focus on technology in buildings. High-tech solutions are implemented to comply with stricter regulations, but do not always favour the users of a building since users are unable to affect their surroundings.

3.3 Architects' skills

Interviewees reported that solar energy was not a critical design aspect, so it might be asking too much to expect architects to have in-depth knowledge

of solar energy. Since all interviewees had worked with the implementation of solar energy in buildings, they identified a need for greater technical knowledge in order to design solar-integrated architecture.

Greater knowledge about solar energy was found to provide a twofold benefit: architectural offices could then make informed decisions themselves about design, and they would have better dialogue with engineers. Most of the interviewees felt that they needed to acquire more knowledge about solar energy, and responded mainly in two ways: offices either looked for opportunities to train their own employees or they set up close collaborations with engineers. In Denmark, interviewees mainly preferred the first approach, while Swedish interviewees mainly said they preferred the second.

Interviewees also said that much of the knowledge they gained about solar energy was through 'learning by doing', i.e. by being part of a design team. This in inherent to the profession of architects, where theory can and has to be applied to real-world cases. Study trips were also mentioned to be an inspiration source.

Interviewees were asked what knowledge about solar energy is needed in order to achieve a good implementation of solar energy in buildings. Basic knowledge about solar energy was found to be an overview of available solar technologies and systems. A deeper specific knowledge about local climatic conditions, active solar components, costs and grid connections was also found to be necessary.

3.4 Design process of the projects

Interviewees were asked to explain how the design process of a specific was organised: who took what decisions, based on which information?

Many projects started with the brief of the client requesting a 'sustainable' building; however a clear, measurable or quantifiable goal was hardly ever set. In almost none of the projects was the contribution of solar energy clearly set from the very beginning.

In projects prior to 2000, a more traditional design process prevailed but, after 2000, a shift towards an integrated design process (IDP) could be seen in the discussed projects. Architects and engineers work collaboratively to develop a design and technical system for a building and, often, the design process was started with workshops in order to set a common goal.

Close collaboration with the engineer was found to be crucial, and interviewees often expressed that this collaboration was very positive. However, the collaboration did not always work flawlessly. Interviewees

said that engineers did not always 'speak the same language' or did not always understand the architect's intentions.

In the discussed projects, the architectural integration of an active solar system was rarely set as a goal from the beginning. In the built projects, the implementation of active solar system can be divided into two groups: invisible and visible. In some projects, the choice was that the active solar systems should be invisible, often due to a lack of aesthetically pleasing solar products that could be incorporated into the architecture of the building. When active solar systems were chosen to be visible, it was rather often to serve as a *pedagogical example*; clients wanted to show that they care about energy, although it might mean that some systems did not end up in the most favourable position.

The passive use of solar energy (daylight, heat through windows) is always part of a design process, although it might not always be very well considered. In the discussed projects, interviewees mainly mentioned overheating and the design of solar shading devices to be crucial, since stricter building regulations makes it rather impossible to have fully glazed facades. Integrating solar shading devices into the architecture of a building might require customised solar shading devices or at least a well-designed solution with standard systems.

In the discussed design processes, different tools were used. In many projects, simple tools were used to carry out qualitative solar studies, for instance looking at shading patterns throughout the year. Also, simple rules of thumb were used for estimating appropriate dimensions of active solar components (and expected output), the inclination angle and the orientation of the system. For more qualitative assessment of solar energy, architects in Sweden relied on engineers (who used more advanced BPS tools), while in Denmark, more architects worked with such programs themselves. The ability to use such a program and perform iterative energy modelling enables the architect to evaluate different design options.

In some cases, architects tried to persuade real estate developers to install solar energy by providing an overview of financial benefits and costs.

3.5 Solar energy: barriers and drivers

Interviewees were asked to identify the barriers and drivers relating to the implementation of solar energy in buildings. The major barrier was found to be the relatively high costs of active solar systems, but this should be considered in context: 1) a long payback time makes it harder to convince real estate owners to invest in solar energy (especially those interested in short-term ownership of the building), 2) if clients had decided from the

beginning 'to go for solar', it was often pushed along, and 3) in Sweden, the current political climate was found to be a limiting factor for solar energy. These factors are beyond the control of the architect but decisions taken by the clients are, of course, critical in the design process.

Interviewees also said that the possibilities for import/export of solar electricity to the grid could be a barrier or a driver for solar energy; interviewees referred to the German feed-in tariffs that have worked as a driver for the installation of PV.

Building Assessment Methods were found to be a driver for the implementation of solar energy in a building. The interviewees noted increasing interest in real estate owners certifying a building according to a certain certification method. In such certificates, points can be gathered for the installation of solar energy.

The offer of attractive solar products was found to be very limited. A product which is adaptable and fits into the architecture of a building will make integration easier, and interviewees thought it best when the active solar system can replace building materials.

3.6 Summary

In this chapter, the results of an interview study have been presented. The objective of these interviews was to gain insight into the design process used in architectural offices for solar integrated projects and to identify the barriers against and drivers of solar energy in architectural projects. In 2011, 23 architects in Denmark, Norway, and Sweden were interviewed who had implemented solar energy into a building or urban planning.

The following main issues concerning solar integrated architecture and its design process were identified as important by the interviewed architects:

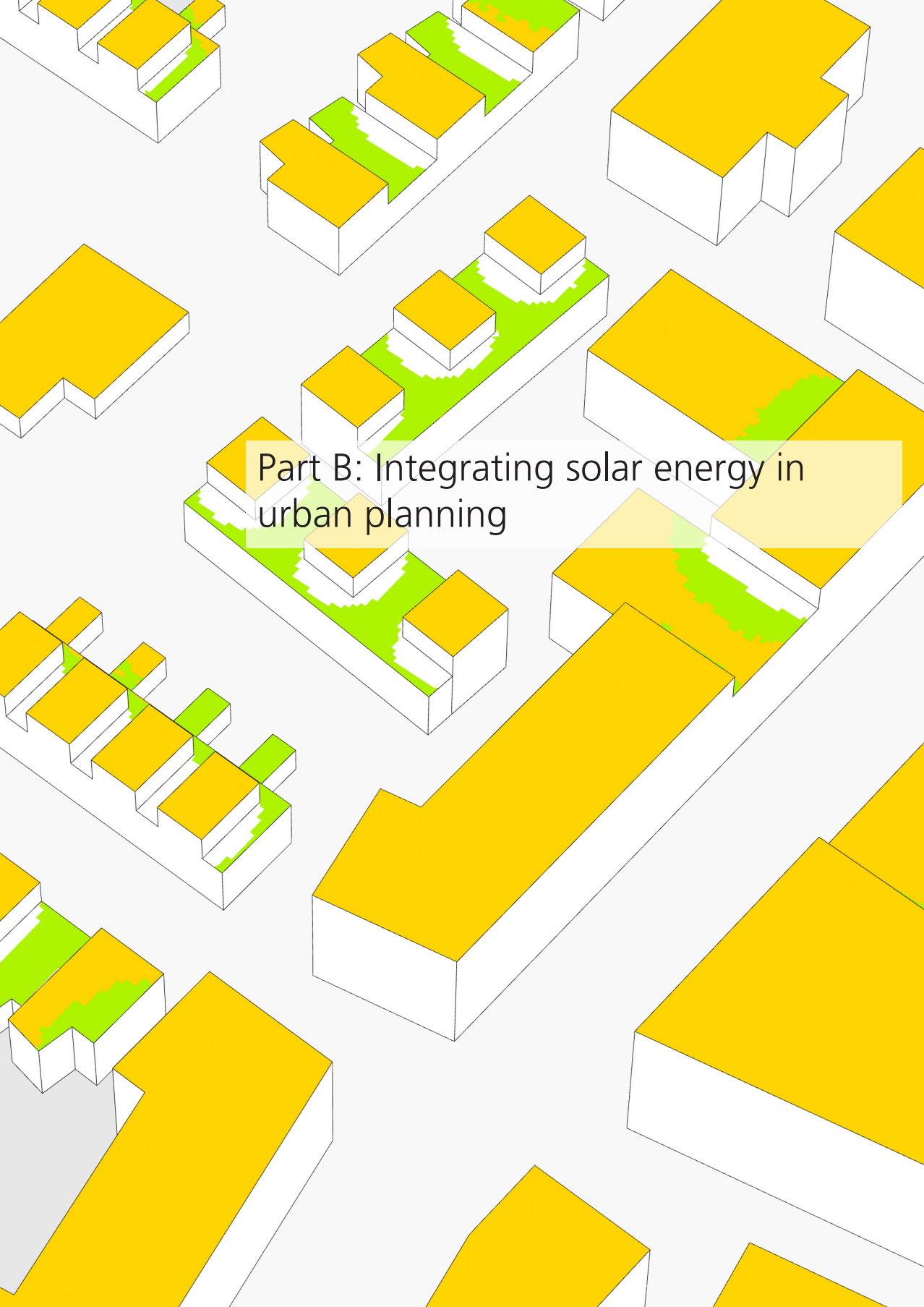
- Teamwork is crucial. Good collaboration between architects, engineers and clients is very important to reach the goals set for solar energy.
- Clients did not prioritise solar integrated architecture. This was mainly due to a resistance to investing in active solar technologies that did not provide short-term profit.
- Sophisticated BPS tools for solar energy were only used in a small number of projects, and 'rule-of-thumb' was far more common. Architects lacked the skills to use them or found them simply too complicated.
- There is a lack of aesthetically attractive active solar products.

- A zoning plan can limit or facilitate a building's solar potential due to placement of surrounding buildings or other obstruction factors, resulting in shading.

The results from the interviews with architects led to a focus on two key issues:

1. The urban planning process: how can we ensure favourable conditions for solar energy in buildings in an urban context?
2. Tools: how can tools be developed and/or improved to increase knowledge about solar energy throughout the design process of buildings?

These two key issues form the foundation for Part B.



Part B: Integrating solar energy in urban planning

The research question for this part was: '*How can we improve the urban planning process to facilitate a better integration of solar energy in urban environments?'*

The results of Part A, combined with a literature review, led to the creation of a theoretical map of the design process, as described in Chapter 2. An analysis of this theoretical model, together with the input from local urban planners, identified the following gaps in knowledge regarding the implementation of solar energy in buildings (the core of **Part B**):

1) Under which conditions is solar energy considered to be feasible?
2) How can we quickly consider solar energy in an early design stage in buildings within an urban context?
3) What effects do urban design decisions have on the solar potential of building blocks?

4 When is solar energy considered feasible?

The following conference papers relate to this section:

CP2 Kanters, J., & Davidsson, H. (2013). Mutual shading of PV modules on flat roofs: a parametric study. Paper presented at the SWC 2013, Cancun, Mexico.

CP5 Kanters, J., Wall, M., & Kjellsson, E. (2014). The Solar Map as a Knowledge Base for Solar Energy Use. Energy Procedia, 48(0), 1597-1606. doi: http://dx.doi.org/10.1016/j.egypro.2014.02.180

Assessing the suitability of surfaces for producing solar energy can be done in terms of many parameters, e.g. *which threshold irradiation level is considered to be financially feasible* or *how can a surface be used in such a way that it produces the most energy?*

These questions are therefore discussed in the following sections.

4.1 An analysis of solar maps

Solar maps have become an increasingly popular tool for assessing the solar potential of existing buildings in cities. The method of such solar maps is discussed in literature, although the focus of most of the literature is on how solar maps are constructed and how data is obtained and filtered (Gadsden, Rylatt, Lomas, & Robinson, 2003; Girardin, Marechal, Dubuis, Calame-Darbellay, & Favrat, 2010; Izquierdo, Montañés, Dopazo, & Fueyo, 2011; Jakubiec & Reinhart, 2013; Kapfenberger-Pock & Horst, 2010; Kraftringen, Lunds kommun, Lunds Tekniska Högskola, & Solar Region Skåne, 2012; Lukač, Žlaus, Seme, Žalik, & Štumberger, 2013; New York City Solar America City Partnership; Theodoridou, Karteris, Mallinis, Papadopoulos, & Hegger, 2012; Wiginton, Nguyen, & Pearce, 2010).

Although the technological background of these maps is very crucial, other important aspects remain to be investigated/developed:

- What assumptions are made in the rating of the suitability of surfaces?
- What additional information is provided to accelerate the implementation of solar energy?
- How is the information provided from the solar maps used (by front- and back-end users)?

To answer this, a total of 19 solar maps were studied. The objective was to gain more insight into how different solar maps are arranged, and because it was thought to provide useful information about thresholds set in different countries, i.e. when solar energy is considered 'feasible'.

The solar maps were studied from two perspectives: 1) how are surfaces categorised in these solar maps, and 2) how are the solar maps used as a tool for increasing the amount of solar energy installed in cities?

The analysed solar maps were: Aachen (Germany), Amersfoort (the Netherlands), Arnhem (the Netherlands), Basel (Switzerland), Berlin (Germany), Boston (USA), Bristol (UK), Dusseldorf (Germany), Geneva (Switzerland), Gothenburg (Sweden), Graz (Austria), Lisbon (Portugal), Los Angeles (USA), Marburg (Germany), New York City (USA), Osnabrück (Germany), Porrentruy (Switzerland), Solingen (Germany), and Vienna (Austria).

A quantitative analysis was performed, looking at the following aspects:

- Annual solar irradiation level (kWh/m^{2}a)
- Considered technologies (PV, ST)
- Total output per roof (kWh/a)
- Assumed efficiency of the technologies

- Heritage limitations (buildings with a cultural heritage are marked)
- Threshold value per category (kWh/m^2a)
- Minimum surface of the solar system (m^2)
- The percentage of maximum available annual solar irradiation level
- Maximum annual solar radiation
- Information on which parameters the categories were based upon

For the qualitative analysis, the owners were asked the following questions:

1. In your solar map you have different categories (good, very good, not suitable) for assessing solar energy. How did you choose the actual limits for the different categories? (E.g. based on financial motives, subsidies, etc.?)
2. How do you plan to work with the acquired information from the solar potential map (or how do you already work with it)?
3. Is it only meant for citizens or do you use it as an instrument for urban / energy planning? (Is it used for deciding political goals for the use of solar energy?)
4. Is the total potential summarised for the city or for different areas or categories of buildings?
5. Have analyses been carried out for ranking or comparing areas with, for example, apartment buildings and single family buildings respectively?

4.1.1 Results of quantitative analysis

Categorisation

The most important factor was the categorisation of surfaces. Figure 4.1 shows the values of the categories 'reasonable', 'good', and 'very good' of the different solar maps. In the box plot, the white part of the box represents the second quartile of the range, the black box the third quartile of the range.

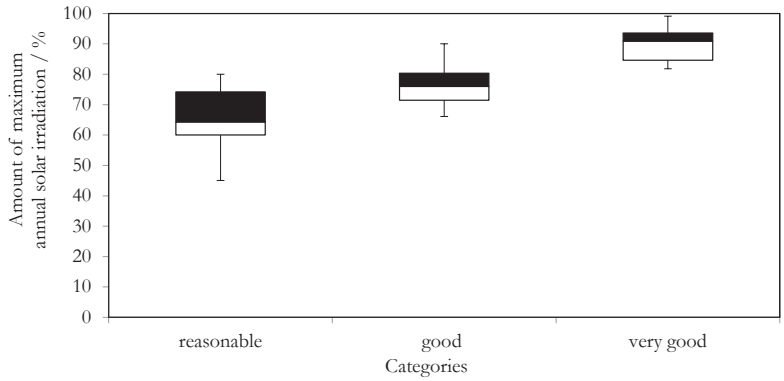


Figure 4.1 Box plot of categories applied in solar maps

Figure 4.1 shows that there is no common agreed way to set categories for a solar map. By comparing the categories as a percentage of the local maximum solar irradiation, the differences between the thresholds of the categories can only be explained by other parameters than solar irradiation, i.e. political, social, financial parameters.

Interestingly, the maximum value of the 'reasonable' category range is higher than the minimum of the 'good' category. This is also true for the highest value of the 'good' category and the lowest value of the 'very good' category. The spread of the values in the 'reasonable' category is quite high (35%), while spreading in the 'good' category is smaller (15%), and even smaller in the 'very good' category (13%).

The owners of the solar maps were asked to clarify how they categorised the surfaces on the map. It was expected that they would base their categories on a certain payback time of the applied solar technologies, but there was a mixture of answers: sometimes owners answered that the categories were based on the radiation level (which does not answer the question); in other cases, categorisation was done by best guesses, and only in some cases was categorisation based on detailed calculations of payback times. The Los Angeles solar map, for example, based the categories on a payback time shorter than 15 years, taking into account the general electricity costs and installation costs after subsidies.

Other parameters

Figure 4.2 provides an overview of the main parameters users of the solar maps can extract: heritage limitations, irradiation levels, PV output, and ST output. More than half of the solar maps provided an assessment of the output of a PV system installed on the roof, while less than half could

provide an assessment of the output of a ST system. Half of the solar maps showed culturally / historically important buildings where the implementation of solar energy might not be allowed or needs to be considered very carefully. Also, half of the solar maps were able to show the irradiation levels on roofs, while the other half did not show the irradiation levels but rather the output of solar energy systems. This might be due to the fact that, for laymen, it is easier to relate to the output of a system and the corresponding surface area than the incoming radiation.

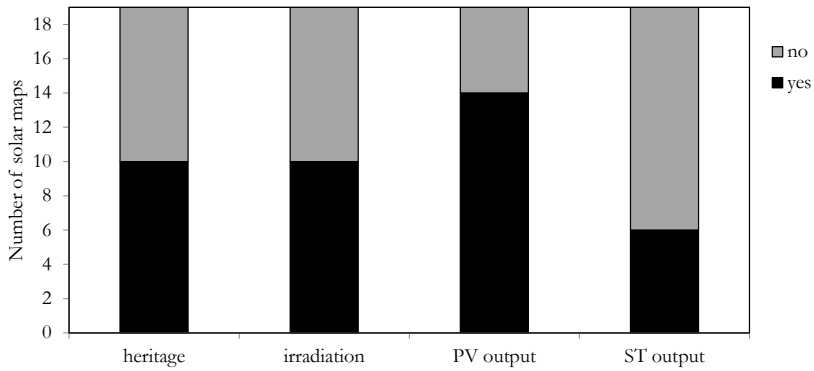


Figure 4.2 Main parameters of the solar maps

4.1.2 Qualitative analysis

Many of the studied solar maps not only focus on the quantification of the solar potential of roofs in the involved cities; they also serve as a platform to inform inhabitants about the possibilities of solar energy. In general, the analysed solar maps served both as a front-end and back-end tool platform. Most solar maps came with a short description of the solar energy potential and which methods were used to calculate it. Many solar maps also provided a rather detailed set of assumptions which are needed to calculate the output of solar energy systems, but it is often stated that the solar potential is just a 'first estimation', and that the owner (of the solar map) cannot be hold responsible for the calculations.

One example of how a solar map can be used both as a back- and front-end tool is in case of the City of Basel, Switzerland. This city launched an environmental program where inhabitants were encouraged to first renovate their roofs, and then install PV; if their roofs had the right conditions for both of the measures, the city would provide subsidies. A website

contained information on how inhabitants should proceed, and the city also approached the owners of the 500 best roofs for implementing PV.

Using the solar map and obtaining the solar energy potential of roofs is often the first step in decision-making for both inhabitants and cities. Front-end users need guidance in order to understand what the solar energy potential actually means. Some of the solar maps therefore focus on two additional items:

- Financial aspects of the system: revenues and costs
- Installations: which installers are available etc.

With this information, a well-founded decision can be made on the implementation of solar energy.

For the back-end users (and most often the owners of the solar maps), solar maps serve as an underlying information base for local energy decisions. In their responses, the involved cities say that they use the solar map for estimating the solar potential of all their own real estate. Some cities have underlying information about building types and year of construction. Performing such analyses takes time and money, and the benefit of such an analysis was not always clear to the cities.

4.1.3 Level of detail of solar maps

Analysis of the solar maps and the results of the surveys made it possible to classify the solar maps (Table 4.1). The basic solar map shows basic information about the irradiation level. Preferably, irradiation levels are also categorised. Such a solar map is the base for the medium and advanced solar maps, the features of which are all based on the analysis of annual solar irradiation of surfaces. The medium solar map provides the energy output of the suitable areas as PV / ST. The most advanced solar map not only provides quantitative data, but also information about how to proceed when people want to install PV or ST. A useful addition to solar maps could also be a feature that maps solar systems already installed within the city, with their size and output.

Table 4.1 Classification of solar maps

Basic	Medium	Advanced
- Irradiation levels - Categorisation of irradiation levels (not in all cases)	- Irradiation levels (not in all cases) - Output of solar systems (PV / ST) - Categorisation of suitable area for production - System effect (PV)	- Irradiation levels (not in all cases) - Output of solar systems (PV / ST) - Categorisation of suitable area for production - System effect (PV) - Monthly output (not in all cases) - Financial considerations (investment costs, revenue) - Information regarding installers - Information about solar energy

4.2 From a flat roof to a PV system setup – a case study

The following conference paper relates to this section:

CP2 Kanters, J., & Davidsson, H. (2013). Mutual shading of PV modules on flat roofs: a parametric study. Paper presented at the SWC 2013, Cancun, Mexico.

Roofs are normally the most exposed part to solar energy and therefore the most valuable area to use for installing solar energy systems. Calculating the solar potential of roofs is not always straightforward, especially not for flat roofs. Are panels to be placed in such a way that, together, they will generate as much energy as possible annually, or in such a way that they receive the highest irradiation level per solar panel? Mutual shading between the PV modules will result in lower outputs than when modules are unobstructed. The effect of mutual shading has been discussed in literature, but was often estimated rather than calculated.

The layout of a system on a flat roof depends mainly on the distance between rows and the inclination of the panels. To find out the effect of mutual shading, the following parameters were studied:

- Distance between rows *d* (0; 0.5; 1; 1.5; 2; 2.5 m and unshaded placement)
- Inclination α (0°, 15°, 30°, 45°, 60°, 75°, 90°)
- Location (Lund, Sweden (55°42′N 13°12′E) and Miami, USA (25°47′N 80°13′W))

The two locations were chosen to see the effect of latitude on the results, as well as the ratio between direct and diffuse irradiation. The first two factors result in the total amount of solar modules that can be put up on top of the roof; varying from 29 to 386 m^2. The output of a module (1.6 m^2) was calculated by simulating the incoming irradiation per cell and by taking the lowest irradiation for every string. Annual solar irradiation was simulated using DIVA-for-Rhino.

4.2.1 Results

Figure 4.3 shows the simulated annual output of a 1 m^2 module in Lund, compared to an unshaded module. It shows that the maximum output of the reference module is at an inclination between 30° and 45°. When the inclination of the rows is 0°, the effect of mutual shading is absent. When the row distance is 0 metres, the effect of mutual shading is greatest. When rows are placed further apart, the impact of mutual shading is reduced. The lowest output of a module was only 9% of a fully unshaded module.

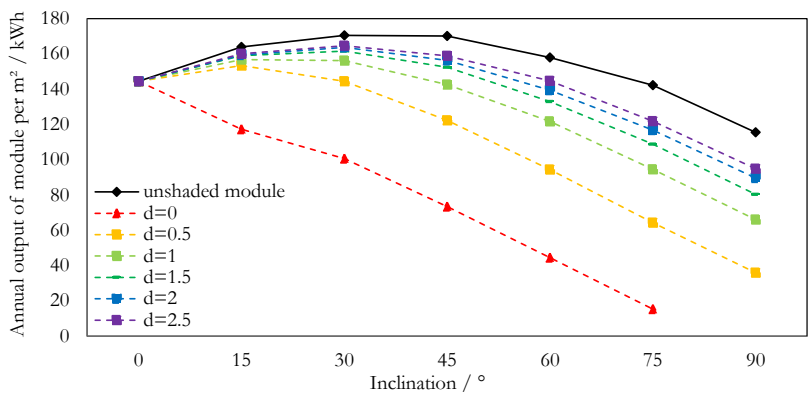


Figure 4.3 *Output of the reference module and the shaded module in Lund*

A similar figure can be drawn if the system were placed in Miami (Figure 4.4).

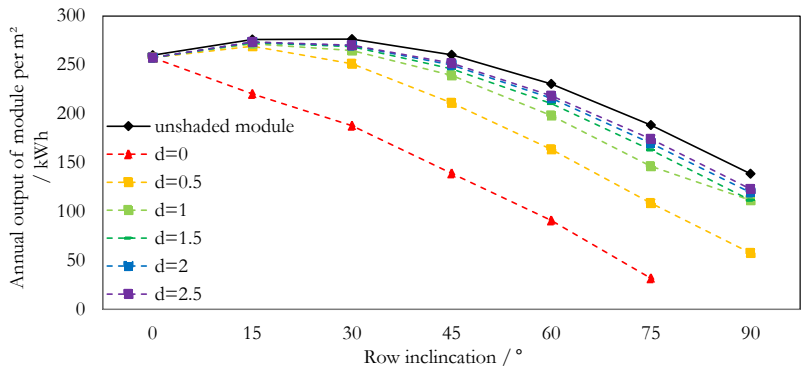


Figure 4.4 *Output of the reference module and the shaded module in Miami*

Comparing the results of Lund and Miami shows that the effect of mutual shading is less in Miami than in Lund. This is mostly due to the difference in solar altitude at the two places; in Lund, the altitude of the sun ranges from 11° (Jan) to 58° (July), in Miami, the altitude of the sun ranges from 41° (Jan) to 87° (July). The ratio between direct and diffuse radiation may also have an impact on the results.

The output of the whole system was calculated as follows: output of 1 unshaded row + output of *n* shaded rows (n is dependent on how many rows fit on the rooftop). The output of the whole system is shown in Table 4.2, with the highest output highlighted (maximum output of the system = 1).

Table 4.2 Relative output of the whole system

Lund	0m	0.5m	1.0m	1.5m	2.0m	2.5 m	Miami	0m	0.5m	1.0m	1.5m	2.0m	2.5m
0°	1.00	0.67	0.50	0.40	0.34	0.29	0°	1.00	0.67	0.50	0.40	0.34	0.29
15°	0.83	0.71	0.55	0.45	0.37	0.32	15°	0.88	0.70	0.53	0.43	0.36	0.31
30°	0.80	0.72	0.58	0.46	0.39	0.34	30°	0.84	0.71	0.55	0.43	0.36	0.31
45°	0.71	0.70	0.58	0.47	0.40	0.34	45°	0.76	0.68	0.54	0.43	0.36	0.30
60°	0.62	0.65	0.56	0.46	0.38	0.34	60°	0.71	0.63	0.51	0.41	0.33	0.29
75°	0.41	0.59	0.52	0.43	0.36	0.31	75°	0.48	0.56	0.45	0.36	0.29	0.25
90°	x	0.50	0.45	0.37	0.31	0.26	90°	x	0.45	0.43	0.29	0.23	0.19

In both Lund and Miami, the most favourable placement of the PV modules is with a 0° inclination, 0 metres row distance. Even though a 0° inclination reduces the yearly output by 15% (Lund) and 7% (Miami) compared to the optimal inclination, the fact that rows do not get shaded (i.e. the effect of mutual shading is 0) plays a very beneficial role. When row distances increase, it can be noticed that the most favourable inclination is the optimal inclination in both cases (30-45° in Lund, 30° in Miami).

When carrying out solar irradiation analyses at city level, the solar potential of flat roofs is often calculated by multiplying the surface area with the irradiation level of this area. This is however only partly correct; it is only valid when the row distance could be 0. With a row distance of 0.5 m, the total output of the system decreased by 28% in Lund and 30% in Miami in comparison to 0° inclination, 0 metres row distance.

The energy output of large PV systems is not the only important aspect to evaluate; investors are interested in both the investment costs and payback times. As can be seen in Table 4.3 and Table 4.4, configurations with a short row distance (or 0) generate more kWh but require greater module area (and consequently higher investment costs). A calculation of the payback time will take both aspects – value of the produced energy and investment costs – into account.

Table 4.3 shows the payback time for a system in Lund for two different electricity prices.

Table 4.3 Payback times of system in Lund

Payback time /yrs at price 1 kWh = 0.2 Euro							Payback time /yrs at price 1 kWh = 0.5 Euro						
	0m	0.5m	1.0m	1.5m	2.0m	2.5m		0m	0.5m	1.0m	1.5m	2.0m	2.5m
0°	16	16	16	16	16	16	0°	6	6	6	6	6	6
15°	20	15	15	15	15	15	15°	8	6	6	6	6	6
30°	23	16	15	15	14	14	30°	9	6	6	6	6	6
45°	31	19	16	15	15	15	45°	12	8	7	6	6	6
60°	50	24	19	18	17	16	60°	20	10	8	7	7	7
75°	144	35	24	21	20	19	75°	57	14	10	9	8	8
90°	x	63	35	29	26	25	90°	x	25	14	12	10	10

When the electricity prices are at their current level in Lund (1 kWh = 0.2 Euro), the shortest payback time can be reached by putting rows at a distance greater than 2 metres, inclination 30° . If the electricity price and/or feed-in tariff were to increase (1 kWh = 0.5 Euro), then multiple options provide the same results. Because of its higher irradiation levels, Miami will be more favourable for installing PV systems than Lund.

Table 4.4 shows the payback times of a system with different parameters in Miami. Both with the current electricity price as well as with a higher price, the most favourable placement is to put the PV modules with a 15° inclination at a distance of at least 0.5 metre from each other.

Table 4.4 Payback time of system in Miami

Payback time /yrs at price 1 kWh = 0.1 Euro							Payback time /yrs at price 1 kWh = 0.5 Euro						
	0m	0.5m	1.0m	1.5m	2.0m	2.5m		0m	0.5m	1.0m	1.5m	2.0m	2.5m
0°	18	18	18	18	18	18	0°	4	4	4	4	4	4
15°	21	17	17	17	17	17	15°	4	3	3	3	3	3
30°	24	18	18	18	18	18	30°	5	4	4	4	4	4
45°	33	22	19	19	19	19	45°	7	4	4	4	4	4
60°	50	28	23	22	22	22	60°	10	6	5	4	4	4
75°	138	42	32	29	28	27	75°	28	8	6	6	6	5
90°	x	78	41	42	39	38	90°	x	16	8	8	8	8

4.2.2 Strategy – maximise profit or energy output?

What is more important, a short payback time or as much output as possible (or a balance between those two)? Electricity prices tend to increase over time; Tables 4.3 and 4.4 show that when electricity prices go up, inclination and row distance become less important. In that sense, there is no longer a need to make a choice: those system setups that deliver a high output also become feasible. Results also showed that it would be most favourable to install the PV modules horizontally at a row distance of 0 metres, but a row distance of 0 metres is quite hard to achieve in reality, since installing and maintaining the panels require a certain amount of space.

A further development of this study is desirable. It would be useful to look at the monthly output of the whole system and to value the output differently for each month, since electricity prices in Sweden differ per month. Such a study might lead to a different system setup (inclination and row distance). Furthermore, the development of a script in Grasshopper (the environment where Rhino is connected to DIVA-for-Rhino) might be useful to determine the best inclination and row distance of a specific roof. This would make it easier for architects to make decisions during the design process.

4.3 Summary

In this chapter, an analysis of existing solar maps has been presented, as well as a study of how to set up a real-world PV system on a flat roof. Both studies consider decision-making not only based on solar irradiation, energy production, costs and payback time, but also on available space for installing solar energy systems mainly on roofs.

Solar maps have become a well-used tool for both front-end and back-end users to assess how suitable their roof is for installing solar energy. The analysis of 19 solar maps showed that there is no common methodology for assessing the solar potential of roofs. Three levels of detail of solar maps were identified: basic (showing mainly irradiation levels), medium (providing energy output of ST / PV systems) and advanced (providing not only the energy output and financial data, but also serving as an information platform for solar energy).

Flat roofs are rather common in the urban context. Most solar maps do not distinguish between flat and inclined roofs although they have different potential. In a real-world setup of a solar energy system, the parameters row distance and inclination will determine how much energy could be produced.

To examine the technical and economic consequences of mutual shading of PV systems, a parametric study was carried out to assess the influence of row distance and inclination. Results showed that row distance smaller than 1 metre significantly reduced the output of a module. Modules placed with a bigger row distance produced less output than unshaded ones, but were less affected by mutual shading (less than 10%). The effect of mutual shading was more significant in Lund than in Miami, mostly due to higher sun altitudes all year round. Results also showed that the solar potential of a flat roof cannot simply be calculated by multiplying the roof area with the irradiation level on that flat roof, but that a conversion factor also needs to be built into the equation, ranging from 0.26-1.

This chapter has not answered the question of when solar energy is considered to be feasible. However, what it has has revealed is that there is no common accepted methodology to assess feasibility of solar energy, since feasibility means different things to different players. It also became clear that other factors affect such a financial assessment; is it necessary to produce as much solar energy on a roof (often leading to a sub-optimised panel setup) or is it necessary to optimise the panels (often leading to a lower production per roof)?

Until now, most solar maps have only assessed roofs. Although this is normally the most logical place to install solar energy systems, facades might in some cases be suitable too. The next chapter describes the de-

velopment of a tool that can assess whether facades are suitable building components on which to install solar energy.

5 Tools

5.1 Development of FASSADES: a facade assessment and design tool for solar energy

The following article relates to this section:

PR3 Kanters, J., Wall, M., & Dubois, M.-C. (2014a). Development of a Facade Assessment and Design Tool for Solar Energy (FASSADES). Buildings, 4(1), 43-59.

Stakeholders in the design process need to obtain all necessary information to assess *if* and *how* the implementation of solar energy would be a feasible alternative for generating renewable energy. Providing decision-makers with information in the design process by means of tools is a valid strategy in making informed design decisions.

Several tools are currently available for assessing solar energy in the built environment. The abovementioned tools consider many aspects of solar energy, but most of them focus on a specific scale (city scale, building scale, system scale). Therefore, a facade assessment and design tool for solar energy (FASSADES) was developed, providing the necessary information for all stakeholders involved in the design process. The secondary objective was to validate the tool by performing an analysis of a building block.

5.1.1 Workflow of the FASSADES tool

The FASSADES tool performs a full assessment, and consists of simulating the solar irradiation on the entire facade (taking into account shading caused by surroundings), calculating the (hourly) output of a possible ST or PV system, the economic value of this production, and the payback time of the solar energy system. The workflow of the tool is shown in Figure 5.1.

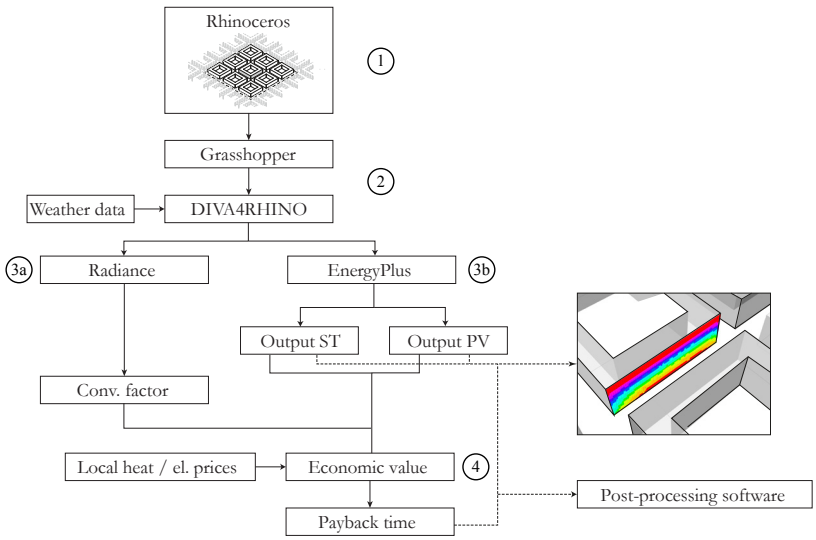


Figure 5.1 Workflow of the FASSADES tool

5.1.2 Validation of the tool

The FASSADES tool was used to demonstrate its capacity to perform a full assessment of the solar potential of a building block. The energy production and the financial return of ST systems integrated in facades of a typical building block representing a typical urban planning situation in Sweden were assessed. A section of the building block can be seen in Figure 5.2.

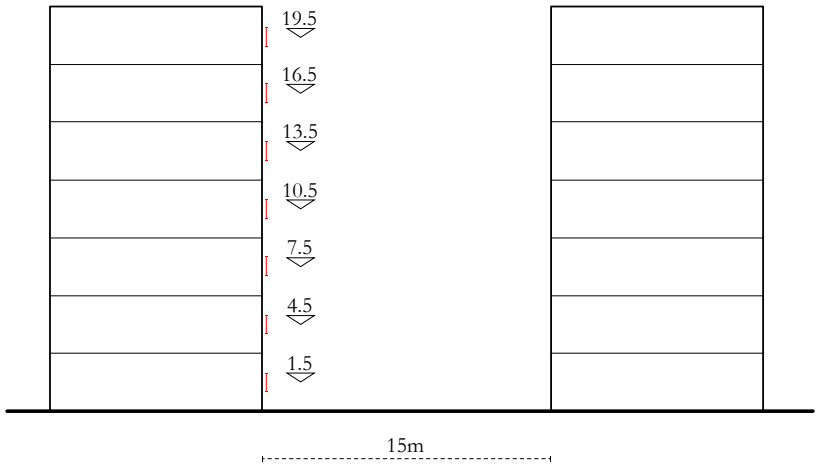


Figure 5.2 *Section of building block and location of sensor points*

The facades were analysed one-by-one in the FASSADES tool, with a running time of around 3 minutes per facade. The facade area was divided into a 1 m x 1 m grid and the output of 1 m^2 surface can be calculated as a PV solar cell or as ST solar panel with different system temperatures, calculated through different equations. Figure 5.3 shows an example of the output of a 1 m^2 facade surface, seen as a function of the height from the ground.

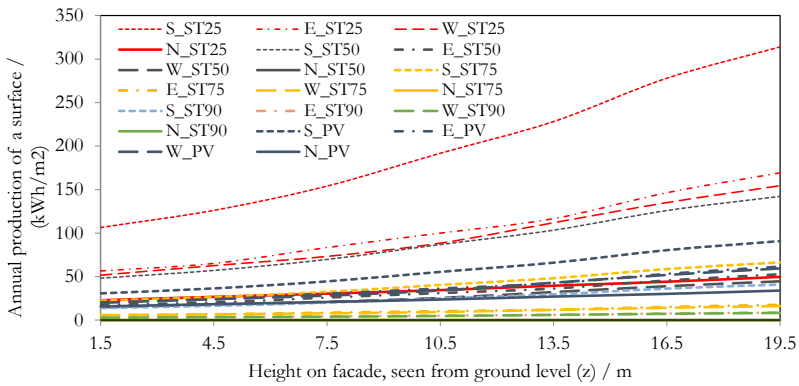


Figure 5.3 *The annual energy production as a function of height from ground. The value after ST and PV corresponds to the system temperature (25°, 50°, 75°, 90°C)*

With the simulated production data, a financial assessment of the facade can be performed. The FASSADES tool calculates the production of ST/PV and the economic value of the produced energy, both for heat and electricity, based on current heat and electricity prices. Real estate owners, as well as other people in the position to install solar energy systems in buildings, need to assess the economic benefits of installing solar energy technologies. The payback time is one important metric to calculate the feasibility of investment decisions. Another metric could be the profit after 25 years of use. Figure 5.4 shows the payback time as a function of the height from the ground on the south facade, based on the production as shown in Figure 5.3 and the economic value of this produced energy.

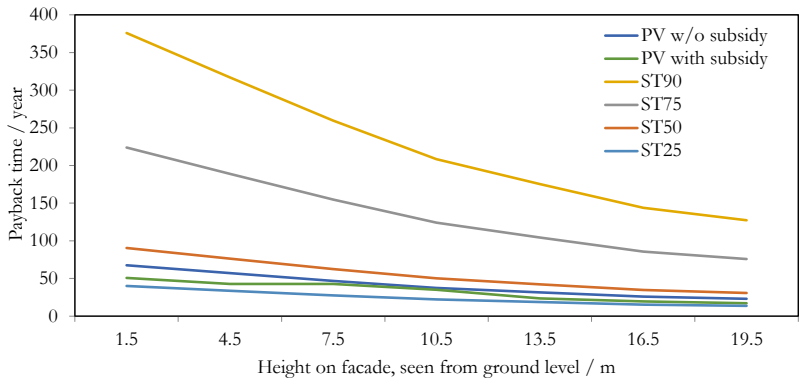


Figure 5.4 Payback time as a function of height

The results also highlighted that a detailed simulation on an hourly basis is needed to fully assess the solar energy potential production and cost benefits.

The FASSADES tool can also display the annual production of the different technologies per facade, as shown in Figure 5.5.

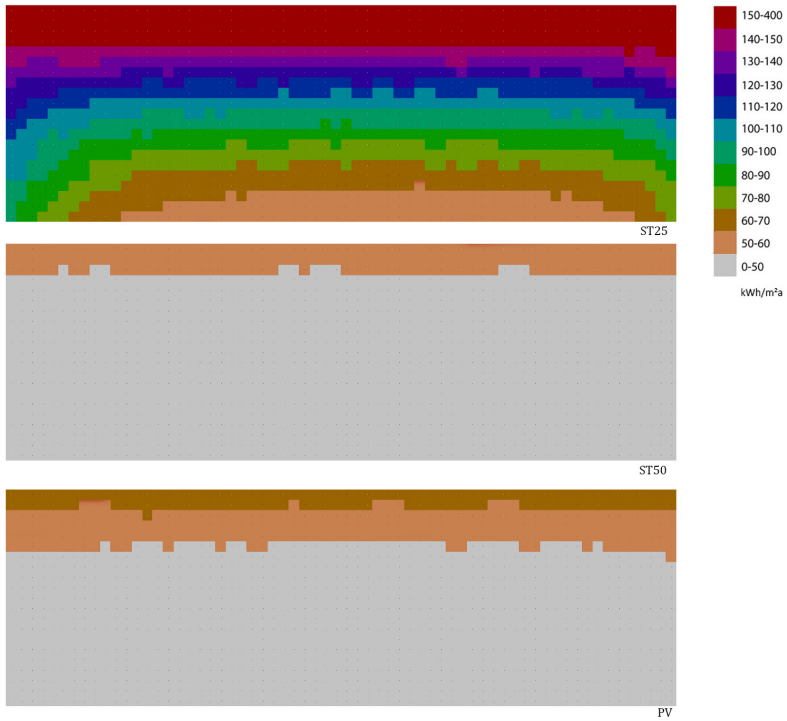


Figure 5.5 Annual production of ST 25°C, ST 50°C and PV on the east facade

The FASSADES tool can be improved further: at the moment, only one part of the building envelope at a time can be analysed. Another improvement would be to make the tool easier by using user-defined objects, thereby lowering the knowledge level needed to use the tool. Calculations performed in the FASSADES tool depend on many parameters, which could cause errors: many assumptions are made, especially regarding the financial costs and benefits.

5.2 Summary

This chapter described the development of an assessment and design tool for solar energy on facades, based on combining the simulation software Radiance / Daysim with EnergyPlus in the DIVA4RHINO environment.

The facade tool first calculates the hourly irradiation on the building envelope, then calculates the possible heat production from a solar thermal system with a certain system temperature or the electricity production from a PV cell. Then, the economic value of the produced energy is predicted by taking into account the current local heat and electricity prices. The payback time is then calculated based on the investment costs and the annual revenues.

The tool was validated by using it to analyse a typical Swedish building block. Results of this analysis showed that shading due to surrounding buildings significantly affects both irradiation and production, leading to long payback times. The results also highlighted that a detailed simulation on an hourly basis is needed to fully assess solar energy potential production and cost benefits.

The analysis performed in this chapter has confirmed that shading from surrounding buildings significantly affects the solar potential of a building block. This leads to the question: how can urban planners plan new buildings in such a way that they fully exploit the incoming solar radiation without blocking solar access of other buildings? In the next chapter, this issue is discussed.

6 Influence of design decisions on the solar potential of building blocks

Urban planners shape conditions for solar energy in mostly new building projects, since zoning plans may either limit or allow the implementation of solar energy. Workshops and meetings with urban planners have led to the question of what a zoning plan would be like if solar energy was the only design parameter – but considering common building blocks.

Two parametric studies were carried out to examine this. The first focused on the solar energy potential of existing building blocks and newly planned building blocks. The second focused more on new building blocks and various roof shapes, but also on what load match can be reached within new buildings.

6.1 Parametric Study 1: Urban District Design

The following conference paper relates to this section:

CP4 Kanters, J., Wall, M., & Dubois, M.-C. (2014b). Typical Values for Active Solar Energy in Urban Planning. Energy Procedia, 48(0), 1607-1616. doi: http://dx.doi.org/10.1016/j.egypro.2014.02.181

In this section, a parametric study is described focusing on the influence of density, form and rotation of urban districts. Four typical Swedish city blocks designs were modelled based on city blocks in the southern cities of Malmö and Lund (Figure 6.1); two were based on existing city

blocks (Rörsjöstaden and Norra Fäladen), and the other two were based on planned city blocks (Hyllie and Brunnshög).

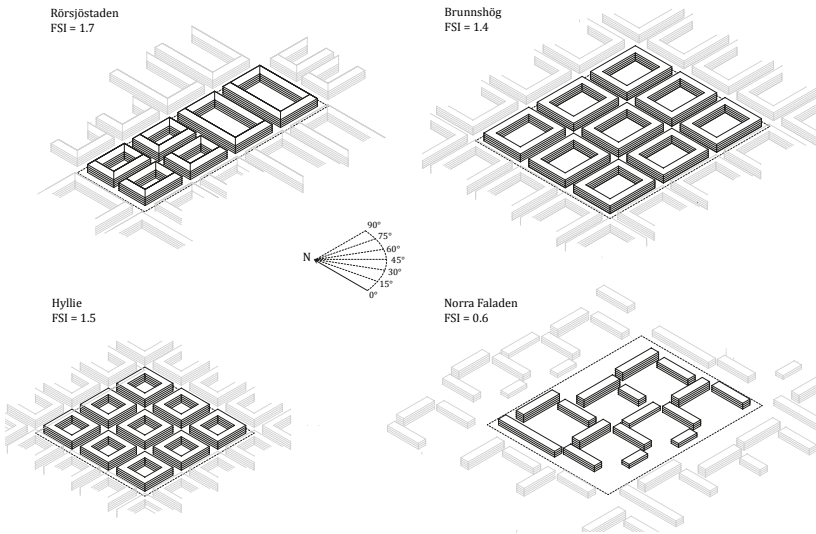


Figure 6.1 The four simulated city blocks and their actual FSI

The first step in the analysis was to simulate annual solar irradiation in DIVA-for-Rhino (D4R) embedded in the CAAD program Rhinoceros, using the GenCumulativeSky (Robinson & Stone, 2004) model for solar radiation.

The next step consisted of comparing the total annual solar irradiation with the energy demand of the buildings. The surfaces on the roof and facade that received annual solar irradiation exceeding 650 kWh/m²a were considered suitable, which is justified in an earlier study (Kanters & Horvat, 2012). The ratio between produced energy and consumed energy is called energy coverage in this study.

Two hypotheses were tested: 1) the Norra Fäladen design would perform poorly compared to the other designs due to self-shading, and 2) the Rörsjöstaden design would perform better than the Brunnshög design due to its pitched roofs.

Results

Figure 6.2 shows the annual electricity coverage of the different designs. A 100% coverage means that the annual electricity produced by PV equals the annual electricity use.

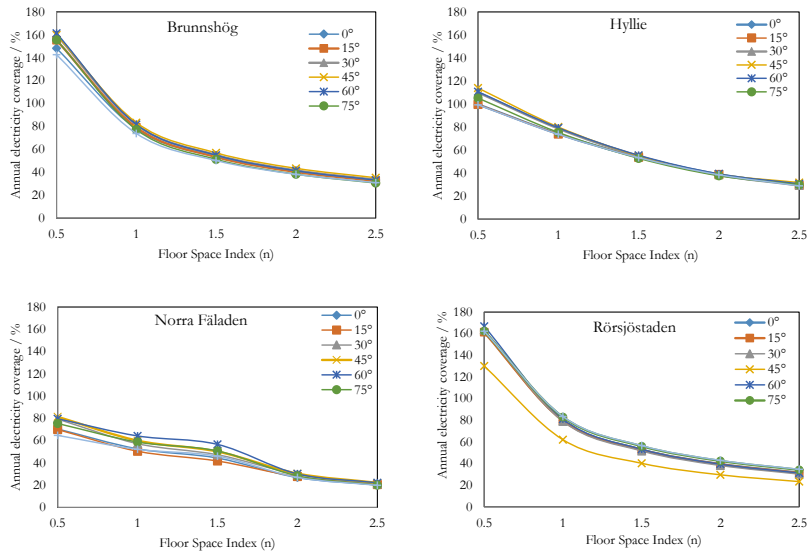


Figure 6.2 *Annual electricity coverage at different densities. The different curves represent the building blocks with different orientations*

The four graphs in Figure 6.2 show that there is a significant difference in annual electricity coverage due to the layout of the city blocks, especially for the lowest densities. In general, it can be seen that for the higher densities (>1.5), the absolute differences between the different layouts are less significant. This can be explained by the decreasing suitable area (roof area plus suitable facade) per floor area. At lower densities, the amount of suitable area is relatively high compared to the floor area, while at higher densities, this ratio decreases. The patterns in Brunnshög and Rörsjöstaden are almost identical, also at lower densities. Hyllie does not follow the same pattern as Brunnshög, although their geometry is quite similar (Brunnshög is slightly more rectangular). The irregular pattern in the results obtained for Norra Fäladen is most likely caused by its special "scattered" geometry increasing the impact of self-shading.

As expected, the rotation of the building blocks had less impact in the Brunnshög, Hyllie and Rörsjöstaden layouts, except for the Rörsjöstaden 45° rotation, which provided less energy covering for all densities. This is because, at exactly 45°, much of the roof received slightly less than the threshold due to shading at the place where the two sloped roof surfaces meet. The results also show that rotation had a greater impact in the Norra Fäladen layout compared to the other layouts. Noteworthy is that differences between orientations also became less significant at higher densities.

The annual heating coverage showed a similar pattern compared to the electricity coverage, but the heating coverage was lower than the electricity coverage.

The first hypothesis was confirmed. In none of the cases did the Norra Fäladen design return the highest energy coverage. This configuration also proved to be more unpredictable than the others, i.e. the energy coverage varied in a "chaotic" way for different densities and rotations. The design of the Norra Fäladen area consisted of various scattered building blocks, resulting in strong mutual shading effects.

The second hypothesis was rejected. Most of the building blocks with pitched roofs did not return much higher energy coverage, which was expected. The Rörsjöstaden design was comparable to the Brunnshög and Hyllie designs, basically similar but with flat roofs. The design of a roof solar system should obviously be kept in mind; a flat roof can have a high potential, but the setup of the system – number of rows, row distance, and inclination – also plays a crucial role in converting these flat roofs into energy producing surfaces. In the present study, the collectors were assumed to lay flat on the roof (no inclination resulting in no mutual shading, no row distance).

Results also showed that 100% coverage or higher with solar energy can be achieved only for low densities (FSI<1.25) for the studied conditions in Sweden. This therefore confirms the fact that a significant contribution could come from active solar energy but that solar energy systems need to be supplemented by rigorous energy conservation measures and other renewable energy sources like wind, geothermal energy, and waste heat.

One great limitation of this study concerns the issue of annual versus monthly or hourly production and coverage by means of solar energy. A further study into the monthly and even hourly coverage would be very useful, since the amount of solar energy fluctuates significantly during the year and day in Sweden.

6.2 Parametric Study 2: Building Block Design

The following journal article relates to this section:

PR4 Kanters, J., & Wall, M. (2014). The impact of urban design decisions on net zero energy solar buildings in Sweden. Urban, Planning and Transport Research, 312-332. doi: 10.1080/21650020.2014.939297

With the European Directive on Nearly Zero Energy Buildings, a legitimate question is how much solar energy can contribute as a renewable energy provider for buildings within the urban context, since the surroundings will determine the possibilities for exploiting solar energy. The Swedish zoning plan determines the density of cities, the shape of buildings, the height, inclination of roofs, roof types, function, etc. Conditions for solar energy – both passive and active – are therefore indirectly set by the design of such a plan, which could lead to further constraints in the design phase if buildings, for example, are too shaded (Kanters, Dubois, & Wall, 2012).

The objectives of this study were to examine the limitations of solar powered net zero energy buildings and to look into the effect of early urban planning design decisions – mainly density, orientation, roof type, and form. Four different design parameters were explored in this study: the design of the urban building blocks, the orientation, roof type and density. Four typical *building block designs* were chosen as input for the study (Figure 6.3). Three different roof types were studied and the density of the building blocks varied (between 0.5-2.5). Orientation also varied.

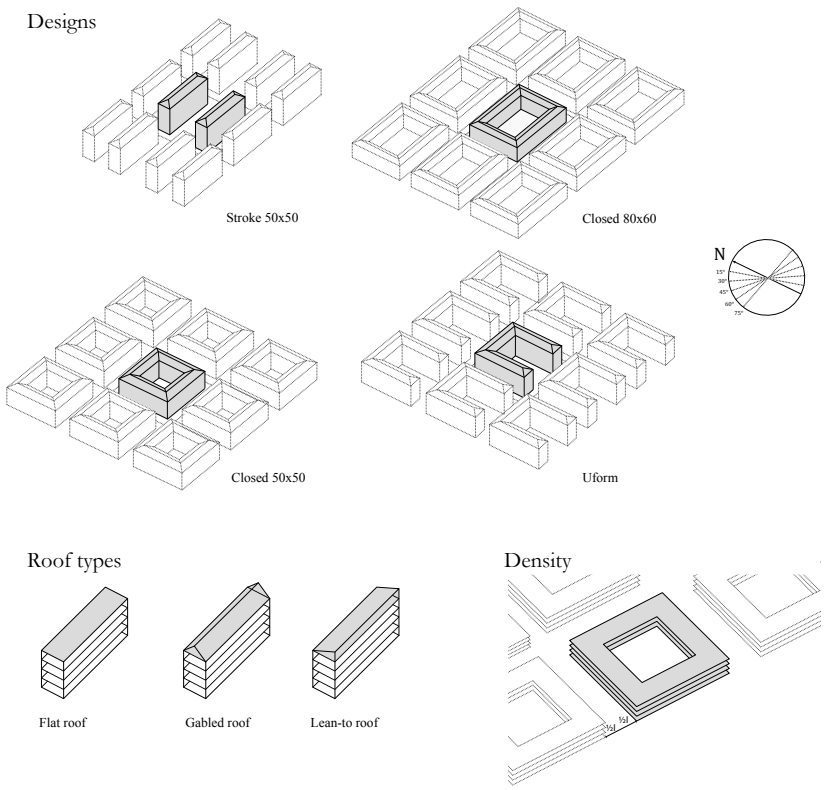


Figure 6.3 *Geometries and parameters used*

The total energy demand of the buildings was calculated according to the Swedish building regulations and the low-energy standard for building FEBY.

The second step involved simulating annual irradiation with the tool DIVA4RHINO. The simulations resulted in a list of surfaces with their respective area and irradiation level. The surfaces were then divided into four categories: unsuitable, reasonable, good, and very good. Surfaces were placed in one of these categories on the basis of their collected amount of annual irradiation.

The third step was the calculation of the load match; the ratio of produced energy compared to the needed energy.

Results of Parametric Study 2

One outcome of this parametric study was a new metric for the solar potential. In literature, the solar potential is often referred to as the amount of solar irradiation received on the building envelope or as the ratio of suitable area (those areas that receive greater irradiation than a certain threshold) of the building envelope. These metrics do not have a link to the building's energy need, which is often connected to the size of the floor area, so an alternative metric is introduced in this article called $SAFAR_n$ (Suitable Area to Floor Area Ratio), where *n* represents the threshold value in kWh/m^{2}a. This gives us the ratio of suitable area (area receiving an amount of solar radiation greater than or equal to the preset threshold *n*) to floor area of the considered building.

Plotting the $SAFAR_{650}$ (Figure 6.4) for all design options to the density (FSI) shows that the graph is similar to a power function.

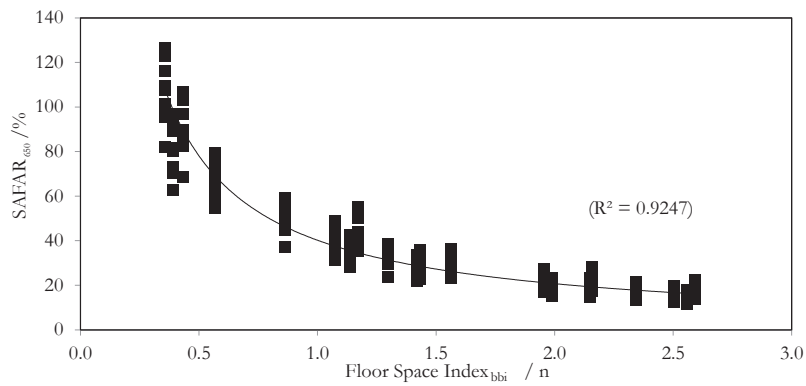


Figure 6.4 *$SAFAR_{650}$ for all design options (averaged for all orientations)*

One reason for using the $SAFAR_n$ metric is that it might be a way to prepare a Swedish zoning plan for solar energy. Since urban planners (in Sweden) are not allowed to prescribe use of a certain technology in the zoning plan, it should be possible to use the $SAFAR_n$ metric, since it is officially energy-neutral (although its thresholds are indirectly based on active technologies).

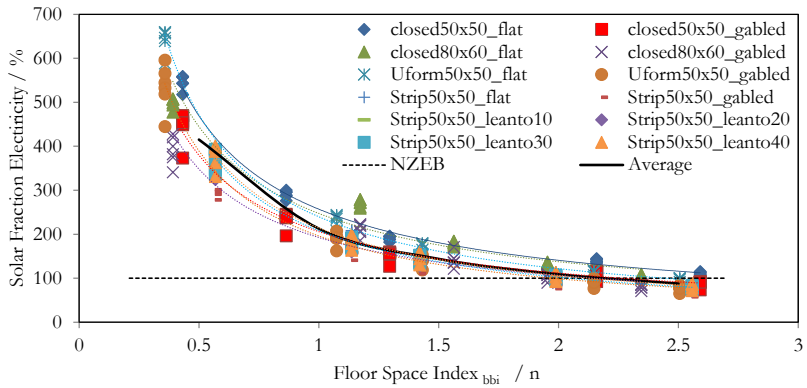


Figure 6.5 FEBY / BBR load matching for electricity demand

The results in Figure 6.5 show that the average of all options resembles a power function. A 100% electricity load match can be reached for the BBR and FEBY standards at low densities. At densities greater than ~2.25, most of the building block configurations no longer reach a 100% load match. The highest electricity load match is achieved for the option Uform50x50flat while, at roughly the same density, Closed80x60gabled returned only 50% of the load match of Uform50x50flat, which is a very significant difference. Especially for the lower densities, differences between the design options are greatest; at higher densities, the differences are almost negligible.

Generalisations of results

To plan for energy-efficient cities, it would be beneficial for energy and urban planners to work with rules of thumb. To produce such rules of thumb, the average value for the load matching for heating and electricity for all design options and orientations was explored, taking the following parameters into account: the ratio PV-ST, the electricity and heating demand, and the density. This resulted in the following set of equations:

$$R_{PV} + R_{ST} = 1 \qquad \text{Equation 6.1}$$

$$L_{PV} = \frac{4258.6}{Q_{electricity}} \cdot R_{PV} \cdot d^{-0.964} \qquad \text{Equation 6.2}$$

$$L_{ST} = \frac{11356.4}{Q_{heat}} \cdot R_{ST} \cdot d^{-0.954} \qquad \text{Equation 6.3}$$

Where:

R_{pv} = Ratio of Photovoltaics [-]
R_{st} = Ratio of Solar Thermal [-]
L_{PV}: Electricity load matching with photovoltaic systems [%]
$Q_{electricity}$: Annual electricity demand [kWh/m^2]
d = Density (Floor Space Index) [-]
L_{ST}: Heating load matching with thermal systems [%]
Q_{heat} = Annual heat demand [kWh/m^2]
d = Density (Floor Space Index$_{bbi}$) [-]

The influence of roof type was also analysed. The results show that in the majority of the cases, the flat roof returns the highest value. This is interesting since it was expected that in most cases, the lean-to roofs would generate the highest production. The stroke option consists of two strokes; roofs with a high inclination will therefore shade the stroke behind the first stroke more. The biggest relative difference between the different roof types was 32%. Furthermore, the gabled roof never had the highest load match, but in some cases it was rather close to the maximum. That means that in reality, the well-oriented parts of the gabled roof receive a higher amount of solar radiation, but that a large part of the roof receives less than the threshold value due to its orientation. However, the investment costs per m^2 of installed solar system are lower since the irradiation per m^2 is higher.

A flat roof, however, raises the question of how to set up a PV system efficiently (row distance, inclination), an issue that can significantly determine the production the whole system (Kanters & Davidsson, 2013). The results show that the type of roof affects the possibilities for utilising solar energy significantly. In this study, the gabled roof and the lean-to roof were options, but in reality, the consequences for some of these options would be significant. A lean-to roof with an inclination of 40° and a building with a width of 12 metres would result in a height of 10 metres (see Figure 6.6), which implies multiple storeys.

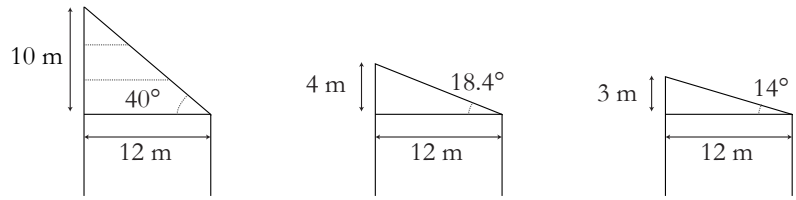


Figure 6.6 Consequences of roof types on building height

A more reasonable inclination would be one-storey height, e.g. 3 or 4 metres (Figure 6.6). This would result in inclinations of 14° and18° respectively. A lean-to roof with a lower inclination (10° or 20°) would not produce the greatest amount but, in some cases, it produces more than a flat roof.

An analysis of the effect of orientation on the load match shows that there is no apparent optimal orientation, except that the maximum is often achieved at orientations between 15° and 60°. The worst performance in this case was for the Closed80x60_gabled roof with an orientation of 30°, with almost 29% difference.

For all options, a distinction was made between the suitable area on the facade and on the roof. The ratio between roof and facade differs per option.

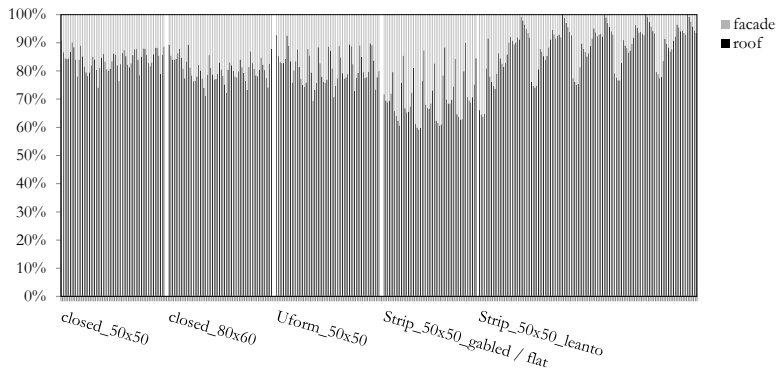


Figure 6.7 The proportion of irradiation on all suitable areas (roof and facade) per design type

Figure 6.7 shows that the options of the Stroke_50x50_gabled/flat design in particular have a greater proportion of suitable façade area than other

options. This type also gives the largest variations. It can also be seen that options in the Stroke_50x50_leanto design have some very high proportions of suitable roof area, and even some cases when the proportion is 100%, i.e. no facade area was found suitable.

6.3 Summary

In this chapter, two parametric studies have been discussed, both focusing on the influence of design decisions on the solar potential of building blocks, while also looking at the boundaries for net zero energy solar buildings in the Swedish context.

The zoning plan developed in the early urban planning stage already frames the conditions for solar energy for buildings in the urban context. The shape of building blocks, density, roof shape and orientation are the main design decisions that urban planners take and that are determined in the zoning plan.

Results from this study show that the urban density is the most sensitive parameter. It was also shown that the relation between the load matching level and the urban density can be described as a power function. For the electricity load, urban densities had to be lower than FSI = 2.5 to reach a 100% load match while, for heating, it was harder to meet a net zero energy balance. In many of the building blocks, flat roofs instead of pitched roofs resulted in a higher load match, while gabled roofs never resulted in the maximum load match. This study shows that the contribution of facades is rather limited and, since they receive less irradiation than the roof, also have a limited contribution in production. However, facade areas might be a feasible place to install solar energy systems if roofs are (partly) shaded, or to produce additional solar energy at those times that the optimally placed solar systems are not producing at their peak.

Also in this chapter, the $SAFAR_n$ metric is introduced, which is intended to provide Swedish urban planners with an instrument to assess how well a zoning plan performs in terms of solar energy potential. The metric enables requirements to be set for the design of a zoning plan within the legal framework in Sweden. The objective of the $SAFAR_n$ metric is to drive urban planners, architects and real estate developers to make well-informed solar energy decisions. Even though the real estate market is showing increasing interest in implementing solar energy in buildings, the metric $SAFAR_n$ will elucidate the solar potential and motivate the players involved to discuss how solar energy can be implemented in future building.

7 Discussion and conclusions

The implementation of solar energy in buildings in an urban context has been the main theme in this thesis. Two research questions were formulated at the start of the work: *What are the barriers and drivers for implementing solar energy in buildings*? and *How can we improve the urban planning process to facilitate a better integration of solar energy in urban environments?* In this chapter, those two questions will be discussed.

The first question takes up the issue of barriers and drivers for the implementation of solar energy in buildings. The interviews with architects and the action research with urban planners have given insight in what these players consider as barriers and drivers.

7.1 Barriers

The main barriers for implementing solar energy in the urban planning and building design process are:

- Long payback period: Real estate owners aiming for a short-term ownership (i.e. developing the plot, constructing and then selling the building) do not see any return on investment in this short time frame. The added value of solar energy systems on the property value is still uncertain.
- Current legal framework and legislation: The lack of a clear attitude from national administrations in the Scandinavian countries on solar energy makes it hard for all types of real estate owners (private, commercial and non-commercial) to make decisions. Although there seems to be some, if slow, progress towards a more favourable legal framework for solar energy, the uncertainty about possible future developments in legislation makes real estate owners nervous and hesitant.

- Lack of knowledge among real estate owners: In many cases, real estate owners experience that it is hard to perform a full assessment on the financial feasibility because of uncertainty about the latest prices of solar energy systems, future electricity prices, energy production of a solar energy system and the legal framework.
- Lack of knowledge among architects: it is not always clear how to acquire more technical knowledge about solar energy. What information is needed in what phase? Which products are available?
- Responsibility for the implementation of solar energy as an important factor in the whole planning process. An example of a design factor in future urban planning is public transport. It is quite clear that there is a need for planning of, for instance, a tram line, and urban planners have gained experience how to work with it. For solar energy, there is not one single player driving this aspect. Since the final decision about solar energy is normally not made by one major player but by many small ones (the real estate owners), the driving force is limited. A complicated situation arises since a full financial feasibility study can only be performed after the detailed assessment study of the output of solar energy system. This leaves it unclear who is paying for such a detailed study on the solar system.
- Limited offer of attractive solar products: Players in the design process – architects and real estate owners – experience a limited choice of solar products that would make building integration easier.

7.2 Drivers

The following drivers were identified:

- Personal belief: many private owners and smaller real estate owners want to install solar energy because of financial benefit and a feeling of independence.
- Corporate image and indirect financial benefit: Real estate developers care about their corporate image, and installing solar energy systems might improve this. Building Assessment Methods have helped to find a structured way to demonstrate their environmental engagement (keeping in mind that real estate developers see them often as a way to increase the value of a property).
- Pedagogical value: In some cases, non-commercial real estate owners include solar energy systems when they see the pedagogical value in it.

- Long-term economic feasibility: long-term owners of real estate are inclined to include solar energy systems because it gives a return on investment.

7.3 Approach

Different players make decisions based on different values: the main concern of the commercial real estate developer is a return of investment, while the private real estate owners might focus their decision on independence or long-term return on investment. In conclusion, these barriers and drivers leads to the following approaches on solar energy (Figure 7.1).

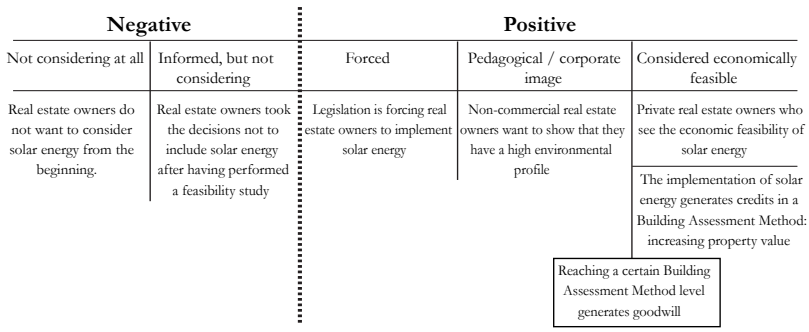


Figure 7.1 Different approaches on solar energy

The forced approach is not common in the Scandinavian countries, but in other countries this might be a possible approach.
Why are financial issues in focus, while other issues – lack of knowledge, responsibility, and architectural issues – do not weigh that much? The current hierarchy in the design process does not allow players other than real estate owners to make the final decision on the implementation of solar energy (Figure 7.2). However, other players may have a strong influence on the final decision-making by providing the right information to the real estate owners.

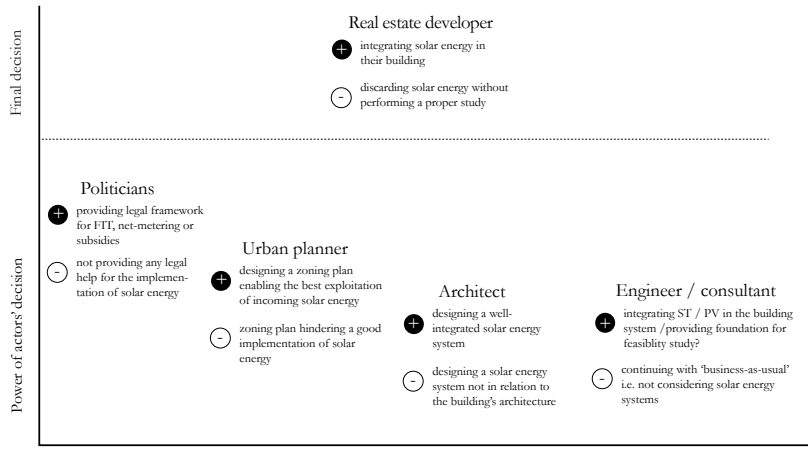


Figure 7.2 Different power positions in the design process

While the urban planners, architects and engineers have a large influence on decisions made about solar energy, the role of the architect in the design process is often limited to what is represented by the client's brief. If the real estate developer is negative to solar energy, solar energy will not be implemented in the building. The architect might try to persuade its client, but will most probably not get paid to do this. New tools, like the FASSADES tool, will make it easier for architects to prepare a foundation for the client's feasibility study. The right tools could also directly be used by real estate developers.

The role of urban planners is not much different. Only in high profile urban development areas is solar energy taken up as a parameter to 'consider' although, in most cases, urban planners do not have any legal instruments to force all players to take solar energy seriously. However, urban planners do shape the conditions for solar energy in cities by the design of the zoning plan, when they decide building volumes, roof shapes and heights. Without knowledge and easy-to-use tools, it is hard for urban planners to assess the effect of the design of the zoning plan on the conditions for solar energy. Assessing the solar potential of buildings in a zoning plan will enable urban planners to see if they can improve the zoning plan for solar energy.

By identifying barriers and drivers, it became clear that the right information at the right time is the foundation for decision-making regarding solar energy.

To improve the status of solar energy in the design process, the decision making of three main players – real estate owners, urban planners

and architects – must be improved. Therefore, important aspects of the financial, architectural and urban planning decision making will now be discussed in more detail.

7.4 Financial decision making

The legal framework is an important factor affecting the conditions for solar energy, but is also hard to change, and much depends upon the current political agenda. Investors in solar energy need to stay up to date when the legal framework changes. It is not only policies that can change rapidly, prices can too, as they did the last decade. Furthermore, the development of solar products also can change the conditions for financial decision making.

Since the real estate developer has been identified as one of the most important decision makers on solar energy in the design process, it is important for them to have the right material on which to base the right decisions.

What information do real estate developers need?

An important instrument in the decision making by real estate developers is the economic feasibility study. To perform such a study, the following steps and information are necessary:

Step 1: Calculating the investment costs and the revenue of the system:

- Estimated output of a solar energy system
- Educated guess on future energy prices
- Current solar energy system prices

Step 2: Assessing the economic feasibility by calculating the payback time and/or the profit after a certain period of time.

How to obtain the necessary information

Obtaining an estimate of the output of a solar energy system is the most technical part of the information needed to conduct a proper feasibility study. Advanced tools, like the FASSADES tools, are needed to assess the solar potential of a building, especially in obstructed environments like cities.

Who is responsible?

It is in the interest of real estate owners to perform a feasibility study. First of all, the underlying data to calculate the output of a solar energy system may be produced by engineers or architects. Then, if this data is obtained, there are two alternatives when it comes to performing a feasibility study. Either a real estate owner has the competence to perform such a study themselves, or the study will be outsourced to an engineer or architect.

Complicating factors

A complicating factor regarding solar energy is understanding how real estate owners make a decision; when do they consider an investment to be feasible? What might be considered feasible for one real estate owner does not automatically mean the same thing for another. This could also be seen in the study on the threshold values used in solar maps. Those threshold values were often not based on payback time, but more on rough estimates or experience.

Another factor is the availability of suitable area for solar energy. While the NZEB directive drives towards buildings with as much as energy production on-site as possible, this might not always be the most financially feasible option. An example is the flat-roof study, where two approaches were discussed.

7.5 Architectural decision making

The majority of architectural projects are initiated and paid for by clients, mainly real estate developers. If the client is interested in solar energy, then the architect can bring solar energy into the design process. If this is not the case, the architects could develop some basic ideas but do not have a budget, and therefore time, to take the issue further.

During the early design stages, the surroundings are known (if present and given by the zoning plan), and the early volume study of a building is being developed. In this first stage, architects, possibly supported by engineers, should perform a simple solar assessment of the building to locate the suitable areas. With this information, architects should see if their design can be optimised to increase the solar energy potential. In later stages, a more detailed analysis can be carried out (roof and facade). Another important step is to identify a strategy on the architectural integration of the solar energy system in the building envelope: should the elements be visible or not visible, how do these elements fit into the architecture in terms of material, colour, and rhythm?

Complicating factors

Many tools are too detailed to use in early design stages. Such tools require a high level of knowledge.

In some cases, architects might experience a 'competition for available area' on the building envelope. Architects were clearly used to designing fully glazed facades, although stricter energy regulations have made it (almost) impossible to continue on this path. Opaque parts could be used to harvest solar energy if they receive enough irradiation. Another aspect is the fact that many real estate owners think about installing green roofs and wonder if solar energy systems could be installed on such roofs.

Also, good quality solar products easily integrated into architecture are still rather limited.

7.6 Urban planning decision making

While there are many different urban planning traditions, it could be said that urban planners design (future) urban environment by planning the use of land. Reformulating the scheme as discussed in Chapter 2, combined with the outcome of the other chapters, a set of guidelines or checklist can be formulated:

Step 1: Develop a strategy (pre-zoning planning phase)

- Determine early goals: what role do we want solar energy to play in our future urban district?
    - Can we set any reasonable energy targets? How much should solar energy contribute in the new urban district?
    - How does solar energy relate to the rest of the energy mix?
- How can we ensure that these goals will be achieved and maintained?
    - (Swedish) urban planners do not have many legal instruments at their disposal to exert pressure on real estate developers, so solar energy needs to be part of an early dialogue with future real estate developers, architects and other relevant players. However, non-descriptive ways to focus attention on solar should be sought; $SAFAR_n$ is an attempt that will be tested within the urban planning department of Malmö.

Step 2: Assess the zoning plan (urban planning phase)

- How can we 'design with solar energy' within the urban planning department? Do we have the right level of competence?
- Perform an assessment of the zoning plan (at least once):

  Assessment of solar potential (total amount of kWh/a and m^2 of suitable area)

  Daylight conditions: ensure that public spaces receive enough daylight
- Can we improve the zoning plan for solar energy (without decreasing the overall quality of the zoning plan)? This requires an iterative process; an assessment of a design might lead to an improved design, which needs to be assessed again.
- How do we transfer the information of early assessments to the building developer and their team?
- How do we ensure the architectural quality of the integration of solar energy?
- How can we ensure the use of solar energy while protecting the quality of the urban environment (heritage)?

Step 3: Follow-up in the building design phase

- How can we as municipality / city administration follow the process of implementation of solar energy into the architecture of the new building blocks?

Step 4: Register the final results

- How can we learn from the obtained results? Are there lessons to be learnt?

These guidelines are by no means the key to success but they would provide a foundation for discussions about solar energy on an informed level.

8 Future work

This work seems far from complete. The research conducted so far has contributed to the research within IEA SHC TASK 51 on the role of solar energy in urban planning, which will continue until 2017. Performing action research with local urban planners provides a constant feed of interesting issues to analyse and study. One current important issue is how to incorporate the 'solar factor' / SAFAR (introduced in PR 4 'The impact of urban design decisions on net zero energy solar buildings in Sweden') into the urban planning process. Legal issues are currently complicating the introduction of this metric.

Another important aspect that needs development are tools. Within IEA SHC Task 51, task members are currently discussing the introduction of a 3D GIS tool, which would give a more complete assessment of buildings in urban context.

On the building block level, it would also be interesting to study the trade-off between ST, PV and daylight (in the form of windows). Do these two different kinds of utilisation of solar energy (passive and active) conflict, or can they complement one another?

Another interesting area that could be developed is a solar resource map for planning non-building integrated solar energy systems, i.e. in the countryside.

Another very important aspect is to disseminate the results of research, including the development of a platform for the entire process with links to tools, methods, and guidelines at different stages. A start was made with the website www.solarplanning.org, which currently presents results of parts of this thesis.

Summary

Buildings currently account for around one-third of Sweden's total energy use. New legislation will place stricter demands on future buildings' energy use, but will also demand that buildings produce part of their own energy. Solar energy can play a vital role in the production of this on-site energy.

In the past decade, there has been a significant increase in the use of solar energy as a power supplier in our cities, although the installed effect per capita varies significantly from country to country, mainly due to the political framework. Favourable political conditions have led to a high installed effect in many countries. Generally, legislation depends on the political situation in a country and will normally last a political term. However, a zoning plan and a building design could last for several hundred years. Planning for such solar buildings therefore requires a high level of competence among players, since decisions made in the urban planning and building design process now will lock a building's solar potential for decades.

This thesis focuses on the role of architects and urban planners when planning for solar buildings in urban contexts. Research was based on two questions: *What are the barriers and drivers for implementing solar energy in buildings?* and *How can we improve the urban planning process to facilitate a better integration of solar energy in urban environments?*

To answer these questions, a mixed research method approach was chosen: I) a qualitative study was conducted consisting of semi-structured interviews with Scandinavian architects who integrated solar energy in their building projects, and II) action research with local urban planners supported by quantitative studies on solar maps, the potential of a flat roof, the effect of design decisions, and the development of a facade assessment tool.

To understand how solar energy is considered throughout the entire planning and design process, a process map has been presented. This process map was based on a literature review and ongoing research within the framework of IEA SHC Task 51 Solar Energy in Urban Planning. The process map distinguishes five different phases: political decision

phase, urban design phase, building design phase, renovation phase, and implementation phase.

In the political decision phase, legal conditions are set for solar energy. These legal conditions could be either favourable (feed-in-tariff, subsidies, net-metering, building codes, etc.) or unfavourable for solar energy (the lack of such legislation). On a local level, city administrations might be able to set additional rules on property developers to install solar energy. If they are not able to set such additional rules, local administrations might try to set up a 'carrot' system by providing incentives. In the urban design phase, urban planners create a zoning plan, setting heights and placement of buildings as well as the appearance of the buildings. Using tools, a zoning plan can be assessed on how well it performs for the implementation of solar energy. In the building design phase, a building is designed from concept to full detail. The implementation of solar energy becomes clearer and more detailed towards the end of this phase.

Ideally, architects should strive after a complete architectural integration of solar energy systems. Tools play an important role in this phase to assess where solar energy systems can be placed and to simulate how much energy will be produced. In the renovation phase, it is important to consider solar energy from the very start. Solar maps can help assess the solar potential of existing buildings, and also the potential of those buildings in need of renovation. In the final phase, the solar energy systems are installed.

The presented process map underlines that every player in the design process has the power to influence the final decision on whether to install solar energy on buildings. This power can be either direct or indirect, although the amount of power exerted by the respective player varies. Providing the right players with the right information might accelerate the implementation of solar energy.

Interviews

It was unclear how, in practice, solar energy was considered in the design process of buildings in Scandinavia, so semi-structured interviews were held with 23 architects in Denmark, Norway and Sweden. The main focus was on which decisions were taken, based on what information, what kind of tools they had used, and what the architects considered to be the biggest barriers and drivers for solar energy.

The interviews with the architects identified the following main issues about solar integrated architecture and its design process as being important:

- Teamwork is crucial. Good collaboration between architects, engineers and clients is very important for reaching the goals set for solar energy.
- Clients did not prioritise solar integrated architecture. This was mainly due to a resistance to investing in active solar technologies that did not provide a short-term profit.
- Advanced BPS tools for solar energy were only used in a few projects and, instead, mainly rules of thumb were used. Architects lacked the competence to use advanced tools or simply found them too complicated.
- There is a lack of aesthetically attractive active solar products.

Architects who had been designing buildings within cities experienced that a zoning plan can limit or facilitate a building's solar potential due to placement of surrounding buildings or other obstruction factors that caused shading.

These findings led to the next stage in the research, with a focus on how to ensure favourable conditions for solar energy in buildings within an urban context.

Solar maps

One of the most important questions as regards to solar energy is how a certain player takes the decision to finally install solar energy. Solar maps are increasingly used for assessing the solar potential of existing buildings in cities. Generally, a solar map assesses the amount of irradiation on roofs and categorises (parts of the) roofs into suitable and unsuitable area.

To understand the underlying principles, 19 solar maps were analysed. This analysis showed that there is no common methodology for assessing the solar potential of roofs. It was expected that solar map owners would have based the categorisation of the map on a certain payback time, but this was often not the case. The analysis also showed that the level of detail between the analysed solar maps varied greatly. Three levels of detail were distinguished: basic (showing mainly irradiation levels), medium (providing energy output of ST / PV systems) and advanced (providing not only the energy output and financial data, but also serving as an information platform for solar energy). It could be said that a solar map has great potential to accelerate the implementation of solar energy, provided that it is at the highest level of detail.

Solar potential of flat roofs

New buildings often have flat roofs. Many solar maps assess the potential production of a flat roof as irradiation times area and efficiency, although in reality, a solar energy system consists of rows of panels, inclination and row distance, which all have a considerable effect on the final production. To examine the technical and economic consequences of mutual shading of PV systems, a parametric study assessing the influence of row distance and inclination was carried out. In this study, the production on a roof in Lund (Sweden) and Miami were analysed, since they not only differ in annual solar irradiation levels, but also on the ratio between direct and diffuse irradiation. Results showed that row distance smaller than 1 metre significantly reduces the output of a module. Modules placed with a greater row distance produce still less output than unshaded ones, but are less affected by mutual shading (less than 10%). The effect of mutual shading was more significant in Lund than in Miami, mostly due to lower sun altitudes all year round. Results also showed that the solar potential of a flat roof cannot simply be calculated by multiplying the roof area with the irradiation level on that flat roof, but that a conversion factor also needs to be incorporated into the equation, ranging from 0.26-1. Not only is the energy output of a system important, but also the payback time of a system is a key performance indicator. Results showed that, for a low electricity price, it is more favourable to place rows as much as 2-2.5 metres apart. For higher electricity prices, multiple setups would result in the same payback time.

FASSADES tool

Roofs on buildings in cities are normally small compared to their facade area, leaving a limited area on which to install a solar energy system. It might therefore be interesting to analyse whether facades have reasonable solar access to install solar energy systems. A facade assessment and design tool (FASSADES) was developed and tested for this purpose.

The tool is based on the simulation software Radiance / Daysim combined with EnergyPlus in the DIVA4RHINO environment. To assess whether facades are reasonable places to install solar energy, the focus of this tool was not only on the irradiation on the facade, but also on the energy output and the payback time. The facade tool first calculates the hourly irradiation on the building envelope, then calculates the possible heat production from a solar thermal system with a certain system temperature or the electricity production from a PV cell. The economic value of the produced energy is then predicted by taking into account prevailing local heat and electricity prices. The payback time is calculated, based on the investment costs and the annual revenues. The tool was validated by

using it to analyse a typical Swedish building block. Results of this analysis showed that shading due to surrounding buildings significantly affects both the irradiation and production, leading to long payback times. The results also highlighted that detailed simulation on an hourly basis is needed to fully assess solar energy potential production and cost benefits.

The effect of design decisions on the solar potential

One of the main tasks of urban planners is the design of a zoning plan. Such a zoning plan can enable or hinder solar access to building blocks, since shading from surrounding buildings significantly affects the solar potential of a building block. The shape of building blocks, density, roof shape and orientation are the main design decisions that urban planners take and that are stipulated in the zoning plan. To understand the effect of the design decisions taken in the zoning plan, two parametric studies were carried out.

In the first study, four different existing urban districts were analysed, three closed building block designs and one more open, scattered design. Results showed that the more open design never returned the highest energy coverage. This configuration also proved to be more unpredictable than the others, i.e. the energy coverage varied in a "chaotic" way for various densities and rotations. Furthermore, one building block had pitched roofs and was expected to outperform the building blocks with flat roofs. Results showed however that, in most cases, the building blocks with a pitched roof did not return much higher energy coverage.

The second parametric study focused on one building block surrounded by similar shaped building blocks. The parameters in this study were density, block design, roof type and orientation. Results from this study showed that urban density is the most sensitive parameter. It was also shown that the relation between the load matching level and the urban density can be described as a power function. For the electricity load, urban densities had to be lower than FSI = 2.5 to reach a 100% load match while, for heating, it was harder to meet a net zero energy balance for any density.

In many of the building blocks, flat roofs instead of pitched roofs resulted in a higher load match, while gabled roofs never resulted in the highest load match. This study shows that the contribution of facades is rather limited in area, and since they receive less irradiation than the roof, also have a limited contribution in production. However, facade areas might be a feasible place to install solar energy systems if roofs are (partly) shaded, or to produce additional solar energy at those times that the optimally placed solar systems are not producing at their peak.

In the second parametric study, a new metrics for expressing the solar potential in an early stage was introduced: the $SAFAR_n$. This metric is the

ratio between suitable area, i.e. that part of the building envelope receiving more than a preset threshold value, and the floor area in that building. The intention is to provide Swedish urban planners with an instrument to assess how well a zoning plan performs in terms of solar energy potential. The metric enables requirements to be placed on the design of a zoning plan within the legal framework in Sweden. The $SAFAR_n$ metric has the objective to drive urban planners, architects and real estate developers to make well-informed solar energy decisions. Even though the real estate market has growing interest in implementing solar energy in buildings, the metric $SAFAR_n$ will elucidate the solar potential and motivate the players involved to discuss how solar energy can be implemented in future building.

Planning for solar buildings in urban contexts has been the focus in this thesis, and the design processes, methods and tools used in planning. Since the planning for buildings in cities is a long process involving many players, it is not that straightforward to pinpoint one weak point in the chain leading to the final decision on whether or not to install solar energy. It requires action and a positive attitude from all players but, above all, the right information. This means up-to-date information with a level of detail appropriate to the design phase and the decisions to be taken.

Sammanfattning

Solenergi kommer att vara en av de viktigaste miljövänliga energikällorna i framtiden, vilket innebär ökat antal solpaneler (för el och värme) som integreras i våra hus men också som fristående produktionsanläggningar. När man planerar framtida hus och stadsdelar är det viktigt att skapa de bästa förutsättningarna för solenergi eftersom hus och stadsdelar finns kvar i flera generationer. Men hur tar vi i dagsläget hänsyn till solenergi i designprocessen och hur kan det förbättras?

Denna avhandling fokuserar på arkitekternas och stadsplanerarnas roll vid planeringen för solbyggnader i stadsmiljö. En blandad forskningsmetod valdes: I) en kvalitativ studie genomfördes bestående av intervjuer med skandinaviska arkitekter som integrerat solenergi i sina projekt, och II) kvantitativa studier som behandlar solkartor, solpotentialen av ett platt tak, effekten av designbeslut samt utvecklingen av ett verktyg för att bedöma fasaders solpotential.

I den första forskningsdelen intervjuades skandinaviska arkitekter som hade arbetat med solenergi under designprocessen. Arkitekterna identifierade flera kritiska punkter för att kunna utforma byggnader med solenergi: vikten av samarbete, brist på attraktiva solenergiprodukter samt beställare som inte prioriterar solenergi. Intervjuerna visade också att arkitekter sällan använder några sofistikerade verktyg för att bedöma omfattningen av solenergiproduktion. De som hade ritat byggnader i stadsmiljöer upplevde att en detaljplan kan begränsa eller underlätta en byggnads solenergipotential genom placeringen av omgivande byggnader eller andra skuggande faktorer.

Dessa resultat ledde till nästa steg i forskningen med fokus på hur man kan säkerställa goda förutsättningar för solenergi i byggnader inom stadsmiljöer. Genom flera forskningssätt har det undersökts hur designbeslut i stadsplaneringen påverkar möjligheterna för utnyttjande av solenergi, samt hur dessa beslut stöddes av analysverktyg.

Solkartor används alltmer för att bedöma solens potential i befintliga byggnader i städer. En analys av befintliga solkartor i olika länder visade dock att det inte finns någon gemensam metod för att bedöma solenergipotentialen och att metodiken bakom framställningen varierade kraftigt. Analysen visade vidare att det finns en stor skillnad i detaljnivå mellan

solkartorna. Solkartor används ofta bara för att analysera befintliga byggnader medan en realistisk solpotentialbedömning av nya byggnader kräver avancerade simuleringsverktyg.

Nya byggnader har ofta platta tak. Många solkartor bedömer den potentiella produktionen av ett platt tak som solinstrålningen gånger area och solpanelens verkningsgrad, men i verkligheten har man ett platt tak med ett system bestående av rader av paneler. Lutningen på och radavståndet mellan panelerna har en betydande effekt på slutproduktionen. För att undersöka de tekniska och ekonomiska konsekvenserna av skuggning genomfördes en parameterstudie med fokus på radavstånd och lutning. Resultaten visade att solcellerna bör placeras horisontellt och raderna bör placeras direkt bredvid varandra för att maximera energiproduktionen.

Takarean på byggnader i städer är normalt liten jämfört med fasadarean vilket resulterar i begränsade areor för att installera ett solenergisystem om bara tak används. Det är därför intressant att analysera om även fasader har en tillräckligt god solexponering för att installera solenergisystem. För att bedöma solenergipotentialen av en fasad utvecklades ett verktyg som kallas FASSADES. Verktyget simulerar solenergiproduktionen och beräknar det ekonomiska värdet av energiproduktionen och återbetalningstiden.

En av de viktigaste uppgifterna för stadsplanerare är utformningen av en detaljplan. En sådan detaljplan kan möjliggöra eller förhindra soltillgång till byggnadskvarter eftersom skuggning från omgivande byggnader avsevärt påverkar solpotentialen. Formen på byggnadskvarter, hur tätt man bygger, takform och byggnadernas orientering är de viktigaste faktorerna som stadsplanerare tar beslut om och som bestäms i detaljplanen. Simuleringar har kartlagt hur dessa designbeslut påverkar solpotentialen i byggnader. Hur tätt man bygger visade sig vara den mest känsliga parametern. Hemsidan www.solarplanning.org har skapats för att informera stadsplanerare och andra intressenter om resultaten, som ett sätt att sprida kunskap.

Slutsatsen av arbetet är att förutom de tekniska aspekterna kräver integreringen av solenergi i våra framtida hus ett bra beslutstagande under hela designprocessen. Med rätt information vid rätt tillfälle kan alla aktörer tillsammans skapa de bästa förutsättningar så att vi kan utnyttja solenergi på bästa sätt. För att uppnå detta fullt ut krävs en fortsatt utveckling av analysverktyg, kunskapsspridning och metodutveckling.

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Architects' design process in solar-integrated architecture in Sweden

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Architects can play a key role in future solar-integrated architecture as they are involved in the building process from the beginning. Solar-integrated architecture takes both passive and active use of solar energy into account. The aim of this research was to gain insight into the actual design processes of solar-integrated buildings. Therefore, semi-structured interviews were conducted with Swedish architects who designed such buildings. Results showed that teamwork was experienced as crucial and building performance simulation tools were hardly used by the architects themselves. Results from these interviews serve as input for the development of new architectural guidelines for designing solar-integrated architecture as part of IEA-SHC Task 41: Solar Energy & Architecture.

Keywords: Design process; architectural design; solar energy; teamwork; design tools

Introduction

In the last decade, sustainable architecture has grown from a niche market to a more mainstream movement. In Europe, the Energy Performance of Buildings Directive (EPDB 2010) requires all new buildings to be nearly zero-energy buildings by 2020. In order to achieve such buildings, they not only need to be energy efficient, but also need to generate energy; obviously, this implies that solar energy can play an important role. By rationally taking into account the characteristics of solar radiation in both a passive and an active way, a solar-integrated architecture can be achieved.

The aim of this research was to gain insight into the design process used in architectural offices for solar-integrated projects in Sweden. Therefore, a series of 11 interviews was performed among Swedish architects. It was important to see which actors were involved, what kind of information those actors shared, what kind of knowledge they needed, what design tools they used etc.

Architects can contribute significantly to a more energy-efficient built environment as they make key decisions early in the design process (Wall *et al*. 2009). It is, however, unclear as to how architects make design decisions concerning energy and on what grounds these decisions are made. Research performed earlier has shown how architects have dealt with designing solar-integrated architecture in Canada, Denmark, Singapore and the USA (Charron 2008, Brunsgaard 2011, Kosoric *et al*. 2011, Otis 2011). The role that design tools played was new and crucial. In the design process of Danish low-energy houses, two methodical approaches of building performance simulation (BPS) tools' use existed; a case-based approach and parametric approach (Hansen and Knudstrup 2008). With the parametric approach, engineers can take a proactive role in the design process. Other Danish research showed that the collaboration of different actors, an interest in each other's disciplines and a common goal were beneficial for the design process (Brunsgaard 2011).

In the case of Canadian low-energy houses, Genetic Algorithm software was shown to be highly efficient in solving complex problems in the design process and therefore an important support for the architect (Charron 2008). In the design process of a building with integrated photovoltaics in Singapore, different design alternatives were developed and with the help of a multi-criteria decision-making tool, the best alternative regarding energy performance, economic performance and functional-aesthetic criteria was selected (Kosoric *et al*. 2011). At the Harvard Graduate School of Design, a study was carried out to evaluate how solar design tools may affect the development of form in the design process (Otis 2011). It was shown that students who used solar design tools outperformed those students who did not use any design tool.

BPS tools and other design tools can provide feedback to architects and help them make decisions in the design process. Research performed earlier within IEA-SHC Task 41: Solar Energy & Architecture has shown that many architects still see a need to improve tools and methods for architects (Kanters 2011a). Other researchers arrived at a similar conclusion; BPS tools are not yet suitable for architectural design work, are found to be too complex and not compatible with the architect's working methods (Attia *et al*. 2009), and have serious shortcomings when

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net-zero-energy buildings have to be designed efficiently (Biesbroek *et al*. 2010). Recently, however, new design tools have been launched which connect the architect's CAD environment with solar analysis tools, to name a few: IES VE for Google SketchUp and REVIT (IES 2010), Ecotect (Autodesk 2011a) and Vasari (Autodesk 2011b) and DIVA for Rhino (GSDSquare 2009). With the introduction of these programmes at least one parameter – embedding into the architect's work flow – might be solved, but still a lot of parameters remain unsolved (for instance, a good interoperability between the programmes).

It is known that passive application (solar heating and daylighting) and active application (photovoltaic and solar thermal systems) of solar energy both imply significant architectural consequences (orientation, geometry, fenestration, HVAC system, etc.). Active solar elements can become part of the architecture of a project when the architect applies a holistic approach (Hestnes 1999), and when these solar elements replace other building elements (Lundgren and Torstensson 2004). The passive application, with the current focus on passive houses – a house which requires a highly insulated climate shell, a high-efficiency heat exchanger in the ventilation system (Janson 2010) and appropriate orientation – shows that a positive development within the building industry is possible.

The new emphasis on energy efficiency starts to change the building process from the so-called traditional building process to newer forms. The traditional design process was divided into the following phases according to Jones (1992): (1) briefing, (2) pre-conceptual design, (3) conceptual design, (4) preliminary design, (5) detailed design and (6) design documentation. Newer forms, like the integrated design process (IDP), are built upon teamwork, all actors are involved from the early design phases and has the following sequence (AIA 2007): (1) conceptualization (programming), (2) criteria design (schematic design), (3) detailed design (design development) and (4) implementation documents (construction documents). Within IEA-SHC Task 23: *optimization of solar energy use in large buildings*, the subject of IDP was dealt with in a more extensive explanatory way and several projects were showcased to give concrete examples of IDPs (IEA 2003). The case studies selected in this research were supposed to use a design process that could be qualified as an IDP rather than a traditional process. It was also expected that architects who already designed solar-integrated architecture and urban master plans could serve as an example for other architects willing to design solar-integrated architecture. Furthermore, it was expected that the selected architects could indicate where the possibilities and problems had been and would be able to compare it with design processes and conditions of 'regular' buildings.

The conducted interviews contribute to the research carried out within subtask B of IEA-SHC Task 41: Solar Energy & Architecture. This task gathers researchers and architects from 14 countries with the aim to accelerate the development of high-quality solar architecture. Subtask B focuses on tools and methods that architects use when designing solar architecture. Previous publications of subtask B consist of an overview of BPS tools (Dubois and Horvat 2010) and an international survey on the adequacy of design tools (Horvat *et al*. 2011).

Methods

The semi-structured interview was selected as the main research instrument since the focus of the investigation was on the process. Semi-structured interviews also give a certain degree of freedom to express ideas and to highlight areas of particular interest and expertise. It also makes it possible to explore some responses in greater depth (Horton *et al*. 2004). The interviews can be seen as a supplement to the IEA-SHC Task 41's international survey which was mentioned earlier.

Procedure

After the decision was taken to use semi-structured interview, a selection of architectural offices was made. The architects who were selected for the interviews had been participating in projects with a focus on solar utilization. Furthermore, several buildings were part of a selection of case study buildings gathered within the IEA-SHC Task 41 during task meetings. In Table 1, an overview is presented of the selected projects. Although it was intended to focus mostly on built examples of solar-integrated buildings/urban master plans, not all the case studies were actually finished at the time of the interview.

The selected architects were contacted by email and phone and all approached architects participated. Within the architectural offices, these architects who had been project leaders were selected as interviewees. The interview questions were sent to the interviewees prior to the interviews to allow the architects to prepare themselves for the interview. The interviews usually lasted from half-an-hour to more than an hour, depending on the architect and the available time. Interviews were held in Swedish and tape-recorded. After the interviews had been conducted, they were directly transcribed in Swedish and later entirely translated into English. The interview questionnaire (Table 2) was developed during IEA-SHC Task 41 work meetings with other Task members and was set up in order to serve as a basic guide to all interviews, although architects were free to express other thoughts or reflexions on solar-integrated architecture. One pilot interview was conducted which allowed refining the questions. Answers given in the pilot interview were, however, considered not to be different from other interviews and were therefore fully taken into consideration in the final analysis.

Data analysis of the interviews was carried out using Glaser and Straus' grounded theory (Glaser and Strauss 1967), which has been used earlier in analysis of the

Table 1. Overview of projects.

Architect	Office location	Project location	Latitude	Type of project	Built
1	Stockholm	Kolding, Denmark	55.7N, 11.9E	Residential	Yes
2	Stockholm	Trosa, Sweden	58.9N, 17.5E	Residential	Yes
3	Stockholm	Stockholm, Sweden	59.3N, 18.1E	Urban plan	Yes
4	Stockholm	Stockholm, Sweden	59.3N, 18.1E	Commercial	No
5	Gothenburg	Stockholm, Sweden	59.3N, 18.1E	Residential	Yes
6	Gothenburg	Gothenburg, Sweden	57.7N, 11.9E	Urban plan	No
7	Gothenburg	Gothenburg, Sweden	57.7N, 11.9E	Commercial/public	Yes
8	Gothenburg	Visby, Sweden	57.6N, 18.3E	Public	Yes
9	Malmö	Malmö, Sweden	55.6N, 13.0E	Residential	Yes
10	Malmö	Stångby, Sweden	55.7N, 13.2E	Residential	No
11	Malmö	Malmö, Sweden	55.6N, 13.0E	Residential	No

Table 2. Interview guide.

Introduction	Competences	Design process	Lesson learnt and barriers
Question 1 What is sustainable architecture for you and how important is it for you? What is solar-integrated architecture for you and do you think it is an important aspect of sustainable design?	*Question 2* What basic information and/or knowledge should an architect have before starting designing a project like this?	*Question 3* Could you describe the early design phase for this project? What was done and what was the role of the participants? *Question 4* Could you describe the rest of the design process in phases? *Question 5* Which design tools did you use during the design process and how useful did you find these tools?	*Question 6* How did you gain the skills that you presently have with the tools and solar energy in general? *Question 7* What are your lessons learned in this project and how is this project different from other projects done by your office? *Question 8* According to you, what are the most important barriers for exploiting solar energy as an architect?

(architectural) design processes (Wong 2010). Within the grounded theory the following steps are performed after data collection (Bryman 2008): 'coding' (the process of categorizing data), 'constant comparison', 'saturate categories', 'explore relationships between categories' and 'conceptual and theoretical work'. By using an interview guide, a list of categories could be made prior to the coding in order to make the process of coding easier. Furthermore, transcriptions were read several times before coding, as well as notes taken during the interview. Then, transcriptions of the interviews were imported into the programme QSR NVivo 7 (QSR-International 2006). This data analysis programme allows users to process raw data into categories, and is especially helpful when large amounts of data need to be analysed. The coding in NVivo is done by selecting a part of the transcriptions and dragging it into the selected list of categories. Within the programme, the categories were saturated with all data from all interviews and all categories were exported to a word-processing software.

After the interviews, the architects were asked to provide some data from the design tools used in the processes, as most of the interviewed architects answered to have used design tools and BPS tools in some way or the other. In this way, it would be possible to see at what level architects make use of tools. However, only three architects responded to the request and there was a large variation in the quality of the sent documents.

Sample

Eleven interviews were conducted from January 2011 to May 2011. All interviews were at the architectural offices of the architects, which were located in Stockholm, Gothenburg and Malmö in Sweden. Additional interviews were carried out in Norway and Denmark, but these will be discussed in a future publication.

Most of the interviewed architects – of which four women and seven men – had more than 10 years of experience as architect. In almost all case studies, the project architect was leading a small team of other architects and, if applicable, was responsible for contact with external consultants. The architectural offices were also carefully selected in order to ensure a rather equal distribution of sizes as it was expected that offices of different sizes would use different design methods, which is related to the means in terms of organization and available in-house skills. In the

sample, two offices had 1–5 employees, three offices had 5–10 employees, two offices had 10–50 employees and four offices had more than 50 employees.

Results

The architect's view on solar-integrated architecture

When asked about their definition of sustainable architecture, all architects came up with their own definition. However, most of them agreed that sustainable architecture has a minimal impact on its environment in the long term. In Figure 1, an overview is presented of the themes mentioned by the interviewed architects when asked about the term sustainability (note that the architects were allowed to give more than one answer).

The architects defined solar-integrated architecture as an important part of the whole sustainability field. The term 'integrated' meant for architects that it was part of the architecture and the aesthetics of the whole building. In some cases, integrated was conceived as solar energy products replacing other building components and materials, not as an add-on afterwards.

When talking about solar-integrated architecture, most architects mentioned first the active application of solar-integrated architecture – solar panels and solar cells – and secondly the passive application of solar-integrated architecture – passive heating and daylighting. Furthermore, architects seemed to be aware of the relationship between solar radiation and energy use in buildings; windows were seen not only as a way of confronting the inner environment of a building with its outer environment, but also as devices letting in daylight and heat. The risk of overheating in the summer was considered to be taken into account by providing proper solar shading – while still providing sufficient levels of daylight; a situation which could lead to a conflict. Some architects used this conflict as a driving force in the design of the building by both blocking abundant solar radiation and producing electricity by solar cells at the same time.

When it came to solar-integrated urban planning, architects experienced solar energy as only one of many parameters to consider. One architect conceived orientation in urban planning based on passive solar principles in conflict with the dense city. Another architect thought that making more use of solar energy in cities could avoid turning agricultural land into solar energy plants.

Technical competences of architects

The architects were asked what competences they should have for designing solar-integrated architecture. Some architects mentioned that architects are generalists and that they should know a little about a lot of aspects of the building, including technical systems. Many architects saw the architect as someone who can do much more than only aesthetically designing a building but he/she needs to have more technical and engineering knowledge in order to be able to design solar-integrated architecture. With this increased technical knowledge, architects should be able to quickly assess design situations. This need for increased (technical) knowledge was often felt as a relatively new demand by the interviewees. However, some of the architects experienced that the architect should not get too much technical knowledge, as it could limit creativity during the design process. In contrast, one architect mentioned that many recent 'sustainable' projects were very superficial; this architect felt more confident with a more fact-based architecture than a sense-based architecture when it comes to sustainability.

Some architects expressed the view that they did not have sufficient knowledge or have the wrong type of technical knowledge and therefore worked together with engineers. One architect also mentioned that gaining and

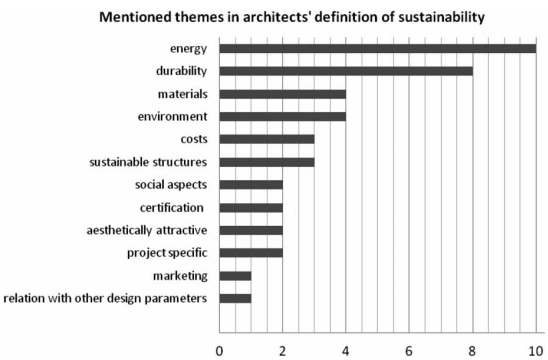

Figure 1. Architects' definition of sustainability.

maintaining an extensive technical knowledge puts a high demand on a small-scale architectural office. Other architects expressed that they did not see the need to have an extended technical knowledge and that they are therefore teamed up with engineers. For many architects, such a close collaboration with engineers – mainly building service engineers – is relatively new and came into the picture after the introduction of stricter Swedish building regulations (building regulations in Sweden included already in 1993 rules about energy issues like heat and transmission losses and since the last decade, they also included demands on the maximum energy use of a building expressed in terms of kWh/m^2, year). The collaboration between architects and engineers does not, however, always go that smoothly; architects and engineers tend to speak different languages and use different kinds of input in order to perform their job.

> The engineer was pretty categorical and technical and (…) 'engineering'. You could get mad at him as an architect. He didn't think like an architect. (architect #7)

> [during a conversation between the architect and the engineer about solar cells, the engineer says] 'it has to be this angle and in this direction', but then we as architects sketch and say: 'we want this angle and this direction because it looks better'. Then the engineers perform calculations and then they see that there was not much of a difference. That is the dialogue you want to have (architect #5)

Convincing the client

Another competence an architect should have is the skill to convince clients to go for solar-integrated architecture. This means that architects had to be able to clearly present the advantages and disadvantages of the integration of solar energy, both regarding the active and passive approach. This was often done by providing a financial overview with the benefits of using less energy vs investment costs. Some architects tried to highlight the symbolic value of solar-integrated architecture for the client.

One architect saw it as her duty as an architect to protect the tenants' interests, which the architect experienced as being endangered by the amount of technology applied in new buildings. Tenants might feel limited in their possibilities to affect their work environment and this architect therefore tried to include the possibility to have a partly manual override for the technical systems in the project.

Basic knowledge

When asked about the necessary basic knowledge regarding solar-integrated architecture, most architects found it difficult to answer that question. Architects' answers were mainly focused on the technical side of that knowledge. Architects often answered that there is a need for having an overview of available solar technologies and other technical systems. With this overview, an architect should be able to compare different systems with each other based on their conditions and requirements. The following system requirements were mentioned by the architects:

- angles in which solar systems can have maximum efficiency, which direction suits the situation best;
- how much solar systems could contribute to the energy use of the building;
- need and dimensions of storage tanks.

Other architects mentioned that with this standard technical knowledge, the dialogue with the building service engineers could become easier and it will also give the architect the possibility to propose and adapt systems in order integrate them in a more aesthetical way. Furthermore, architects expressed a need to have an extensive knowledge about the impact of the physical environment on the building:

- impact of the sun's capacity to heat, but also to overheat a building;
- local wind conditions;
- airtightness;
- how internal loads affect the thermal balance of a building;
- knowledge about window properties and position.

Further education

As it was found necessary to have more knowledge about solar-integrated architecture as an architect, gaining this new knowledge was found to be difficult by several architects but many of them had a personal interest in the subject. On the urban scale, general as well as technical knowledge was considered to be more elusive for architects to gain, as it is not their direct field of education. Architects experienced that institutions, municipalities and companies could help architects gain more knowledge on this urban level.

Gaining an overview of available solar technologies in buildings and remaining updated was found difficult, mainly due to rapid changes and the development of new products.

> You have to update yourself all the time basically. You become very dependent on technology and the technology changes all the time (architect #11)

Many of the architects answered that they mainly gained knowledge by taking part in real projects. Some architects did not have any experience in solar-integrated architecture before starting the discussed project but by going through projects with a focus on solar integration, architects were confronted with the problems and possibilities of the integration of solar energy into buildings.

Another way of gaining knowledge was through collaboration with engineers. Building service engineers were often involved during the design process and architects gained a lot of knowledge by collaborating with engineers. The method of transferring knowledge between architect

and the (building service) engineer differed in each case. In one case, the architect described a working situation where the building service engineer and the architect sat down and sketched together. In another case, the project architect had meetings and email correspondence with the engineer. On the urban scale, transfer of knowledge to architects often occurred through collaboration with larger groups of engineers gathered in municipal departments or other state institutions.

Study trips were considered as an important means of gaining knowledge by architects. They saw it as a source of inspiration directly showing how they could integrate solar energy into architecture. By seeing different examples of integration, architects can make a judgement for themselves of several systems and applications, which could be vital information when designing new buildings. The possibility of visiting good examples can also be an inspiration source for other actors in projects, mainly clients.

> That's why it is good and important to have good examples; to visit, to see, to experience it yourself, to have evidence: it is done. This works and it looks damn good. As an architect, I also think that it is very important to show non-architects that kind of examples (architect #4)

Architects also gained knowledge from the literature. Besides books on solar energy, architects saw building regulations and additional building standards as literature, which they need to know extensively. Furthermore, when clients decided to have their buildings certified with additional building standards – like LEED, BREEAM, Building Programme South (a standard developed in Southern Sweden) or Green Building – architects need to be aware of these extra sets of rules. They are often supported by the building service engineers in order to see whether they comply with the rules.

The majority of architects did not attend any course in the field of solar energy. However, some architects did take short-term courses, or invited speakers, mostly other engineers or architects. One architect complained about the lack of possibilities of good further education; according to this architect, nothing had changed that much in the available knowledge on solar technology in the last 20 years.

Education as an architect

Concerning the role of architectural education in relation to sustainable architecture, architects answered differently and found it hard to judge. Some architects stated it was reasonable that the basic architectural education focused on fundamental elements of architecture and aesthetics, because it is hard to learn them afterwards. Working in the industry was often seen as the start of the second education as an architect, when one learns by taking part in projects. Some architects experienced that it is easier to gain technical knowledge afterwards than to gain the aesthetic fundaments of architecture.

> There are a lot of people you can just call and ask [regarding solar energy products]; 'How big is the tank? How much insulation do we need?' There is no one you can call and ask 'is it nice or ugly with this roof angle?' You have to learn that in school (architect #2)

Other architects mentioned the lack of technical focus within architectural education. According to one architect, newly graduated architecture students are designers, not architects, because they do not learn technical aspects of buildings.

The design process

Early consideration

When comparing 11 projects with their own specifications, conditions, actors and (design) processes, it becomes clear that the emphasis on energy efficiency and the integration of solar energy has been in focus from the early design phase. In almost all cases, it was the client who assigned the architect to design an energy-efficient building. Some of the case studies show that clients were focusing on sustainability/energy efficiency already in the beginning of the 2000s. Because of the current development and attention towards this topic, case studies from the late 2000s and the beginning of the 2010s showed that they also had this emphasis, which is mainly a result of stricter building regulations (in Sweden) and because of the introduction of energy classification systems as a marketing instrument. In some cases, it was not the client, but the architect, who had a focus on sustainability in the early design phase.

Cases studies showed that Swedish municipalities have a special role to play in the design process. In some cases, the municipality was the client (both on building and urban level) and had high ambitions regarding sustainability. When the municipality was not the client of a project, they could still ensure a high sustainability level through the instrument of competitions. When municipalities develop new urban districts, the land is often property of the municipality. Potential property developers are invited to join the competition to be able to buy a piece of land and develop it into properties. This is, however, only possible if the proposed buildings comply with stricter rules as set by the municipality on top of the regular building rules. In this way, municipalities have the possibility to demand these stricter building standards, which would not be possible in the standard procedures.

The architects experienced that throughout the year, clients have become increasingly interested in the positive effect of sustainable architecture. Although the Swedish national building regulations became stricter, clients started to demand certified sustainable buildings that could be according to either BREEAM, LEED, Green Building Standard, Passive House Certificate or Building Programme South (a Swedish programme). When clients are demanding such higher standards, they often want to show that the building is sustainable, which for instance can be done

by clearly displaying solar cells and panels, even though these solar elements were not always located in the most energy-efficient place.

Teamwork

In order to fulfil the task of designing a sustainable building, architects often team up with engineers to investigate a sustainable strategy for the project from the early design phase. The involved engineers are mostly building service engineers, structural engineers and energy consultants. In the early design phase, the architect and engineer often decided what technical systems were most suitable for the building (based on energy sources available in the surroundings), and how the lowest possible heating and cooling load for the building could be achieved. These components of the project required a lot of knowledge and it was for this reason that the collaboration between engineers and architects was found so important. In smaller, mono-functional buildings, the architect can have this knowledge about technical systems himself/herself. In bigger, multifunctional buildings, the architect can hardly have this advanced knowledge as the technical systems can exhibit a high level of complexity. Architects also did not see the need to have all this extensive knowledge, because it is too technical and difficult to stay updated.

The development of the architectural shape of projects went often hand-in-hand with the applied technical systems; when a certain change in the project was made because of aesthetics reasons (for instance a change in geometry or facade), engineers calculated or estimated the consequences of this on the energy performance of the building and reported it back to the architect.

> Then we ended up in the hands of the building service engineer who said 'never in all my life. Check out the new building regulations, we are never going to pass the energy requirements'. The building service engineer said we should start tightening the building; we should have a window composition instead of having [everything in glass] (architect #7)

In this iterative way, the architect could, together with the engineer, decide on what design options were best. It also worked the other way around; engineers proposed a technical system that had consequences for the design of the project. In many cases, this led to compromises; the architecture of the building could not always be as wanted by the architect and the technical systems could not always be how the engineer wanted it. However, this collaboration was often perceived as positive by the architects.

> We [the architect and the building service engineer] sat down and sketched together. I think that this is usually the fastest way to [do;] that a person says something about a system that fits together [with the project]. And if it is like this, then you start to discover which consequences it has for the building. If it had [non-desirable] consequences, then you ask … is there another system that we can have as well? But we also proposed solutions the engineers didn't think of. (architect #8)

Solar integration

In the majority of cases, active solar technologies were integrated in the building in the form of solar panels or solar cells. The visibility of the solar panels and cells had a large impact on the architecture; in some cases this was desirable, and in other cases this was not desirable. Displaying the active harvesting of solar energy as an active architectural element is a way of marketing the building and could therefore be wanted by clients and architects. When solar technology was to be displayed in the project, the architect often put some effort in trying to get the solar technology as aesthetically pleasing as possible, for instance, by designing special details.

In some cases, the architect considered that current solar products were not aesthetically pleasing and, therefore, they were not displayed in an obvious, visible way. Even though active solar technologies were proposed in the early design phase of most of the projects, they sometimes did not survive the design process, which was often due to financial considerations by the client. In some cases, solar energy was not applied due to local conditions, which were often related to the local sources of energy (for instance, cheap heat from a district heating network) and made the feasibility of solar technologies less attractive compared with other renewable energy sources. In general, there was a strong belief among architects that they themselves were not the biggest barrier for solar-integrated architecture, but that other factors beyond their power decided whether active solar technology was used or not.

Design tools

On the question concerning the type of design tools used in the design process, some architects answered that they did not use any. One architect explained that the expression *design tool* is not a familiar expression for what architects use, at least, in Sweden. When design tools are considered as tools or aids when designing, architects used mostly the traditional design tools, that is, hand sketches, two-dimensional and three-dimensional drawings in a CAAD programme as well as physical models. In order to maximize the potential of sustainable architecture and/or solar-integrated architecture, basic information about the energy performance and production in the building could be a useful design aid for architects. This could be achieved in two ways: manually using rules of thumb or by computer with simulation programmes. More recent developments within the software industry have provided more available simulation programmes, but in the case studies from the beginning of the 2000s, only one architect simulated the building using a computerized simulation tool. The interviewed architects were asked to name all BPS tools used in the design process, both used by themselves and by the

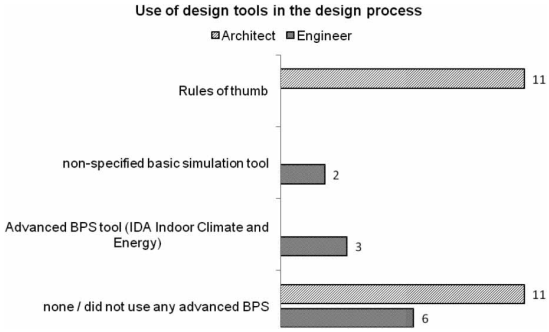

Figure 2. Design tools used in the design process.

involved engineers. If these programmes were used at all, the architects most often ignored what BPS tools were used by the engineers. All architects answered to have mostly used rules of thumb as a design tools, but no architect used advanced BPS tools themselves; if it was used, then it was often the engineer who used these programmes (Figure 2).

Building information modelling (BIM) was not used in any of the case study buildings, even though Swedish results from an international survey showed that BIM software is commonly used nowadays in Sweden (Kanters 2011b). The absence of BIM can be due to the fact that it is quite a recent development in the building industry, and many case studies in this research were older than BIM. Furthermore, BIM is often used in large-scale buildings, whereas many case study buildings in this research were small scale.

All architects mentioned that they used (simple) rules of thumb when designing sustainable/solar-integrated architecture. These rules of thumb often provided a first estimation on

- window area;
- thickness of outer walls;
- dimensions, energy output and most appropriate inclination of solar panels/cells on the building.

Very few architects used BPS programmes by themselves. Sometimes, simple simulation programmes were used by the architects, but more advanced simulation tools were operated by the (building service) engineers. Some architects expressed that using advanced simulation programmes as an architect would imply a big investment as these tools are expensive and future users need to gain knowledge on how to use the programmes.

Besides required investments, some architects doubted that it should be the architect's responsibility to perform advanced simulations; engineers are considered to have more technical knowledge, which is needed for input in the simulation programmes. In line with that two architects also mentioned the issue of responsibility when it comes to the simulated energy performance of a building.

> It's also a bit difficult … not knowledge-wise, but it is difficult concerning responsibility. You can think of simulation tools as design tools, but you should know whether the outcome is right (or not) (architect #11)

Architects also used other forms of design aids. Some architects mentioned that they saw the national building regulations and additional (stricter) building regulations as a design aid.

Conditions and barriers of solar-integrated architecture

Incentives

Almost a third of the architects answered that the biggest barrier for solar-integrated architecture was the lack of client interest. At the same time, all architects mentioned that they experienced that solar products – solar cells and panels – were too expensive at the moment.

> Investment costs I would say [is the biggest barrier]. It is expensive and the cost coverage is very uncertain; how do you get [the investment] back? I don't think architecture is the obstacle (architect #3)

Architects experienced that clients seemed to have a lot of prejudices when it comes to sustainable/solar-integrated architecture. There is also a significant difference between clients; the small-scale private client has other means and incentives than the larger-scale professional clients.

Financial incentives

Several architects mentioned that the connection between the two main barriers – lack of client interest and expensive active solar products – is a result from the short-term benefit culture within the property development and building industry. When the payback time of active solar products is

over 5–10 years, property developers do not see the need to invest in them on financial grounds. Many architects often experienced that property developers were very positive at the beginning of the design process about having active solar products in the building, but that later on in the process, active solar products were considered too expensive. None of the architects mentioned the costs related to the passive application of solar energy.

Some architects tried to convince clients to integrate solar energy by performing not only energy calculations, but also by taking into account investment costs and the reduction of energy use in the building. The fact that clients in the end decided not to integrate active solar products in the building was experienced by architects as disappointing.

Several architects mentioned that the basic grounds for this lack of client interest lies within our society and economic system. Many property developers are only focussed on making profit quickly. In contrast, architects saw a need for more input from the government. Some architects saw energy certifications as a good development for clients who not only focus on financial issues, but also on their 'image'. Subsidies were mentioned by architects as an instrument of the government to increase the penetration of solar products in buildings. Architects also praised the initiatives taken by local authorities to stimulate the use of solar energy, for instance, by stricter building regulations or by competitions. In the process, all stakeholders were forced to do something extra.

Another problem in convincing the client was the fact that property owners and building contractors have a long tradition of building in a certain way. A new way of building, for instance, is needed when building passive houses, and is therefore considered as (financially) risky, even though these techniques have been proven for quite some time.

> It is important to convince the property developers, because they have arguments why not to build passive houses. One is that it is not done before in Sweden, and that they are not the one who should be engaged in 'experimental building'. In Sweden, the first passive house was built ten years ago, so it is not strange. There are so many prejudices about [passive housing]. That makes it tough sometimes (architect #9)

Non-financial incentives

The majority of architects had been involved in projects where the client was eager to have solar-integrated architecture. In those cases, the client often wanted to show that they took the subject seriously; environmental considerations had to be clearly visible in the building.

Projects built in the beginning of the 2000s, and the ones paid by a non-professional client showed this involvement often in a *non-quantifiable* way, for instance, by means of solar panels being expressive architectural elements. More recent projects, and the projects paid by professional clients, often had a *quantifiable* way of showing their involvement; several certification systems are now being adopted by real estate developers to show their future tenants that they care about sustainability. Architects got clear assignments saying that a building needed to comply with an additional set of building standards. When the building is built according to these specific building standards, the building is rewarded. With this reward, property developers are able to profile themselves as being sustainable and this is indirectly a financial incentive.

> What I have noticed sometimes was that a client took a decision that was not economically advantageous, (but) that they can put [the costs] on their marketing account (architect #6)

Energy certified or not, certain projects started serving as an example of sustainable/solar-integrated architecture and/or urban planning. One architect, who was involved in a now well-known sustainable urban planning project, had given many lectures locally and internationally about the project. The involved architectural office had clearly got new assignments based on the fact that they had designed this project.

> The interest for these issues has been very big in Scandinavia and north European countries. We get foreign visitors to the project every day. I don't know how many newspapers I have met and how many interviews I have given. We work now in China and Russia, we have done studies in England. It makes it profitable in that way (architect #3)

Solar products

The majority of the architects experienced a limited choice of attractive solar products on the actual market. However, most of them observed a big development of new products, mainly in the area of solar cells. The recent emphasis on sustainability has made that development possible and necessary.

Architects expressed that they would like to see more solar products which can be really integrated in the building, instead of building added products. This would not only be preferable for the architecture of the building, but replacing building materials and components with solar products makes it financially more attractive as well. Many architects expressed that the current, limited offer of products is also limiting an aesthetically pleasing integration of solar products. Architects would like to see solar products as a building material where colours, sizes, shape and other features could be changed easily. With the right detailing, architects could really integrate them into buildings. One architect mentioned that solar products should be considered by architects as all other building material, with its own characteristics, but this requires a general increase in knowledge.

> … interesting is the border between products and material. As an architect, you really want to work with a material, to choose dimensions yourself, more than having a finished product which is going to be placed somewhere (architect #2)

Conclusion

With regard to solar-integrated architecture and its design process, the following main issues were identified as important by the interviewed architects:

- All involved actors should strive for a sustainable project:
  - *the client*: to make it financially possible;
  - *the engineers*: to make it technically possible;
  - *the municipality*: to make it legally possible;
  - *the architect*: to make it into an attractive, functional and healthy building pleasant for its inhabitants.

However, it was not experienced exactly as that. As teamwork and collaboration become crucial and more intense and necessary, it gets more important for all actors to speak 'the same language'. Architects experienced a gap between engineers and architects because of different backgrounds and difficulties of communication. With the need for more clever, energy-efficient buildings, it could be said that architects need more engineering skills while engineers need to gain more architectural skills. As we see that IDP is becoming a more common and necessary design method, it should perhaps be introduced in the education. Learning how to successfully collaborate within the design team should become part of both the architectural curriculum as well as the engineering curriculum in order to reduce problems in future IDPs.

- Clients did not prioritize solar-integrated architecture. This was mainly due to a resistance of investing in active solar technologies which did not provide short-term profit. Architects mentioned that a change of ownership's type – one which prioritizes a long-term commitment – would stimulate the integration of active solar technologies. This change was seen possible if it would be stimulated by subsidies or other financial incentives. Green building certification systems were often seen by architects as a positive influence on the building process, because clients will more easily invest in sustainable (solar) aspects for the sake of marketing. However, a certain caution is needed when it comes to certification systems. For instance, the LEED certificate gives little incentive for passive solar energy (as it is only considered as part of the operational energy calculation and not as on-site renewable energy) and a LEED certification is no guarantee for a better energy performance (Shaviv 2011).
- All interviewed architects mentioned to have used rules of thumb as a design tool. Those rules provided them basic information and would orientate architects in the right direction in the early design phases. Architects do use rules of thumb on other aspects during the very early design process, for instance, for estimating approximate size of structural elements, as these sizes can greatly affect spaces within the building. Structural engineers make more detailed calculations in the later design phase and will adjust the sizing according to these. Rules of thumb regarding energy aspects can also help architects in the very early design phase but they do not substitute energy simulations, which are needed at later stages (Granadeiro *et al*. 2011). In some cases, advanced BPSs were carried out by (building service) engineers in order to provide more information for the architects and engineers to work with, but those advanced simulation were never performed by architects.
- There is a lack of aesthetically attractive active solar products. Most of the architects would like to consider active solar systems more as a building material, with the possibilities to change colour and dimensions.

Limitations

One limitation in this research can be the limited number of interviewed architects. However, earlier researches show that it is possible to draw conclusions from a limited number of case studies (Flyvbjerg 2006, Ruddin 2006).

Another limitation of this study can be the ambiguity of the terminology within the field of low-energy buildings and solar-integrated architecture. Even though architects were asked to describe the term 'solar-integrated architecture' and its relation to sustainable architecture, it was not always clear as to what the term contained. This was especially the case in the projects where there was no active application of solar energy (solar cells, panels) but where architects worked with the passive application of solar energy (orientation, prevention of overheating, daylight).

Another limitation can be the fact that only architectural offices were visited in the bigger cities in Sweden.

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Tools and methods used by architects for solar design

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ABSTRACT

Architects have a key role to play when it comes to the design of future low-energy (solar) buildings. Proper design tools and working methods could help architects in the design process. In order to identify barriers of existing tools and methods for solar design, needs of architects for improved tools, and to gain an insight into architects' methods of working during the design process, an international survey was carried out within the framework of IEA-SHC Task 41-Solar Energy and Architecture, combined with semi-structured interviews. This paper presents an overview of main results of this study.

Both the survey and interviews strongly indicate the need for further development of design tools for solar architecture, focusing on a user-friendly, visual tool that is easily interoperable within current modelling software packages, and which generates clear and meaningful results that are compatible with the existing work flow of the architect. Furthermore, the survey and interviews also indicated a strong awareness about solar aspects among respondents. However, this was combined with a limited use and knowledge of solar energy technologies, suggesting the need for further skill development amongst architects and tool development to accelerate the implementation of these technologies in future buildings and urban fabric.

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1. Introduction

Our future built environment needs to be low-energy consuming in order to be resilient to future developments in energy resources and distribution. In several countries, legislation is pushing towards nearly zero energy buildings within a decade or two. In Europe, the recast of the EPBD directive [1] is an example of this legislation. These nearly zero energy buildings will not only need to be energy efficient, they will also need to produce their own energy by the integration of, for instance, passive and active solar energy systems.

Architects have a key role to play in future (solar) low-energy buildings, since passive design is related to architectural decisions already made in the early design phase (EDP). This question was addressed in a recent IEA-SHC programme project titled Solar Energy and Architecture [2]. In the context of Subtasks A and B of this task, an international survey was carried out which was separated in two parts. The Subtask-A survey concerned the integration of solar energy systems in architecture, while the Subtask-B survey was about the adequacy of existing tools and methods for solar design, with emphasis on the early design phase. In this article, only results of the subtask B survey are discussed. More detailed results of the Subtask-B survey can be found in the IEA-SHC Task 41 report T41.B2 [3]. In addition to the survey, semi-structured interviews were conducted with architects and urban planners who designed solar integrated buildings or urban plans. These results are discussed in the second part of this article.

The objectives of the Subtask-B survey and the interviews were:

1. To identify barriers of existing digital tools and design methods for solar design;
2. To identify the needs of architects for better or improved tools and methods;
3. To gain an in-depth insight into architects' methods of working with design tools and building performance simulation (BPS) programs during the design process.

The design process and the role of BPS tools have been the subject of several studies. In an overview of widely used BPS tools, Crawley et al. [4] noticed that there is no common language on describing what the tools do. This leads to the fact that architects do not necessarily know which tool would fit their working method best.

Likely, Lam et al. [5] showed with a survey amongst building professionals in Singapore that architects did not see the use of simulation tools as a part of their design responsibilities. In parallel, in a survey performed by de Wilde and Voorden [6], the

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majority of responding architects indicated that they did not use specific tools to support energy related aspects in their design process. With the increasingly high demands placed on energy performances of buildings, evidence-based design by validating different design alternatives and choosing the most suitable options from all points of view [7] becomes more important for all actors in the design process, especially in the EDP.

BPS tools can be of great help when validating these different design alternatives. In an article describing a new, prototypical tool, Schlueter and Thesseling [8] noticed that there is a lack of current BPS tools supporting the EDP, and numerous authors agree with this [5,9,10]. Current BPS tools are found not to be 'architect friendly' [9] because they are not compatible with architects' working methods and needs, as well as it is difficult to exchange information between different tools without losing information [11]. It might explain why rules of thumb are still widely used by architects in the EDP because they provide quick and rough estimates on solar energy.

The lack of appropriate tools has been regarded as an opportunity by many researchers to develop new BPS tools which would fit the needs of architects better. Some examples of these are described by Ellis and Matthew [12], Schlueter and Thesseling [8], Yezioro [13], Chlela et al. [14], Peter and Svendsen [15], and Garde et al. [16]. All of them share the common goal of reduced complexity in input, reduced simulation time, while providing a graphical interface rather than a numerical one, which makes it easier to validate competing design alternatives.

Besides the lack of architect-friendly BPS tools, another complicating factor is the communication between the designers, and other actors, such as engineers, and clients. It is important for a client to understand the outcome of such BPS tools and the implications on the architecture of buildings [6], but many clients still do not see the need for paying consultant fees for performing energy simulations [17,18] even though it might save them money in the long run.

2. Method

In order to identify the barriers of existing tools and methods, the needs for improved tools, and to gain insight into architects' methods, the IEA-SHC Task 41 performed a survey amongst building professionals in 14 participating countries, and interviews were conducted with 23 architects in Scandinavia.

2.1. Survey

The survey was designed by the international Task 41 expert team and then programmed into Questionform [19], an online survey creator. Then, in each participating country, one national coordinator involved in Task 41 distributed the survey to building professionals in his/her own country. These coordinators used a variety of methods to reach practitioners: by publishing links for surveys through national associations of architects, through professional newsletters and magazines, through custom mailing lists developed from yellow pages or the like. A total of 627 responses were received from 14 countries (Australia, Austria, Belgium, Canada, Denmark, France, Germany, Italy, Norway, Portugal, South-Korea, Spain, Sweden, and Switzerland). Of these, 350 were considered in the analysis. Many surveys were not analysed because they contained less than 75% of completion. Unfortunately, it was impossible to calculate a precise response rate due to the different distribution methods in every country. Table 1 gives an overview of the amount of respondents reached in the participating countries. In Table 1 can be seen that, in the most pessimistic scenario, a direct response rate of 5.9% was calculated.

2.2. Interviews

The survey was chosen as a research method in order to reach a large population of building professionals in many countries. In addition, 23 semi-structured interviews were conducted in Denmark, Norway, and Sweden in order to explore ideas and responses in greater depth, and to be able to study a design process. Similar research carried out earlier within the field of architecture, focussing on the design process, also made use of this method [20–27]. The research method of observations was also considered but found inappropriate since it implied following the design process from the beginning to the end, which would have been a problem since many of the selected buildings were already built. It also required presence of the researcher at many critical times in the process which would be hard to achieve due to the geographical distribution of the projects.

Table 1
Amount of respondents reached by direct e-mails or indirectly through links on websites, complete, incomplete questionnaires (missing few questions) and empty questionnaires by participating country.

Country		Indirect contact (i.e. website)	Direct e-mail	Complete	Missing few quest.	Empty	Total	Resp. rate (indirect) %	Resp. rate (direct) %
Australia		est. 9 000	0	78	6	49	133	0.9	n/a
Austria		90	180	17	1	13	31	20.0	10.0
Belgium		n/a	179	16	5	9	30	n/a	11.7
Canada	Eng.			20	9	15	44		
	Fr.			11	3	13	27		
	Total	n/a	1050	31	12	28	71	n/a	4.1
Denmark		n/a	265	2	0	2	4	n/a	0.8
France		est. 29 000	0	8	0	1	9	0.0	n/a
Germany		n/a	776	8	10	28	46	n/a	2.3
Italy		est. 60 000	100	13	13	34	60	0.0	26.0
Norway		unknown	244	10	12	17	39	n/a	9.0
Portugal		n/a	59	6	0	19	25	n/a	10.2
S. Korea		n/a	286	33	3	34	60	n/a	26.0
Spain		n/a	n/a	7	4	8	19		
Sweden		est. 7 000	1775	27	11	25	63	0.5	2.1
Switzerland	Fr.			1	0	1	2		
	Ger.			7	4	8	19		
	It.			8	0	9	17		
	Total	n/a	920	16	1	27	44	n/a	1.8
Total			5 834	272	78	277	627	0.5	5.9

Table 2
Interview guide.

Introduction	Design process	Lesson learnt & barriers
Question 1 What is solar integrated architecture for you and do you think it is an important aspect of sustainable design?	Question 3 Could you describe the early design phase for this project? What was done and what was the role of the participants?	Question 6 How did you gain the skills that you presently have with the tools and solar energy in general?
Competences		
Question 2 What basic information and/or knowledge should an architect have before starting designing a project like this?	Question 4 Could you describe the rest of the design process in phases?	Question 7 What are your lessons learned in this project and how is this project different from other projects done by your office?
	Question 5 Which design tools did you use during the design process and how useful did you find these tools?	Question 8 According to you, what are the most important barriers for exploiting solar energy as an architect?

Instead, an interview guide was set up to serve as a basis for all interviews with architects (see Table 2). This interview guide was developed with other IEA-SHC Task41 members. The interview guide for urban planners was almost similar, but obviously focused on the urban planning scale rather than the building scale.

2.2.1. Procedure

In order to gain a more in-depth insight of architects implementing solar energy into architecture in Scandinavia, several architecture offices were chosen in the countries Denmark, Norway, and Sweden (see Table 3). Additionally, two urban planners were also interviewed in order to highlight barriers in solar integrated urban planning. Many of the selected buildings had also been in the run within subtask C of IEA-SHC Task 41, where case study buildings are gathered with an attractive integration of solar energy.

All selected architects and urban planners were contacted by email and phone and all of them agreed to participate. The architects received the questions prior to the interviews so that they could prepare for it. In general, the interviews lasted between 30 and 60 min, depending on the motivation and availability of the architect. All interviews were tape-recorded. The interviews in Sweden were held in Swedish and translated to English, while all interviews in Denmark and Norway were held in English.

After all interviews were translated and transcribed, data analysis was performed following Glaser and Strauss' grounded theory [28] – a qualitative research method in which theory is derived by systematically gathering data throughout the research process. The provided steps of the grounded theory [29] were followed in order to structure the data and to treat all interviews equally. In order to analyse and code such a large amount of data, the program QSR NVIVO 7 [30] was used. Within this program, it is easy for the user to import a large pool of sources, code data into categories, search data, and change categories. Categories were set up before the analysis. After coding, the categories were exported to a word processing program.

Table 3
Overview of projects.

Country		Type of project		Completion	
Denmark	7	Residential	8	Finished	11
Norway	2	Commercial	5	Not finished	12
Sweden	1	Public	6		
	4				
		Urban plan at architecture office	2		
		Urban plan at planning department	2		

2.2.2. Sample

The 23 interviews were carried out between December 2010 and November 2011 in the cities of Aarhus (DK), Copenhagen (DK), Gothenburg (SE), Karlskrona (SE), Lund (SE), Malmö (SE), Oslo (NO), and Stockholm (SE). The majority of the interviewees (8 female, 15 male) had more than ten years of practical experience. Some of the interviewees were also sustainability coordinators in the office and in one case, the interviewee was an industrial PhD student (a PhD student who is partly employed in an architectural office and partly employed at a university). The interviewed urban planners were also educated as architects. When it comes to the size of the architectural offices and the separate urban planning departments, four of the offices had one to five employees, five had five to ten employees, seven had ten to 50 employees, and seven had more than 50 employees.

3. Results

3.1. Survey results: respondent's profile

One part of the questionnaire contained a series of personal informative questions. This part revealed that the majority of respondents worked for small or medium sized firms (one to ten employees) mostly active nationally. The respondents' work encompassed a wide variety of projects and building types, with residential buildings being the most common type. Sixty-seven percent (67%) of respondents indicated that they used a 'Conventional project delivery method', with 'Design-Build contracts' and 'Construction Management' being the second most common methods used. The majority of respondents were born between 1960 and 1979. Sixty-six percent (66%) of the respondents were males, and most of the respondents were architects or designers, with a few engineers and other professions also represented. The majority (74%) of respondents had more than ten years of experience.

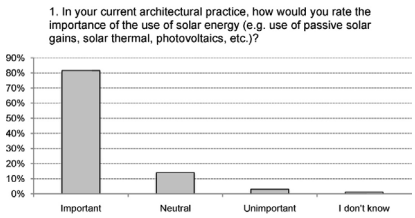


Fig. 1. Distribution of answers for question 1, for all countries (n = 346, four respondents did not answer this question).

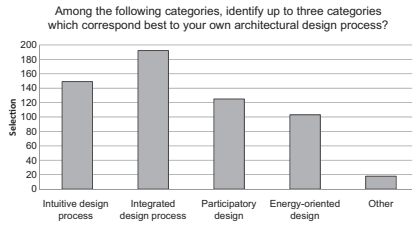


Fig. 3. Distribution of answers for multiple-choice question 16 (n = 587, some respondents selected more than one design process).

3.1.1. Interest for solar energy

Eighty-two percent (82%) of the respondents answered that solar energy aspects were important in their current architectural practice (Fig. 1).

The most common solar design strategy used was 'Daylight utilisation', with 74% answering that this was always or often included in their projects. However, the term 'daylight utilisation' was not defined in the questionnaire so it is possible that respondents answered 'yes' based on the fact that they put windows in their building designs and not necessarily used electric light replacement strategies. The second most common strategy was 'Passive solar for heating', with 57% of respondents always or often including this solar design strategy in their projects. Forty-seven percent (47%) always or often included 'Solar thermal for hot water use', while 'Photovoltaics' and 'Solar thermal for heating' were less common (see Fig. 2). The least common solar strategy was 'Solar thermal for cooling', which was used always or often by only 7% of respondents (see Fig. 2).

3.1.2. Methods for solar design

The survey questions on methods focussed on the design process as well as the decision making process. The results indicated that respondents used a variety of design processes: (note that respondents were able to select multiple answers) of the 587 answers, there were 192 selections for the fact that 'Integrated design process (IDP)' corresponded best to the architect's own practice, with the remainder divided between 'Intuitive design process' (n = 149), 'Participatory design' (n = 125) and 'Energy-oriented design' (n = 103). Out of the 350 survey participants, sixty-nine percent (69%) of the respondents stated that solar energy technologies were first considered in the conceptual phase, underlining the need for well-developed conceptual design tools. Most respondents answered that they base their design processes upon experiences, interaction with the project owner and by collaborating with others (Figs. 3 and 4).

Responses concerning decision making in small projects indicated that the conceptual phase was largely handled by the architect alone (53%). Specialists were more likely to be involved in later design phases, and multidisciplinary workshops played a fairly small role with a 6–10% response rate depending on design phase. Concerning decision making in large projects, 32% of respondents stated that this phase was handled solely by the architect. External solar energy consultants and building science specialists were relatively common in the later phases of large projects. Multidisciplinary workshops also played a more important role than in smaller projects (10–12% depending on project phase).

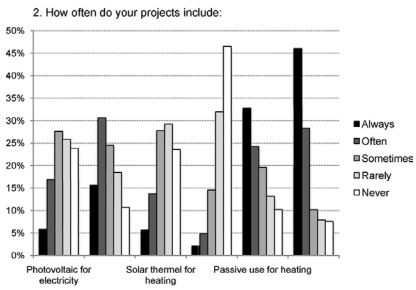


Fig. 2. Distribution of answers for question 2, for all countries (n = 325–342).

3.1.3. Tools for solar design

The majority of respondents described their skills with graphical solar design methods as fair (37%) or poor (20%). With regards to solar design tools in CAAD and advanced simulation tools, the majority answered that they considered their skills to be poor (29% and 27% respectively) or very poor (31% and 41% respectively). However, most respondents described their skills with CAAD software, which is an integral part of architects' practice, as advanced (28%) or fair (27%).

A question concerning the software tools corresponding to various design stage were used returned a number of results (Fig. 5a–c). The most commonly used CAAD tools were AutoCAD, Google SketchUp, Revit Architecture, ArchiCAD, Vectorworks and 3dsMax. The most common visualisation tools were Artlantis, V-Ray, RenderWorks and Maxwell Render, while Ecotect, RETScreen,

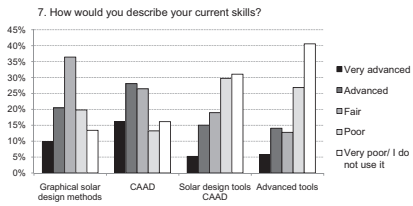
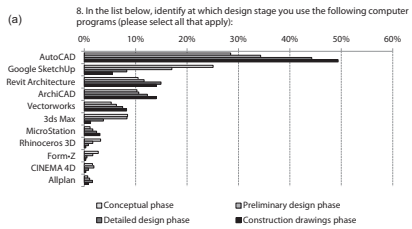
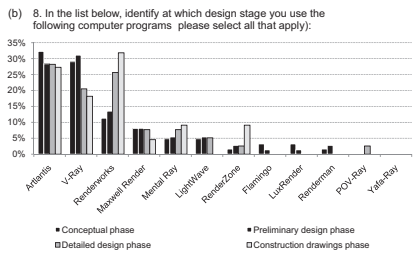


Fig. 4. Distribution of answers for question 7 about the skills with the use of different tools, for all countries (n = 303–310).





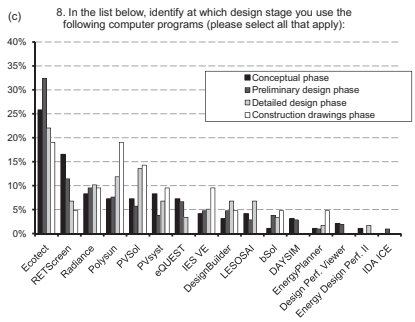


Fig. 5. (a) Distribution of answers for question 8a, for all countries (n = 282). (b) Distribution of answers for question 8b, for all countries (n = 282). (c) Distribution of answers for question 8c, for all countries (n = 282).

Radiance, Polysun, PVSol, PVsyst were the most common tools for simulation.

The most common CAAD, visualization and simulation tools were all used in all project phases, but the distribution of different tools for different phases was specific for each tool. CAAD tools prioritising a simple user interface and rapid modelling (e.g. Google SketchUp) were used extensively in the EDP, while more complex tools (e.g. Revit Architecture, AutoCAD) were more common in the later project phases.

A similar trend is visible concerning simulation software, with some products being preferred in the EDP (e.g. Ecotect, RETScreen) and other, more specific and complex tools, used more heavily in later stages (e.g. Polysun, PVSol). The most common visualization software programs were used fairly evenly across the design phases.

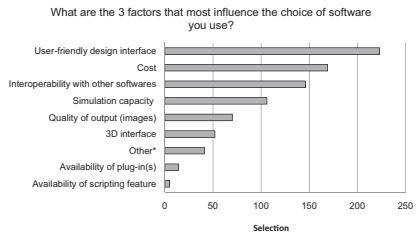


Fig. 6. Distribution of answers for question 9, for all countries (n = 826).

The factor that most influenced the respondents' choice of software was a user-friendly interface (n = 223). The next most common factors were costs (n = 169), interoperability with other software (n = 146) and simulation capacity (n = 106). Quality of output (images), 3d interfaces, availability of plug-ins and availability of scripting features were considered to be less important (note that respondents were able to select multiple answers). (Fig. 6)

3.1.4. Tools: satisfaction and barriers

Respondents reported various degrees of satisfaction with their chosen software programs (CAAD, visualization and simulation tools) in terms of support for solar building design. For many programs, the response rate was so low that it was impossible to formulate meaningful conclusions.

The most common barriers reported by respondents were 'Tools are too complex' (n = 126, see Fig. 7). Other common barriers were 'Tools are too expensive' (n = 97), 'Tools are not integrated in CAAD software' (n = 80) and 'Tools take too much time' (n = 77). Respondents also stated that existing tools are not integrated in normal workflow (n = 71), that the tools do not adequately support conceptual design (n = 60), and that they are too systemic (n = 54). In hindsight, the term 'systemic' might have caused confusion since it can mean either that the program is focussed on one system or that the program looks at the whole range of systems. The answer that existing tools are satisfactory was only selected 13 times (note that respondents were able to select multiple answers).

3.1.5. Improvements needed

Respondents were then asked about the need for improved tools in each design phase. In the conceptual phase, 28% answered they would like to have 'Improved tools for visualization', followed by 'Preliminary sizing' (20%) and 'Tools that provide explicit feedback' (18%). In the preliminary design phase, the most common request was 'Improved tools for preliminary sizing' (26%), followed by 'Tools for key data' and 'Explicit feedback' (22% and 20% respectively). For the detailed design phase, most respondents requested improved 'Tools for key data' (28%), followed by 'Preliminary sizing' (18%), 'Explicit feedback' and 'Visualization' (both 16%). The most common response for the construction drawings phase was 'I don't know/not applicable' (29%). However, 21% also wished 'Improved tools for key data', 16% for 'Preliminary sizing', and 10% for 'Tools that provide explicit feedback'.

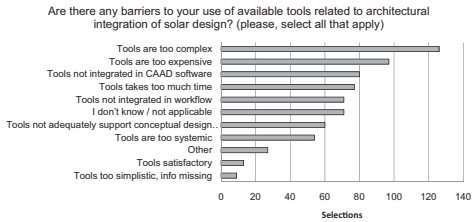


Fig. 7. Distribution of answers for question 11 ($n = 685$).

3.2. Interview results

During the interviews, architects were asked first what solar integrated architecture was for them in order to make sure that the terminology was clear for the rest of the interview. Almost all architects mentioned first the active utilisation of solar energy (PV and ST) and later on they mentioned passive utilisation (daylight, heat).

3.2.1. Knowledge and competences

Many architects mentioned that designing solar integrated architecture required more technical knowledge than usual. The majority of them experienced that their current level of technical knowledge was too low and that they needed to develop this. A high level of technical knowledge was found necessary to talk to the engineers and quickly take design decisions.

The need to develop an *extensive* technical knowledge was not felt in every architectural office. It was seen as something unnecessary, since it was considered to be too costly and outside the architecture domain. Instead, architectural offices developed collaborations with engineering firms. Some architecture offices also employed their own engineers. In two Danish architecture offices, industrial PhD students supported the design process and provided project architects with design tools. At the urban planning departments of the cities of Lund and Malmö, collaborations with engineering firms and other consultants were developed to bridge the gap in technical knowledge. When looking at the content of this technical knowledge, architects mentioned mainly the following elements: (1) local climate conditions (temperature, wind, sun paths), (2) active solar systems (how to implement them, needed components and space, dimensions of the needed active systems in relation to the energy need of the building), (3) costs, (4) other technical systems in the building like ventilation, and (5) construction methods.

It was not always perceived as easy to gain the necessary knowledge. Most architects said they had developed their knowledge by taking part in real projects; a method called by the architects as 'learning by doing'. This result is in line with the results of the survey, which also showed that the design processes of architects are mainly based on experiences. Other forms of knowledge acquisition which was mentioned by the architects were 'working with the engineers', 'attending conferences and workshops', 'going on study trips', and 'reading literature'.

3.2.2. The design process

In almost all design processes, a goal was identified at the beginning of the project: a low-energy (solar) building or sustainable urban district. In the buildings designed before 2000 or in the early 2000s, no specific and measurable goal was defined more than that the building needed to be 'sustainable'. In the later 2000s, goals became more clear and measurable. Using active solar technologies was only in some cases a goal from the beginning; in other design processes, solar technologies were considered from the beginning but abandoned later in the design process since they were found to be too expensive in the clients' view. However, the amount of solar energy contributing to the building's energy balance was never explicitly quantified.

Newer, stricter building regulations in the Scandinavian countries (and the European Union) have forced clients, both private and public, to focus more on energy use and renewable energy sources. In many cases, the clients discovered that getting their buildings certified according to green building labels (LEED, BREEAM, etc.) would increase the value of their property and they were therefore willing to pay extra for this.

3.2.3. Team work

In the projects designed (and built) in the early 2000s, architects started to adapt their usual design process (traditional design process) by consulting engineers in an earlier stage than normally done. In projects designed (and built) later, many architects qualified their design process as an Integrated Design Process (IDP), often in relation to large-scale buildings. It was hard to verify if processes really complied with all the elements of the IDP, but architects mentioned mostly the early engagement of engineers in the process as a clear sign of this. This early collaboration with engineers was found to be crucial for solar integrated architecture, but this collaboration was not always easy: architects experienced that engineers 'spoke another language', were often 'too specialised', and 'not willing to compromise on certain issues'. In some cases, engineers outnumbered the architects in a design meeting, which was felt as uncomfortable for the architect.

3.2.4. Design decisions

The early design phase of the traditional design processes was mostly in the hands of the architects, with a very limited influence of the engineers. After this early design phase, drawings were handed in to the engineers who performed calculations and simulations. In the design processes qualified by the architects as IDP, the process was more iterative and dynamic. In some cases, all actors gathered in a workshop to come up with a first idea and sketch of the building. In other cases, several design alternatives were proposed by the architects and with the help of simulations and calculations performed by the engineer, the best solution was further developed.

In the design process of the urban planners, meetings were organised to discuss solar energy, where researchers and different stakeholders, specialists, were invited to assert the role that solar energy could play in the future. The target group of these

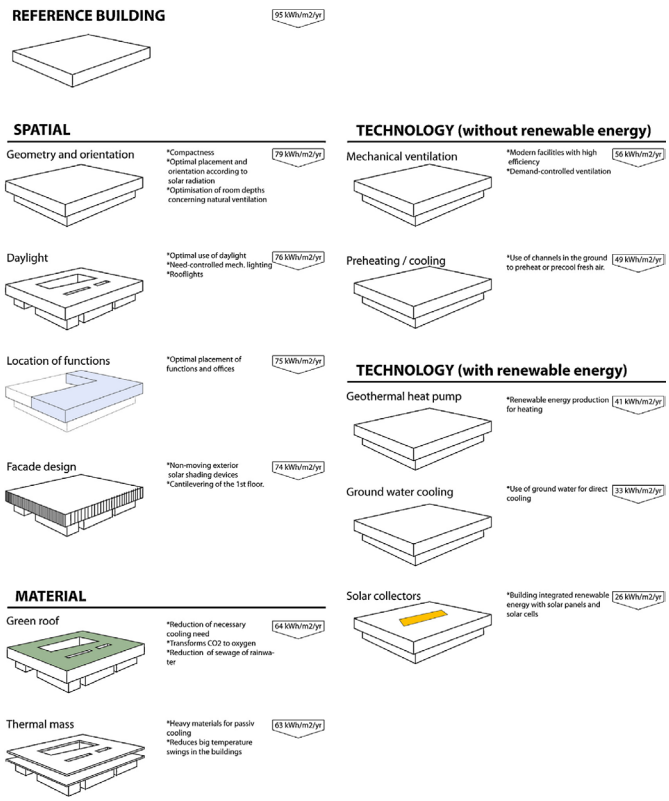


Fig. 8. Consequences of different design parameters on the energy use of a building. An example out of the design process of a Danish architect designing an office building (after Henning Larsen Architects).

meetings was mainly real estate developers. The developed urban plans were regarded by the urban planners as a non-conflicting issue, but a clear and measurable goal for this implementation was never defined. Furthermore, the urban planners acknowledged that they lacked the competence to achieve a solar energy scheme in its full potential.

Communication with the client about solar energy and energy in general was felt as a rather underdeveloped skill amongst the architects, which was due to several factors like a lack of proper tools, and a lack of knowledge. Only some architects were able to give a clear and visual overview of the impact of energy related decisions on the architecture. In Fig. 8, an example can be seen of a roadmap of different design decisions and its impact on the used energy. It was presented to the client to show which steps where necessary in order to reach the desired energy use.

3.2.5. Design tools

In the design processes of the projects prior to or in the early 2000s, no advanced BPS tools were used, simply because they could only be handled by experts and at this time these tools did not integrate well into their work flow. In the projects designed later, i.e. between 2000 and 2011, BPS tools were used more often. Interestingly, there was a noticeable difference between the three different countries. In Norway and Sweden, hardly any architect used BPS tools themselves in the discussed projects. Instead, they used simple rules of thumb while they collaborated with engineers who simulated the building's energy performance (only one Swedish architect had used an advanced BPS program). Some of the architects clearly stated that they did not want to gain an extensive knowledge of these programs because it would be too costly. However in Denmark, many architects were using advanced BPS

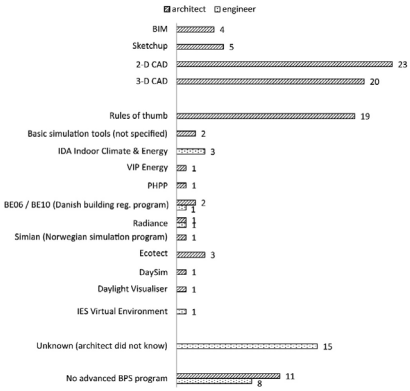


Fig. 9. Tools used in the design process.

programs themselves. Often, architects used these tools as real design tools by comparing different design alternatives relatively (i.e. worse or better performance) rather than absolutely (i.e. a certain energy use of the building). Simulating the absolute energy performance was still in the hands of external engineers who had the legal responsibility for the outcomes. In this way, the Danish architects were able to validate more design alternatives and show the consequences on the architecture, while providing almost instant feedback to the design team instead of waiting for an external engineer to perform a similar simulation.

An overview of the tools used in the design processes is presented in Fig. 9. Interestingly, many architects were not able to name the BPS tools which the engineers used. Architects mentioned to have used simple rules of thumb for solar energy during the design process, which mainly provided input for the dimensions of PVs or Solar Thermal panels, the best inclination and the orientation. Within the urban planning projects, only qualitative studies concerning daylight and shading were performed, mainly with the help of Google SketchUp. In projects achieved in the late 2000s, Building Information Modelling (BIM) was used in the design process and it often concerned large-scale buildings.

4. Conclusions and discussions

This article presented the results of an international survey amongst building professionals in the framework of IEA-SHC task 41-solar Energy and Architecture and interviews conducted with Scandinavian architects with the objective to identify barriers of existing tools and methods for solar design, the needs for improved tools, and to gain an insight into architects' methods of working during the design process. The survey and interviews both strongly indicate the need for further development of software tools for solar architecture, focusing on a user-friendly, visual tool which can generate clear and meaningful results. Also, since each design phase has its own requirements and specifications, design tools should be able to adapt to specific design phases. Future BPS tools should work as a design tool, being able to support comparisons between competing design alternatives in relation to energy use and production in order to support the architects. Respondents answered that there is a need for tools to be easily compatible with the existing work flow of the architect. This can be interpreted in several ways: either future BPS tools should get a (better) integration into current CAAD programs, or they should be able to stand alone with importing (and exporting) geometry in a satisfying way. One attempt to overcome the problem of import and export is the introduction of the current IFC (Industry Foundation Classes) file format. It is becoming a building standard [31] and attempts to have all software producers to use the same standard which increases interoperability. However, interoperability between the IFC file format and major software packages is still not optimal. Architects and other actors can save costly time when the import and export of geometry between programs will run without errors, something which is currently not the case.

Implementing BPS tools into current CAAD software will require a shift from tool developers' focus from purely CAAD towards a whole performance simulation tool. Developing BPS tools as standalone programs can be done by developers who already have built up an extensive knowledge. However, some technical difficulties might occur in both situations, since many BPS tools were developed before the current CAAD standards got widely accepted in the industry. This might lead in many cases to the need for the total reprogramming of the program.

In the interviews, those architects who used BPS tools, often used more than one program at the same time during the design process to simulate several aspects of the energy performance of a buildings, e.g. daylight conditions, energy production of solar technologies, and thermal balance. Combining all such separate programs into one environment, using the same geometry model, would be preferable and speed up the iterative design process. The recent launch of several BPS tools with such features has made clear that the industry is working towards such programs.

A parallel could be drawn to the role of visualisation programs. During the last decade, these programs helped architects to judge design options but more importantly, it helped them to 'sell' their ideas visually.[1] If BPS tools could be used in the same way throughout the design process, architects would be able to sell energy concepts much better. Communicating with the client is crucial for making design decisions in the design process. If the client is shown what consequences some design decisions have on the energy performance of buildings as well as the financial consequences are provided, a better performing, low-energy solar architecture can be reached.

The survey and interviews also indicated a strong awareness about solar aspects among respondents. However, this was combined with a limited use and knowledge of solar energy technologies, suggesting the need for further skill development amongst architects and tool development to accelerate the implementation of these technologies in future buildings and urban fabric.

The results also showed that traditional, graphic solar design tools or rules of thumb are still in use by many architects since they provide more direct insight, supporting iterative design decision. For instance, the inclination of a roof and its suitability for solar cells can be tested more directly. However, results of the survey showed that only a third of the architects judged their skills of graphic solar tools as fair. That means that the potential of these simple, graphic design tools might be underutilised. If rules of thumbs were more widespread, it could help more architects in the very early design phase. There is also a risk that the more recent architectural education, which has focused on computer literacy, may have failed to properly teach the simpler, graphical, performance tools. Taking solar energy into account has been part of several (architectural) student projects, often implemented in a design studio environment [32–35]. Building performance simulations tools were used

[1] However, it needs to be kept in mind that most of the visualisations are pure cosmetic images often not based on true lighting levels.

in most of the projects in order to give feedback to students on the impact of their design decisions on the energy performance of buildings. Often, the students were taught basics of solar energy in the beginning of the design assignment. The use of BPS tools was integrated in such a way that students got familiar with them. In the case of an experiment set up by Otis [35], two groups were formed; one group used traditional solar design tools, while the other group made use of BPS tools. In the end of the experiment, the test group which used a BPS tool outperformed a group which used traditional solar design tools.

If the shift can be made to better and easier-to-use software tools for building performance simulation, design processes will get more efficient as well as the end product of these process; low-energy (solar) buildings.

Acknowledgements

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Appendix A. Online questionnaire

Questions and survey layouts were developed during the IEA-SHC Task 41 meetings and through e-mail exchanges with the collaboration of international experts. The survey consisted of 22 questions and included three question types: multiple choices of specific categories, a single selection of a specific category and open end question (free text). To gather the desired data, the questions were divided into the following categories:

A. Solar energy in general:

Question 1

In your current architectural practice, how would you rate the importance of the use of solar energy (e.g. use of passive solar gains, solar thermal, photovoltaics, etc.)?

<important, neutral, unimportant, I don't know>

Question 2

How often do your projects include: photovoltaic technologies for electricity, solar thermal technologies for domestic hot water, solar thermal technologies for cooling, passive use of solar gains for heating, daylight utilization strategies?

<always, often, sometimes, rarely, never>

B. The design methods:

Question 3

In which design phase would you first consider the integration of solar energy technologies?

<conceptual phase, preliminary design, detailed design, construction drawings>

Question 4

Among the following categories, identify up to three categories which correspond best to your own design process:

<experiences, rules of thumb, design guidelines, computer simulations, expert systems architecture, interactions with the owner, interactions with future users, several propositions, collaboration with others>

Question 5

How would you handle decision making for the integration of solar energy technologies in your project in the case of smaller, less complex projects?

<do it myself; consult a colleague architect; involve an internal solar energy consultant; involve an external solar energy consultant; involve a building science specialist; arrange multidisciplinary workshops; involve other profession>

Question 6

How would you handle decision making for the integration of solar energy technologies in your project in the case of larger, more complex projects?

<do it myself; consult a colleague architect; involve an internal solar energy consultant; involve an external solar energy consultant; involve a building science specialist; arrange multidisciplinary workshops; involve other profession>

C. Tools for solar design:

Question 7

How would you describe your current skills regarding: graphic solar design methods, CAAD, solar design tools in CAAD, and advanced tools)?

<very advanced, advanced, fair, poor, very poor>

Question 8

In the list below, identify at which design stage you use the following computer programs

(8a: CAAD tools: Vectorworks, Rhinoceros 3D, Microstation, Lightworks, Houdini, Form-Z, Digitial project, Cinema 4D, Caddie, Blender, ArchiCad, 3DS Max)

(8b: Visualization tools: Yafaray, V-Ray, RenderZone, Renderworks, Renderman, POV-ray, Mental Ray, Maxwell Render, LuxRender, LightWave, Flamingo, Artlantis)

(8c: Simulation tools: RETScreen, Radiance, PVSyst, PV*SOL, Polysun, LESOSAI, IES VE, IDA ICE, eQUEST, Energy Design Performance, Ecotect, Design Performance Viewer, DesignBuilder, Daysim, bSol, BKI Energieplanner)

<conceptual phase, preliminary design, detailed design, construction drawings>

Question 9

What are the 3 factors that most influence the choice of software you use?

<user-friendly design interface, cost, simulation capacity, interoperability with other software, availability of scripting feature, availability of plug-in(s), quality of output (images), 3d interface, other>

Question 10

For the programs you currently use, express how satisfied you are with their support for solar building design:

(10a: CAAD programs: Vectorworks, Rhinoceros 3D, Microstation, Lightworks, Houdini, Form-Z, Digital project, Cinema 4D, Caddie, Blender, ArchiCad, 3DS Max)

(10b: Visualization tools: Yafaray, V-Ray, RenderZone, Renderworks, Renderman, POV-ray, Mental Ray, Maxwell Render, LuxRender, LightWave, Flamingo, Artlantis)

(10c: Simulation tools: RETScreen, Radiance, PVSyst, PV*SOL, Polysun, LESOSAI, IES VE, IDA ICE, eQUEST, Energy Design Performance, Ecotect, Design Performance Viewer, DesignBuilder, Daysim, bSol, BKI Energieplanner)

<very satisfied, satisfied, neutral, dissatisfied, very dissatisfied>

Question 11

Are there any barriers to your use of available tools related to architectural integration of solar design?

<The tools are not adequately supporting the conceptual design stage; The tools are too expensive; The tools are too complex (high learning curve); Using the tools takes too much time; The tools are too systemic (do not support integration of active/passive/daylight design); The tools are not integrated in our normal workflow; The tools are not integrated in our CAAD software; The tools are too simplistic and do not give me the information I require; No, I

find available tools quite satisfactory; I don't know/not applicable; Other>

Question 12

Do you see a need for improved tools to support the integration of solar building design?

<Yes, we need improved tools for visualization (architectural integration); Yes, we need improved tools for preliminary sizing of solar energy systems; Yes, we need improved tools for providing key data (numbers) about solar energy; Yes, we need tools that provide explicit feedback (key data) in connection with building massing and orientation; No, I find available tools quite satisfactory; I don't know/not applicable; Other>

Question 13

Please specify other needs regarding tools or methods:

(open question)

The questionnaire ended with general inquiries concerning the type of architectural office the respondents worked in and personal informant questions.

Informative factual questions (for statistical purposes only)

Question 14

Number of employees in your firm:

<Less than 3; 3 to 10; 11 to 50; More than 50>

Question 15

Among the following building categories, which one(s) correspond(s) the most to your architectural practice?

<Building renovation; New buildings; Residential buildings; Commercial buildings: retail stores, shopping centers, etc.; Commercial buildings: office buildings, Educational buildings: schools, kindergartens, etc.; Institutional buildings: hospitals, health care facilities; Institutional buildings: museums, exhibition centers, libraries, etc.; Government buildings; Industry/factory/storage buildings; Other>

Question 16

Among the following categories, identify up to three categories which correspond best to your own architectural design process?

<Intuitive design process (i.e. instinctive decisions made without conscious thought. It often refers to the architect's experience.); Integrated design process –IDP (collaboration with others professionals in multidisciplinary teams); Participatory design (interaction between the future users of the

building, e.g. public participation); Energy-oriented design (i.e. practicing sustainability with calculator and computer simulation); Other>

Question 17

Among the following categories, identify the category which corresponds best to your own architectural practice?

<Traditional (conventional) practice with variety of projects; Traditional (conventional) practice with focus on building renovation or restoration; Design-Build (DB); Construction management (CM); Other>

Question 18

Is your firm active. . .

<Nationally; Internationally; Both nationally and internationally>

Personal factual questions (for statistical purposes only)

Question 19

When were you born?

(open question)

Question 20

Gender:

<male, female>

Question 21

Profession:

<Architect/Designer, Engineer, Physicist, Other>

Question 22

Professional experience:

<Less than 5 years; 5 to 10 years; more than 10 years>

The questionnaire ended with an open question ('Please add here any comment you wish to add to this survey').

Interview guide for architects

Introduction	Design process	Lesson learnt & barriers
Question 1 What is solar integrated architecture for you and do you think it is an important aspect of sustainable design?	**Question 3** Could you describe the early design phase for this project? What was done and what was the role of the participants?	**Question 6** How did you gain the skills that you presently have with the tools and solar energy in general?
Competences	**Question 4** Could you describe the rest of the design process in phases?	**Question 7** What are your lessons learned in this project and how is this project different from other projects done by your office?
Question 2 What basic information and/or knowledge should an architect have before starting designing a project like this?	**Question 5** Which design tools did you use during the design process and how useful did you find these tools?	**Question 8** According to you, what are the most important barriers for exploiting solar energy as an architect?

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The design process known as IDP: a discussion

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Abstract

The Integrated Design Process (IDP) was developed to streamline the design process of (solar integrated) low-energy buildings. One of the biggest differences with the traditional design process is the involvement of engineers and other consultants right from the early design stage. Although the IDP has been fully developed in theory with clear and general descriptions, the practical application of the IDP is, however, often far from smooth. In this article, some critical issues of the IDP are discussed, based on literature review, interviews with architects, and experiences with local and international projects, with the hope that these experiences help improving future design process. The discussed issues are: quantification of actors' input, the education of the IDP in the contemporary university curricula, costs of the IDP, and communication.

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Keywords: Design process; IDP; architects; engineers; consultants; communication; low energy buildings

1. Introduction

Future building regulations will require building nearly Zero Energy Buildings (ZEB) in Europe in 2020 [1]. In other countries, similar plans are on their way. Solar energy will contribute significantly both to the energy reduction and production necessary in a nearly ZEB, with both the active (PVs and Solar Thermal) and passive use of solar energy, such as heat and daylight. The design of such ZEB buildings can be a rather complex endeavour; it requires a higher level of technical knowledge from the very start of the design process.

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The integrated Design Process (IDP) is 'a procedure considering and optimising the building as an entire system including its technical equipment and surroundings and for the whole lifespan. This can be reached when all actors of the project cooperate across disciplines and agree on far-reaching decisions jointly from the beginning' [2]. A similar definition of the IDP was formulated by Busby et al.: 'In general, the integrated design process is an approach to building design that seeks to achieve high performance on a wide variety of well-defined environmental and social goals while staying within budgetary and scheduling constraints. It relies upon a multidisciplinary and collaborative team whose members make decisions together based on a shared vision and a holistic understanding of the project' [3]. The IDP has proven to be very effective in producing high-performance and environmentally-friendly building [2-7]. In addition, the IDP optimises project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction [8]. These advantages of the IDP are mainly the result of the shift of the work peak: more is done in earlier stages compared to the traditional processes, reducing the costs of design changes and increasing the ability to change the design (Figure 1).

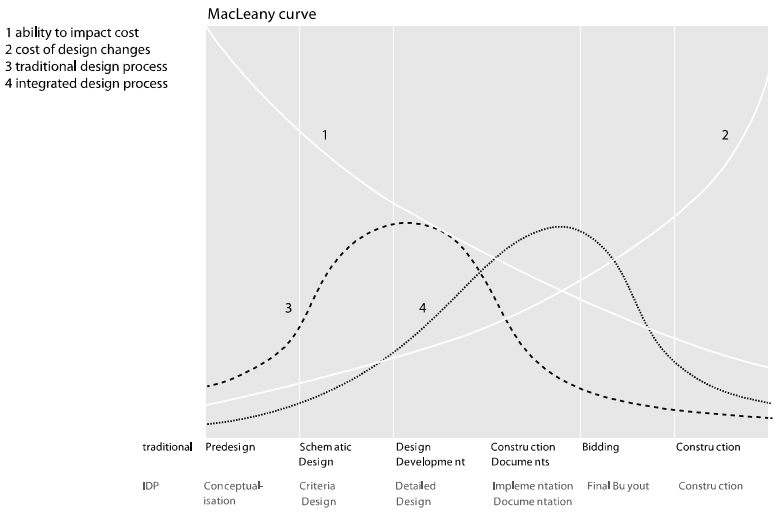

Fig. 1. Macleamy curve showing both the traditional process and the IDP [8]

While the IDP is, in theory, a rather clear and uniform process, the practical execution is often far from that. The discrepancy between theory and practice could be due to the conditions of the specific design process, such as the type of client, type of building, the structure of the design team etc. This article identifies and discusses issues which architects and other actors have been encountering while designing according to the IDP, in the hope that it may start a broader exchange of opinions and, thus, help improve future IDP ventures.

2. Sources

The discussion in this article is based on the following sources: 1) literature review, 2) interviews with architects, 3) experiences based on the local application of the IDP, and 4) different case studies of IEA-SHC Task 41: Solar Energy and Architecture. The literature review consists of the literature from the early 2000s until today. The second source is interviews done with architects on the design processes of solar integrated architecture during 2010-2011, in total: 12 in Sweden, 2 in Norway, and 7 in Denmark (Quotes of the interviews are displayed in italic). The interviews with only the Swedish architects have been discussed in an earlier publication [9], showing, among other things, that good teamwork was found to be crucial in the design process. Interviews were semi-structured and the analysis was done following Glaser and Strauss' grounded theory and with the help of the program QSR NVivo. The third source is the experiences of 'The Sustainable Urbanism Initiative' team from Toronto, which participated in the EQuilibrium House competition organised by Canada Mortgage and Housing Corporation during 2006-2007, where multidisciplinary team of architects and engineers (mostly university professors and graduate students of architecture, building science and mechanical engineering) and consultants worked together to design a Net Zero Energy house in an IDP that was also well documented throughout the process [10]. The last source is experiences which have come forward in IEA-SHC Task 41: Solar Energy and Architecture, the first IEA Task that has been looking into solar design from the architects' point of view in a three years long project that included researchers and practitioners from 14 participating countries. Its goals included identifying barriers that architects are facing related to solar design, helping achieving high quality architecture for buildings that integrate solar energy systems, as well as improving the qualifications of the architects [11].

3. Discussion

Mapping a design process is a theoretical analysis tool, providing an overview of actors and activities during time. The Integrated Design Process has been mapped in several studies. In Figure 2, Table 1, and Table 2, three maps of the IDP are shown according to three different studies [2-3, 8]. The first map, described by IEA-SHC Task 23 (Figure 2) focused more on the design process itself, while the other two, one by Peter Busby et al, and the other by American Institute of Architects (AIA), also included the other stages of the project, such as construction phase, and even post-occupancy-stage (Table 1,Table 2). Interestingly, all three maps give slightly different categories which confirms the fact that it can be very hard to frame and pinpoint the design process. Besides referring to particular stages of the project in a different manner, the mentioned studies also differ on assigning a particular task(s) to each participant / actor in the process.

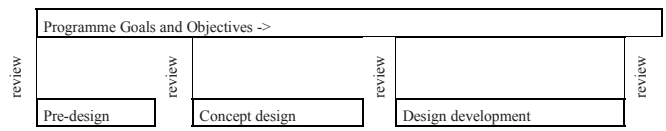

Fig. 2. Division of the design process into three phases (after Löhnert et al. [2])

Table 1. Set of phases of the IPD (after Busby et al. [3])

Phase 1:	Pre Design
Phase 2:	Schematic Design
Phase 3:	Design Development
Phase 4:	Construction Documentation
Phase 5:	Bidding, Construction, Commissioning
Phase 6:	Building Operation
Phase 7:	Post-Occupancy

Table 2. Map of the IDP (after AIA California Council [8])

Design phase / actor	Conceptualisation	Criteria design	Detailed Design	Implementation documents	Final Buyout	Construction	Closeout
Agency							
Owner							
Designer							
Design consultant							
Constructors							
Trade constructors							

While maps of the IDP can be useful to get an insight in what activities are done in which phases and which actors are involved, the reviewed Integrated Design Process documents provide only very broad and general guidelines so that they can be applied in various situations; framing the process more firmly would most probably impose limitations to it [7]. However, such 'loose description' can also be counterproductive and hinder the process itself as it may be difficult to manage expectations and output from various actors.

Interviews with Scandinavian architects, as well as experiences from IEA-SHC Task 41, have indicated that the following issues of the IDP are vulnerable and therefore discussed here: actors vs. activities, costs, competitions, education, and communication.

3.1. Actors versus activities

The role of different actors in the design process is described in the majority of literature, agreeing that all actors need to be involved from the beginning [2, 5, 8, 12]. This was also experienced by the interviewed architects who had gone through an IDP. For example, in the description given by IEA-SHC Task 23, it is stated that in the true IDP settings, the architect becomes a team leader rather than the sole form-giver, mechanical and electrical engineers take on active roles from the early design stages, and the team always includes an energy specialist[2]. By working in such settings after some times, the architect gains deeper knowledge of technical solutions while the engineers simultaneously gain insight in the architectural design [2]. Getting to know more about each other's work can certainly deepen the understanding between different actors in the process as well as it improve the communication between them, thus improving the IDP process itself and hopefully bring final solutions sooner. The interviewed architects experienced working with engineers very helpful.

You need to have generalists who can make people talk together, have the overview, but [you] also need to have competent specialists...[]... so: both the creative architect and the competent energy engineer. If you only have specialists, you have no project. If you only have generalists, you are not cutting-edge

enough. You need to have both in the right combination. And with this you do a very good project. (Architect #13)

Another way of describing the design process is by focussing on activities rather than on actors. Biesbroeck et al. [13] assigned tasks in the early design process of Net Zero Energy Buildings, but they were not assigned to a specific expert. They only provided a domain, like 'Architecture', 'Building Physics', making it able for some experts to perform multiple tasks. This could especially helpful in smaller-scale building design processes, where resources for hiring many disciplines might be limited.

Interestingly, the two ways of describing the process (actors *versus* activities) might contradict each other. For example, an architect might have been able to build up enough knowledge to go through the early phase of the IDP without the involvement of an engineer, although the need of the early involvement of the engineer is seen as an important part of the IDP.

I have been involved in previous [research] on the development of the passive house concept. This gave me the opportunity to do a lot in the first phase without having to involve many others. (Architect #1)

It might be costly to have both an experienced architect *and* an external engineer involved with more or less the same knowledge required for the early design phase, especially in smaller and less complex projects. On the other hand, the disadvantage of not having the engineer involved from the beginning is that the engineer does not get 'attached' to the project, or does not fully participate in defining and, thus, sharing the common goal with other actors in the process, which is one of the essential premises in the IDP. The involvement of (external) engineers in the early design phases is especially needed in large-scale projects or in complex environments since it is harder to reach low-energy architecture in these cases than in a stand-alone house.

Another important aspect is the quantification of actors' input. The majority of interviewed architects answered that their design process was according to the IDP, but this claim was difficult to judge or verify. Even though all actors were involved from the beginning, there might be a big difference in their contribution to the common goal of designing a low-energy / nearly zero energy building. According to the IEA-SHC Task 23, " all potential team members should be screened for their willingness and interest in following the process and in crossing normal professional boundaries" [2], but obviously, it is hard to make this willingness measurable. In those design processes discussed in the interviews, architects experienced that sometimes it was hard to achieve common goals with all actors, since everybody had their own speciality. In other cases, conducting workshops contributed to reach common goals and to gain an interest amongst all actors. Defining common goal(s) usually includes quantitative / measurable outcomes. In one case, however, the architect was recalling that the interdisciplinary team felt that defining mere quantitative goal, a Net Zero House, "didn't feel inspiring enough". Everyone's enthusiasm was awaken, however, when someone started telling a story, a fictional scenario that described first-hand experience and quality of life of a family after living in this house for 20 years, children growing up and parents growing old while enjoying comfort, natural light in every room and being aware that "they didn't take more from the environment than they gave back". Somehow, every participant found a way to relate to this story on a personal level, so it became a very strong common goal that kept everyone not only focused, but also very passionate about the project [14].

In some cases, on the other hand, clearly described performance goals were determined for each design stages, but this time the tasks were specifically assigned to certain actors. A major disadvantage of this specification is the introduction of an abundance of specialists who might be guarding their own *territory*;

making it harder to collaborate. An experience of one interviewed architect reveals quite a frustration with their team-mates' highly specialised roles:

I mean it is a problem, they are so specialised that they don't think of the building as a whole. They think of the air system as one part and the construction as one part. They divide everything. They don't have the ability to balance all these specialities. (Architect #15)

An advantage is, on the other hand, that the issue of responsibility is better defined when every team member is legally responsible for his/her actions. Securing legal responsibility is important in the design process for all actors since actions in the design process might get legal consequences in possible lawsuits, as well as it is important for professional insurances.

3.2. Payment structure and costs of the IDP

The Integrated Design Process has a different distribution of work done during the design process, since the work peak is shifted to earlier phases. However, payment structures were often still adapted to the traditional design process.

If the client only approaches an architect for the design of a building, then it is up to the architect to decide how to work. Some clients might however be aware of the existence of the IDP as an option or the architect can inform the client about the IDP. What is important for the client to know is that the same amount of work will be done, but not at the same time frame as in the traditional process. Another important point to add in convincing the client is the fact that by using the IDP as a model for the design process, the final result will probably end up being better: for example, the energy use of a building can become much lower compared to those designed through traditional processes, which is advantageous for the client in the long run.

3.3. Competitions

Many architectural offices participate nowadays in open or invited competitions besides their normal commissions. In Europe, EU directives have led to competitions being used as a means for clients to purchase architectural services [15]. However, the jury and / or client how focussed on the price rather than on the quality of the service [16]. The uncertainty of proceeding to the next competition round makes that architectural offices do not automatically work according to the IDP. That means that architects might not work together with engineers, even though crucial decisions on the architecture of the buildings (and thus indirectly energy performance) are made in the competition phase. Some offices build up an extensive technical knowledge in-house, which requires an investment and might not always be feasible. When participating in invited competitions, a compensation for the labour of the design team might be provided, something which is not in the case of open competitions.

Setting clear, measurable, energy performance goals for the buildings in the competition brief might put more focus on the consequences of architectural decisions, but it will not solve the lack of compensation for performing such simulations which are needed to be able to provide the energy performance of the building.

3.4 Education

In many architecture and engineering schools, to the best knowledge to the authors, the theory and practice of the Integrated Design Process is not included in the basic curriculum; possibly a review can be done in the near future to verify this.

While it is impossible to verify whether this is statement is accurate or not, its significance lays in a fact that in some cases the actors enter the process with strong preconceptions about the other professions; this surely cannot offer a good start to an open and fruitful collaboration, and can contribute to misunderstandings and the lack of communications between actors in the IDP.

Architecture students are often taught to design within the framework of design studios, but hardly ever with those actors which they will work together later throughout their carrier, such as engineers. At some universities, however, in recent years, projects are set up in which students from multiple disciplines work together in order to design low-energy buildings. An example is the Virginia Polytechnic Institute which decided to join the Solar Decathlon with architecture, industrial and interior design, and mechanical and electrical engineering students [17]; actually, in order to succeed, all Solar Decathlon participating teams end up being multi-disciplinary. Another example are applied, multi-disciplinary projects done at the Eindhoven University of Technology [18]. There, architecture and engineering students work together in a workshop environment, where they have to perform realistic assignments together. The educational program was supported by the Institute of Dutch Architects and Consulting engineers, who applied this setup later in their educational program for practitioners. At Ryerson University in Toronto, students in both Architecture and Building Science graduate programs have a requirement to do a so-called Collaborative Workshop, lasting at least 50 hours, where they have to find a project to work on with colleagues and professionals from other disciplines [19]. In the majority of cases, students choose to do a design competition. Although the IDP is not specifically required, very often students do self-organise in a process that greatly resembles IDP. However, as this is not academically formalised, it cannot be concluded that they are actually taught IDP.

Architecture students, as well as all other disciplines, like engineers, could profit from a good collaboration. This is a good reason to include theory about design processes in the curriculum. Reasons behind the lack of such courses on the design process and collaboration might be that such processes are hard to theorise, as well as that it might be hard to place such knowledge into one institution.

Another important aspect within the context of the education of the IDP is the new role of the architect. By gaining the role of leading the design team, the architect should not only longer have design competences, but also management competences. Managing design teams might not be included in the curriculum either.

Architectural associations however do provide extra courses on design processes and the role of architects. Two examples of such courses are given by the RIBA*:* Continuing professional development courses [20] and the AIA: Continuing education courses [21]. In this way, practising architect can gain more knowledge about the design process as well as management knowledge when this is required.

3.5 Communication

The IDP theory notices that communication between actors is crucial [12, 22], but how is this communication managed? Communication problems between architects and engineers, but also between engineers and engineers, might lead to inefficiency. When more actors get involved, an effective

communication gets more crucial. Within the guidelines of IEA-SHC Task 23, it is stated that "communication competence, openness and interdisciplinary team ability must be secured for all design team members" [2], although it is not described how this competence should be secured.



Fig. 3. The Sustainable Urban Initiative team's IDP design charrette for 2007 EQuilibrioum House competition organised by Canada Mortgage and Housing Corporation [6]

During the interviews, architects experienced that they learnt a lot from working with engineers, but that it sometimes also had led to difficulties [9]. Too many specialised actors needed to work together, resulting in many actors trying to guard their own speciality. Many architects took up the workshop as a good start for the design process and a good example of communication with many actors. In such "kick-off" workshop in the early design phase, the nature of the integrated design process will be explained and it will support the team spirit [2]. In some cases of the interviewed architects, the architects were in minority in such workshops, leading to the fact that architects need to be competent to deal with such situations.

So we had all the largest engineer companies in Denmark sitting at one table. When we started discussing energy and technical solutions, we had workshop with 30 to 40 engineers. I think you need to be a bit of an "archineer". In many ways you need to know some things about technical systems. You have to find the interest in listening to these things. Also, you have to come up with a solution within the architectural concept. (Architect #16)

The role of the client is also very important in the IDP. If the client chooses for this kind of design process, they need to be open for it as well as it requires another way of communication of all actors. Wishes of the client need to be expressed early, as well as the design team needs to give clear feedback to the client. It is especially important to visualise how certain design alternatives are chosen based on their effect on energy performance. Only in such a way, the energy performance becomes a clear decision factor.

4. Conclusions

It is very positive that the IDP has found its way to the architect's office, but there are some issues which need to be dealt with in order to exploit the process to the maximum of its potentials. These issues are actors vs. activities, costs, competitions, education, and communication.

Many models of the IDP are kept very generic in order to highlight the importance rather than serving as a custom-made guideline for every design process. For every building, the design teams needs to be custom-made according to specific demands of the building. A continuation of the design team for several projects is preferable, but in reality this might not be the case.

The early design phase is a very crucial phase for the success of the IDP. Since traditional roles and methods are not effective anymore when designing low-energy architecture, all actors need to be actively engaged from the beginning. This implies that the client needs to demand that the design process is done according to the model of the IDP, engineers need to be involved earlier in the beginning, and architects cannot make all decisions themselves anymore. Structuring the design process in this way, all decisions taken are done by agreement of all actors. A start-up workshop was seen by architects as an important event to agree on common goals and as a way to build up a solid design team. Getting actors engaged in the design process is an important condition for results in the design process, but at the same time a factor which might be hard to achieve.

By embedding theory of the design process as well as setting up interdisciplinary projects / courses, future architects can get acquainted with collaborating with other actors. However, current curricula at architecture schools do often not deal with the design process; neither does it include management courses.

The shift from the traditional design process to the Integrated Design Process has been started, but need to gain more strength. If the issues which are discussed in this article are taken up by the profession, other actors as well as the schools, are solved, then the IDP might start to become the standard design process.

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Article

Development of a Façade Assessment and Design Tool for Solar Energy (FASSADES)

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Abstract: Planning energy-efficient buildings which produce on-site renewable energy in an urban context is a challenge for all involved actors in the planning process. The primary objective of this study was to develop a façade assessment and design tool for solar energy (FASSADES) providing the necessary information for all stakeholders in the design process. The secondary objective was to demonstrate the tool by performing an assessment analysis of a building block. The FASSADES tool is a DIVA4Rhino script, combining Radiance/Daysim and EnergyPlus for simulating the annual production of solar thermal and photovoltaic systems on facades, the cost-effectiveness of the solar energy system, and the payback time. Different output methods are available; graphically within the 3D drawing environment and numerically within post-processing software. The tool was tested to analyse a building block within a city under Swedish conditions. Output of the developed tool showed that shading from nearby buildings greatly affects the feasibility of photovoltaic and solar thermal systems on facades.

Keywords: solar energy; solar thermal; photovoltaics; density; facade; assessment; feasibility; urban planning

1. Introduction

Planning future resilient cities is a challenging task for urban planners, architects and other involved stakeholders. Political directives, such as the EPBD in Europe [1], commands the design of buildings

with a reduced energy demand that can be (partly) met by an on-site generation of renewable energy [2]. Planning such nearly Zero Energy Buildings (nZEB) is especially challenging in the context of cities, where the access to sunlight is scarce due to shading by adjacent buildings, which limits solar gains for passive heating, daylight, and for producing energy by means of photovoltaics (PV) or solar thermal (ST). Even if buildings can greatly reduce their energy demand, it is difficult to produce all of the needed energy on-site by means of solar energy alone [3,4], especially due to the high demand for electricity in modern buildings.

Involved stakeholders need to obtain all necessary information to assess *if* and *how* the implementation of solar energy would be a feasible alternative for generating renewable energy. Providing decision-makers information in the design process by means of tools is a valid strategy to make informed design decisions. This task is addressed by IEA SHC Task 51, which will provide "support to urban planners, authorities and architects to achieve urban areas and eventually whole cities with architecturally integrated solar energy solutions (active and passive), highly contributing to cities with a large fraction of renewable energy supply" [5].

Several tools currently exist for the assessment of solar energy in the built environment. The existing assessment tools can be roughly divided into three categories: (1) tools for the urban scale; (2) for the building scale; and (3) for the system scale.

The most common tool for assessing solar energy at the urban scale is the solar map, which consists of a GIS system providing the annual solar irradiation on building surfaces (mostly roofs), often accompanied by the output of a possible solar thermal or photovoltaic system, and connected to a website [6]. A study performed by Kanters *et al*. [6] showed that there is a large distribution in quality of such solar maps: some of them only provide irradiation values, while others provide additional information concerning the production of a possible solar system; some tools divide roof areas into categories while other tools provide financial feasibility studies. One of the most advanced solar maps is the one from Cambridge, USA, described by Jakubiec and Reinhart [7]. This map provides data about the position and system size of PV systems on roofs, the produced amount of electricity, the installation size, and the financial payback time. In this case, the output of the PV system is, besides the efficiency and additional losses, also calculated by taking into account the air temperatures near urban rooftops. The spatial resolution of this solar map is 1.25×1.25 m^2 and the time resolution is hourly. In parallel to this, other authors [8] described a method of calculating the solar energy potential of roofs and facades in an urban landscape, with a spatial resolution of 1 m and a time resolution of 1 h. However, this method shows only the irradiation on facades and roofs, not the production of a possible solar energy system, although a threshold value is mentioned for PV systems.

A wider variety of tools exists to analyse solar energy at the building scale of which an extensive list of Building Performance (BPS) tools was set up within the framework of IEA SHC Task 41 [9–11]. Architects were asked—in surveys and interviews—which tools they used for solar design and to rate their satisfaction of the listed tools. The conclusion was that a further development of such tools was needed towards an integrated tool that is user-friendly and also could provide graphical results. In the USA, Crawley [12] compared 20 well-used BPS tools with each other, concluding that product developers use different ways to describe the capabilities of BPS tools. More recently, Ibara and Reinhart [13] compared six different well-used irradiation distribution methods, concluding that some of the analysed programs showed large relative errors compared to measured

data. Later, Jakubiec and Reinhart [14] developed the tool DIVA4RHINO which combines several of the most-used programs for daylight, thermal analysis, and solar analysis.

At the detailed system scale, many programs focus either on PV or ST and include many detailed parameters like system components—tanks, storage, inverters, batteries, *etc.* An example used for PV systems is PVSYST, used by e.g., Fartaria [15] to calculate mutual shading of direct normal and diffuse radiation and by Sharma [16] to simulate the output of a grid-connected system. For ST systems, an example of a detailed system simulation software is TRNSYS, used e.g., by Wills [17] to study solar heating with a single-house scale seasonal storage, by Terziotti [18] to study the seasonal solar thermal energy storage in a large urban residential building, and by Bernardo [19] to study the retrofitting of domestic hot water heaters for solar water heating systems.

The abovementioned tools consider many aspects of solar energy, but focus on a specific scale. In addition, the knowledge level needed to operate these tools is relatively high. Actors in the urban planning and building design process need extensive data to assess solar energy potential. Real estate developers are an example of important actors of the design process. In many countries, real estate developers will develop buildings within an urban plan and take a series of decisions really affecting the potential for solar harvesting on building facades and roofs. Real estate developers are mostly interested in investment costs and payback times of the solar energy technology.

The primary objective of this study was to develop a façade assessment and design tool for solar energy (FASSADES), providing the necessary information for all stakeholders involved in the design process. The secondary objective was to validate the tool by performing an analysis of a building block.

2. Method

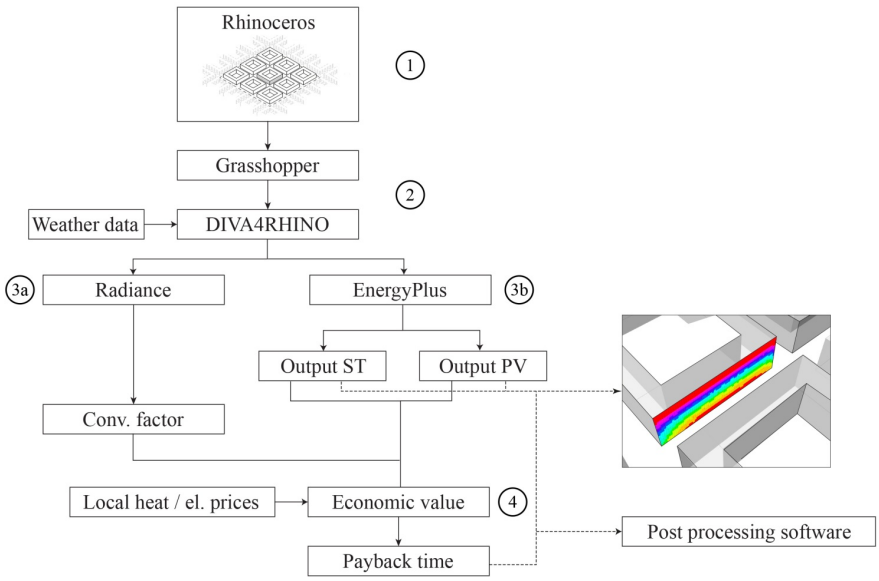
The working method started with the development of a workflow to enable assessment analyses of the solar energy access. The FASSADES tool enables users to fully assess the solar potential of facades. This full assessment can only be done by the simulation of the solar irradiation on the whole façade (taking shading due to surroundings into account), the calculation of the (hourly) output of a possible ST or PV system, the economic value of this production, and the payback time of the solar energy system. The workflow of the tool is shown in Figure 1.

The workflow as displayed in Figure 1 is explained step-by-step in the next sections.

2.1. Steps 1 and 2

All elements affecting the solar access of facades need to be included in the 3D model which is imported in the simulations. In the FASSADES tool, users either construct their model in the CAD program Rhinoceros [20], import files from other CAD applications or users write a script in Grasshopper. Once the 3D model of the building is constructed in Rhino, it is loaded into the plugin Grasshopper; a visual programming language connected to Rhinoceros [21]. In Grasshopper, the facade to analyse is divided into surfaces of 1 m × 1 m.

Figure 1. Workflow of the FASSADES tool.



2.2. Step 3

In Step 3, simulations are performed with DIVA4Rhino—a daylighting and energy modelling plug—for Rhinoceros [14]. DIVA4Rhino runs in this case two validated simulation programs to predict solar energy access: Radiance/Daysim and EnergyPlus [22]. It is beneficial to run these two programs parallel to each other; Radiance calculates the annual solar irradiation on the façade relatively quickly, but is not (yet) able to output hourly values of diffuse and direct irradiation. EnergyPlus is able to provide the hourly direct and diffuse irradiation on a surface, but is not able to run many analyses in an acceptable period of time.

2.2.1. Step 3a

In Step 3a, an annual Radiance/Daysim simulation of the façade is performed. The Radiance/Daysim component in DIVA4Rhino uses the cumulative sky model developed by Robinson and Stone [23].

For the analysis of the building block discussed later in this study, the settings of the Radiance/Daysim simulations are displayed in Table 1. A ground plane and the surrounding buildings need to be included in the scene.

Table 1. DIVA4Rhino settings for Radiance/Daysim and EnergyPlus simulations.

Weather data		**Copenhagen EPW**
Reflectances	Ground	20%
	Buildings	35%
Energy + simulations:	Time steps per hour:	6
	Time period	Annual
	Reflections	Full exterior with reflections
	Output	Zone Beam Solar from Exterior Windows Energy and Zone Diffuse Solar from Exterior Windows Energy
Radiance simulations:	Nodes offset	10 mm
	Ambient bounces	10
	Ambient divisions	1000
	Ambient super-samples	20
	Ambient resolution	300
	Ambient accuracy	0.1

The Radiance/Daysim simulation is used to generate the dimensionless weighting factor σ. In this study, a weighting factor is the ratio of the annual solar irradiation on a surface with respect to the average solar irradiation on the facade (see Equation (1)). These weighting factors are then used to adjust the results of the EnergyPlus simulation, which is Step 3b.

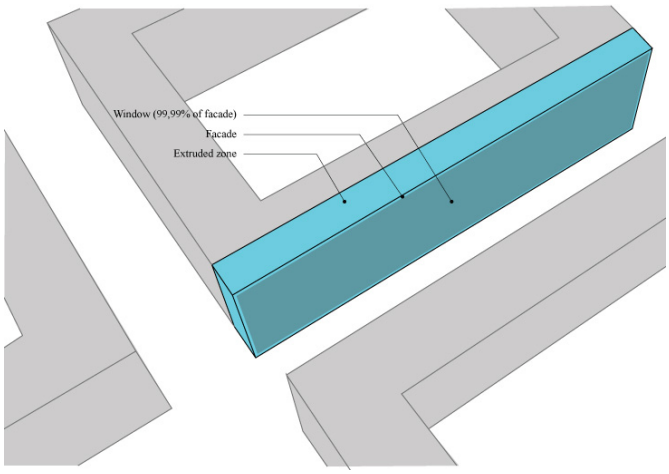
$$\sigma = \frac{H_{\mathrm{n}}/A_{\mathrm{n}}}{H_{\mathrm{f}}/A_{\mathrm{f}}} \quad (1)$$

where, σ, weighting factor (−); H_{n}, annual solar irradiation on surface *n* (kWh); A_{n}, area of surface *n* (m^2); H_{f}, annual solar irradiation on whole façade (kWh); A_{f}, area of whole façade(m^2).

2.2.2. Step 3b

It was expected that the best comparison between the two technologies (PV or ST) was by comparing the hourly output. In order to calculate the hourly output of the solar energy systems, it was necessary to simulate the diffuse and direct irradiation on the façade. Most parts of the façade are shaded by surrounding buildings which makes it complicated to compute the direct and diffuse solar irradiation manually. Therefore, an EnergyPlus simulation was run to simulate the hourly diffuse and direct solar irradiation on the façade, a tool which is used in earlier studies [24–26]. For EnergyPlus to run, the analysed façade is extruded 1 m backwards, constructing a zone (Figure 2). A window is inserted in the analysed façade, with a size of 99.99% of the façade. This window was given the material *window low-iron 2.5 mm* (with a solar transmittance at normal incidence of 0.904). The values for the direct and diffuse solar gain through the windows were then later corrected with a factor of 1/0.904. This will cause a small source of error since the solar angle is normally not at normal incidence. However, the construction of a fictitious zone in EnergyPlus was necessary to include the full effect of shading due to surrounding buildings.

Figure 2. Construction of EnergyPlus simulation.



2.2.3. Step 3c

The output of a solar thermal system is dependent on the connected system. To avoid the simulation of complex system components connected to the solar panels, the hourly output of the ST system is calculated with Equation (2), which is based on previous literature [27], and provides the possibility to calculate the output of a system for absorber temperatures of 25 °C, 50 °C, 75 °C, and 90 °C.

$$Q_{ST} = F'(\tau\alpha)_n(K_b(\theta)I_b + K_dI_d) - F'U_1(T_m - T_a) - F'U_2(T_m - T_a)^2 \quad (2)$$

$$K_b(\theta) = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right) \text{ for } \theta \leq 60°$$

$$K_b(\theta) = (1 - b_0)\cdot\left(\frac{90° - \theta}{30°}\right) \text{ for } 60° \leq \theta \leq 90°$$

where, Q_{ST}, useful output power of the ST system (W/m^2); $K_b(\theta)$, incident angle modifier (–); $F'(\tau\alpha)_n$, zero loss efficiency for beam radiation at a normal incidence angle (–); I_b, beam irradiance (W/m^2); K_d, diffuse angle modifier (–); I_d, diffuse solar irradiance (W/m^2); U, Heat loss coefficient [W/(m^{2}K)]; T_m, Average temperature in absorber (°C); T_a, surrounding air temperature (°C).

The following input parameters are required for solving Equation (2):

- Direct irradiation (W/m^2);
- Diffuse irradiation (W/m^2);
- Incidence angle (°);
- Ambient temperature (°C);
- Features of a solar panel. The following parameters were obtained by comparing several ST product specifications [28]:
- $F'(\tau\alpha)_n$: 0.851 (–);
- K_d: 0.9 (–);

- $F'U_1$: 4.036 (W/m^{2}K);
- $F'U_2$: 0.0108 (W/m^{2}K^2);
- B_0: 0.09 (–).

The EnergyPlus simulation performed in Step 3b provides the direct and diffuse irradiation per hour. The incidence angle is the difference between the normal of the analysed surface and the solar angle. The normal of the surface is extracted from Grasshopper and the solar angle is calculated using the solar vector component in DIVA4Rhino. The hourly ambient temperature is extracted from the weather data. In the FASSADES tool, Grasshopper is connected to Excel to export the hourly results and perform the calculation of Equation (2). For PV systems, the output E_{PV} is calculated with Equation (3).

$$E_{PV} = (I_b + I_d)\cdot\eta_{rel}\cdot\eta_{sys} \quad (3)$$

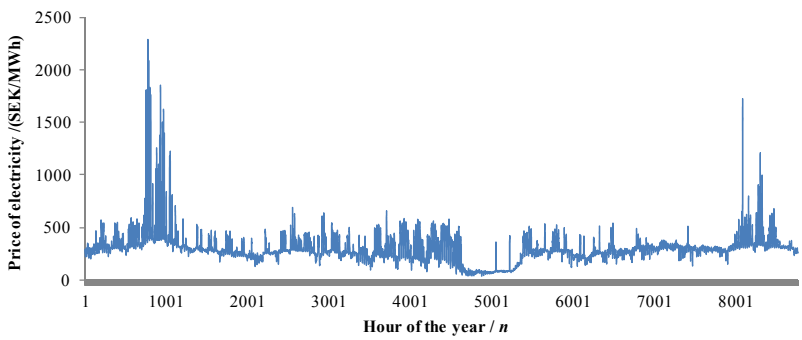
where, E_{PV}, output of the PV system (W); η_{rel}, relative module efficiency (–); η_{sys}, system efficiency (–).

This equation is not taking the temperature dependency of PV systems into account. In the analysis of the building block, an efficiency of 15% and 10% additional losses are taken into account in order to calculate the output of the PV system.

2.2.4. Step 4

In Step 4, a financial value is attributed to the output of a unit surface area, as calculated in Step 3. In Sweden, heat and electricity prices vary greatly over the year. Since Sweden does not have a feed-in Tariff legislation, the value of the produced electricity is calculated in this study as being the saved electricity. The hourly electricity market price is taken from NordPoolSpot, the market organisation in the Nordic countries [29]. In the validation study presented here, the hourly electricity price was from 2012 and from region SE4 (the South of Sweden). The variation of electricity prices over the year is presented in Figure 3.

Figure 3. Hourly market electricity price from NordPoolSpot (in 2012, region SE4) [29]. Reproduced with permission from [29]. Copyright 2013 NordPoolSpot.



In Sweden, it is possible to apply for a subsidy when installing a PV system, with a maximum subsidy of 1.2 million Swedish Crowns (SEK) [30].

Putting value on the output of heat from ST systems is more difficult than for the production of PV systems. Urban district heating networks is the most common heat supply method in the larger Swedish cities. Heat from the ST system with a system temperature of 25 °C and 50 °C directly replaces bought heat from the urban heating district network (representing 100% of the heat price), while heat produced from systems with higher temperatures (75 °C and 90 °C) feed into the urban heating district system, for 90% of the heat price. Table 2 provides an overview of the costs of heat from the urban district heating companies in the largest cities in Sweden. Note that in most cases, the value presented in Table 2 is only one part of the total heat price since consumers also pay for how much heating power they need, although this is not considered in this study.

Table 2. Price of heat from urban district heating networks in Sweden (SEK/MWh).

Provider	Fortum [a]	Mälar Energi [b]	Vattenfall [c]	Göteborgs Energi [d]	Öresunds-kraft [e]	EON [f]	Average
Jan	714	440	748	503	866	559	638
Feb	714	440	748	503	866	559	638
Mar	714	388	748	503	866	559	630
Apr	469	388	748	346	485	161	433
May	285	292	309	99	485	161	272
Jun	285	292,00	309	99	123	161	211
Jul	285	292,00	309	99	123	161	211
Aug	285	292,00	309	99	123	161	211
Sep	285	292,00	309	99	123	161	211
Oct	469	292,00	748	346	123	370	391
Nov	469	388,00	748	346	485	370	468
Dec	714	440,00	748	503	866	559	638

Notes: [a] Trygg (subscription form); [b] in Västerås, 2014; [c] in Uppsala, for houses 2014; [d] 2012; [e] in Helsingborg, 2014; [f] for companies, 2013.

2.3. Step 5

The output of the FASSADES tool can be both visual and numerical. For visualisation, two different approaches can be chosen: the mask and a colour range.

The first visual output option is a mask, which can display the surfaces with a production above a certain threshold value for one of the technologies (ST 25 °C, ST 50 °C, ST 75 °C, ST 90 °C or PV) This threshold value can be chosen per technology. Applying a mask has been used in previous research [31,32], but this was always based on irradiation, not on production.

The second option is to show a colour range over the façade, representing the annual production of this surface, per technology (ST 25 °C, ST 50 °C, ST 75 °C, ST 90 °C or PV).

From the FASSADES tool, it is also possible to numerically process the results. If users are interested in the energy production of a specific surface, they can export the hourly production of that surface. This production Ψ is calculated by Equation (4).

$$\Psi_{PV} = \sigma \cdot E_{PV} \quad (4)$$

$$\Psi_{ST} = \sigma \cdot Q$$

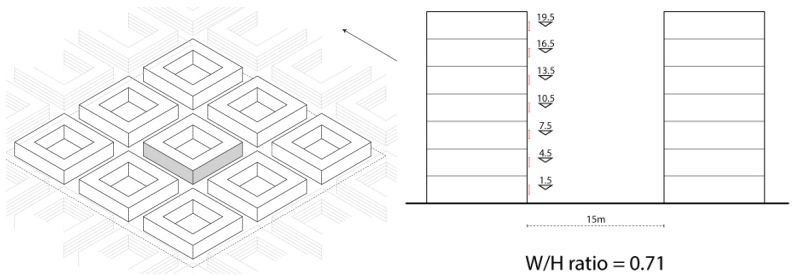
where, Ψ_{PV}, PV output of a surface (W); Ψ_{ST}, ST output of a surface (W); σ, weighting factor (−); E_{PV}, output of the PV system (W); Q_{ST}, output of the ST system (W).

3. Results

The FASSADES tool was used to validate the methodology. The tool was used to assess the energy production and the financial return of ST systems integrated in façades of a typical building block representing a typical urban planning situation in Sweden.

Besides analysing the whole façade, the centre (middle) between two floors (heights of these centres are displayed in Figure 4 were analysed to obtain more detail concerning the shading patterns by surrounding buildings and their effect on the potential for solar energy over the height of the façade. Weather data from Copenhagen was used since it is the closest IWEC data available for the south of Sweden.

Figure 4. The analysed façades and section of the analysed urban canyon.



3.1. Annual and Hourly Production of the Whole Façade

The façades were analysed one-by-one in the FASSADES tool, with a running time of around 3 min per façade. The annual production of the different technologies per façade was visualised, of which some examples are shown in Figure 5.

The production of ST and PV as a function of height on façade is displayed in Figure 6.

The following aspects can be noticed in Figure 6:

- The production of 90 °C heat is very limited and is even 0 kWh on the North façade, due to the relative low irradiation in Sweden;
- The difference between the solar thermal production at 25 °C and ST with the other system temperatures and PV is significant. For example, at z = 19.5 m, the ST production at 25 °C is 314 kWh/m^{2}a, the production of ST at 50 °C is 45% of this value, at 75 °C, it is 21% of this value, at ST 90 °C, 13%, and for PV, the production corresponds to only 29% of the ST 25 °C production. Note also that the ST production (25 °C) on East and West facades is higher than the PV production on the South façade;
- Shading due to surrounding buildings has a significant impact on the solar energy production. The production of almost all technologies decreases by 50%–70% for lower positions

(e.g., 1.5 m) compared to the higher ones (e.g., 19.5 m). This shading effect was also observed in an earlier study [3].

Figure 5. Annual production of ST 25 °C, ST 50 °C and PV at the East façade.

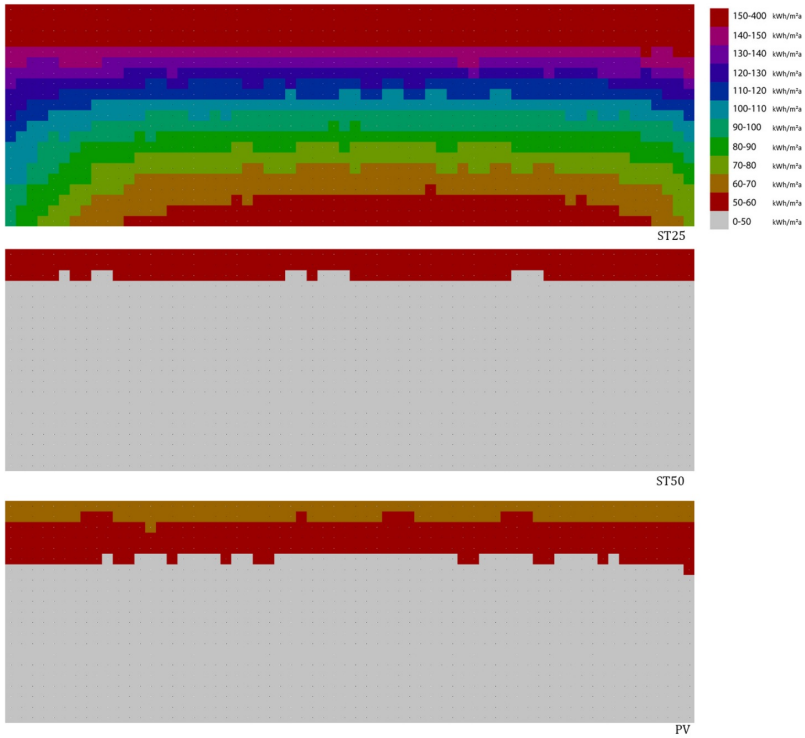
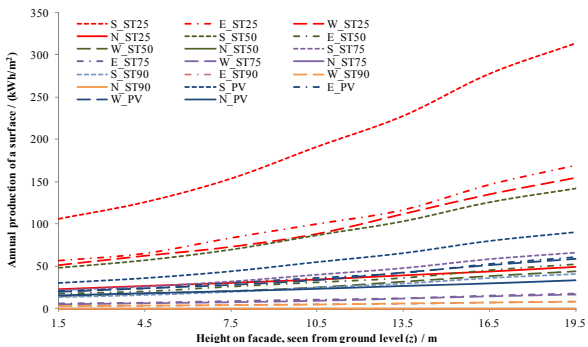
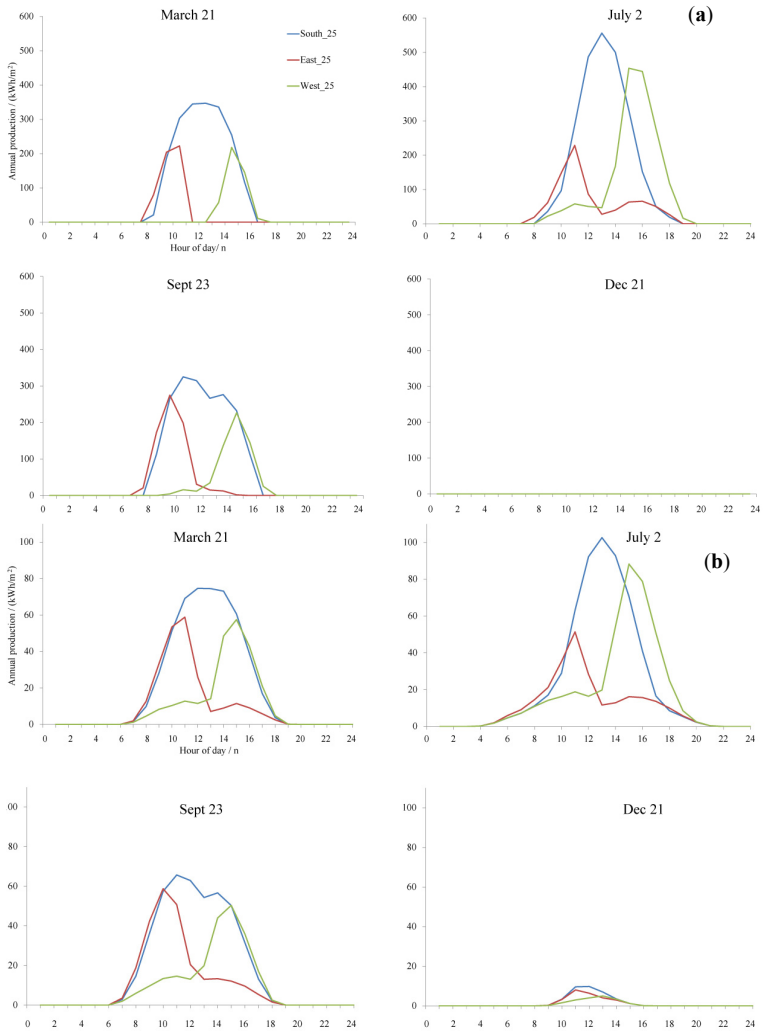


Figure 6. The annual energy production as a function of height from ground.



Since the FASSADES tool is able to export values per surface on an hourly basis, users can also study specific days of the year. As an example, an analysis was performed on four different days of the year in each season: 21 March, 2 July, 23 September, and 21 December. The highest sensor point (z = 19.5 m) was taken to compare the South, East, and West façades. The results are shown in Figure 7a (ST 25 °C) and Figure 7b (PV).

Figure 7. (**a**) Solar Thermal production (25 °C) during the four selected days; (**b**) PV production during the four selected days.



Analysing Figure 7a,b, the following aspects can be noted:

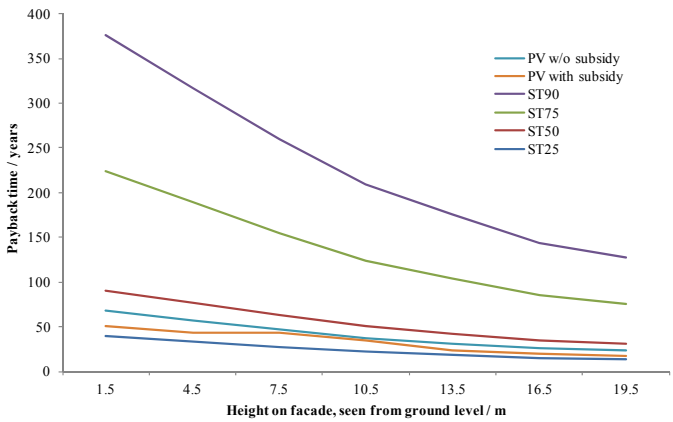
- In the morning, production from the East façade is slightly higher than from the South façade (until 09.00), although differences are very small. In the afternoon, the production from the West façade is higher than the production from the two other facades, especially on 2 July, when the production is notably higher. During the majority of the day, the production from the South façade is higher than from the East and West façades;
- On 21 December, there is no production of solar heat (25 °C) and hardly any production of PV.

Also, the heat production is about 500% higher than the electricity production on the selected days. It is however hard to compare these two different energy sources.

3.2. Assessment of the Whole Façade

The FASSADES tool calculates the production of ST/PV and the economic value of the produced energy; both for heat and electricity, based on current heat and electricity prices. Real estate owners, as well as other people in the position to install solar energy systems in buildings, need to assess the economic benefits of installing solar energy technologies. The payback time is one important metric to calculate the feasibility of investment decisions. Another metric could be the profit after 25 years of use. In this study, a price for Solar Thermal system of 1500 SEK/m^2 was used, and 1666 SEK/m^2 for PV systems. Figure 8 shows the payback time as a function of the height from the ground on the South facade, based on the production as shown in Figure 6 and the economic value of this produced energy.

Figure 8. Payback time as a function of height.



Instead of showing the height from ground level, the production from the South façade *versus* the payback time is shown in Figure 9.

Considering that 25 years is a reasonable payback time, Figure 9 shows the following aspects:

- Installing a ST system providing a system temperature 50 °C, 75 °C, and 90 °C is not financially interesting, since it is unlikely to produce sufficiently on facades;
- Installing a ST system delivering 25 °C heat is economically interesting, especially at higher levels on the façade;
- Installing PV on the façade can be economically interesting, especially with subsidy and on the higher levels of the façade. The differences between subsidised and non-subsidised PV cells are relatively small in the graph, probably because the subsidy is proportional to the investment (Figure 9).

Figure 9 shows that eventually all technologies become economically interesting if the production (and thus irradiation) is high enough; a situation which is hard to reach in dense cities and on facades. Table 3 shows the different production values needed to achieve a certain payback time (5–25 years).

Figure 9. Payback time *vs.* production.

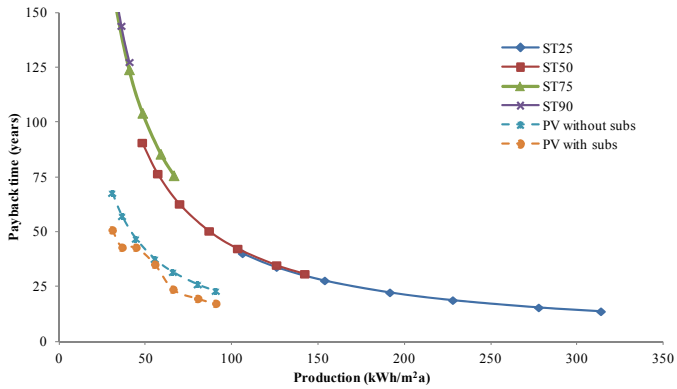


Table 3. Minimum production (kWh/m^{2}a) per technology (for *x* years of payback time).

Years	25	20	15	10	5
ST25	170	213	284	425	851
ST50	175	218	291	437	873
ST75	201	252	335	503	1006
ST90	208	260	347	520	1040
PV w/o	83	104	139	208	416
PV with	76	95	126	189	378

Obviously, production values increase when the surface is unobstructed, on a roof and/or optimally inclined, resulting also in shorter payback times, since higher irradiation values result in a shorter payback time.

The tool also showed that there is a necessity to simulate the output on an hourly basis, since generalising the output by performing only annual analyses—*i.e.*, having one amount of production per year—is not providing the level of detail needed to assess the true value of production, since heat and

electricity prices vary greatly over the year (in Sweden). This is especially true for the value of heat; the average annual price of heat is 0.41 SEK/kWh (average of the far right column of Table 2). In reality, the results of the simulation of the building block in this study show that the effective revenue of heat per façade varies per façade (Table 4).

Table 4. Effective revenue (SEK/kWh).

Orientation of façade/system temperature	ST 25 °C	ST 50 °C	ST 75 °C	ST 90 °C	PV (SE4)
South (averaged)	0.35	0.34	0.30	0.29	0.80
East (averaged)	0.32	0.32	0.27	0.26	0.80
West (averaged)	0.31	0.31	0.27	0.27	0.79
North (averaged)	0.28	N/A	N/A	N/A	0.80

If, on average, every produced kWh would save energy, then the values should equal the average price of heat. Table 4 shows that this is not the case, due to the differences in production over the day and year and the corresponding prices at the moment of production. Finding a way to store heat would benefit the economics of ST systems.

4. Conclusions

An assessment and design tool for solar energy on façades was developed by combining Radiance/Daysim and EnergyPlus with DIVA4RHINO. The Radiance/Daysim module performs an annual solar irradiation analysis on unit surface area, while the EnergyPlus program performs an annual solar analysis with an hourly output. Combining the output of the two programs provides the hourly irradiation on the unit surface area.

The next step is the calculation of the production of a unit surface area as a solar panel (ST) or solar cell (PV). The output of the ST is calculated for system temperatures of 25 °C, 50 °C, 75 °C, and 90 °C. Then, the economic value of the produced energy is predicted by taking into account the current local heat and electricity prices. The payback time is then calculated based on the investment costs and the annual revenues.

The tool was validated by applying it to an analysis of a typical Swedish building block. The results showed, amongst others, that PV and ST (25 °C) for unshaded façade surfaces are the only technologies providing a payback period shorter than 25 years. Shading due to surrounding buildings significantly affects both the irradiation and production, leading to long payback times.

The results also highlighted that a detailed simulation on an hourly basis is needed to fully assess solar energy potential production and cost benefits.

The FASSADES tool can be improved further: at the moment, only one part of the building envelope at a time can be analysed. Another improvement would be to make the tool easier by using user-defined objects, limiting the knowledge level needed to use the tool.

Calculations performed in the FASSADES tool depend on many parameters, which could cause errors: many assumptions are being made, especially regarding the financial costs and benefits.

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Author Contributions

The co-authors contributed actively to the discussion of this research and in reviewing the article.

Conflicts of Interest

The authors declare no conflict of interest.

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The impact of urban design decisions on net zero energy solar buildings in Sweden

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Planning for future energy-efficient and energy-producing buildings requires specific knowledge during the design process. Many design decisions taken by urban planners –form, density, roof type and orientation – have a significant effect on the conditions of such buildings, although urban planners might not always be aware of the effect of their design. This study examines the effects of important design decisions on the solar energy potential of net zero energy solar buildings. Typical Swedish building blocks with varying form, density, roof type and orientation were used to simulate the annual solar irradiation and energy production, and to calculate the load match for heating and electricity under Swedish conditions. Results of this study show that the urban density is the most influential parameter on the solar potential of building blocks. Furthermore, flat roofs often returned the highest load match value, while the effect of orientation on the solar potential turned out not to be that straightforward. With the results of this study, urban planners can make better informed decisions, while it also provides a ground for the net zero energy solar buildings discussion by exposing the boundaries of such buildings in the urban environment.

Keywords: solar energy; urban planning; architecture; net zero energy buildings

1. Introduction

Future buildings need to comply with strict rules concerning their supply and demand energy balance; not only do they need to reduce their energy demand, they should also produce a considerable part of their own energy locally with renewables. In Europe, this is secured in the European Directive for the energy performance of buildings (European Parliament, 2010), requiring member states to build 'nearly' zero energy buildings.

These nearly zero energy buildings can be seen as a derivative of the net zero energy buildings (NZEB), which is a grid-connected, 'energy efficient building able to generate electricity or other energy carriers from renewable energy sources in order to compensate for its energy demand' on an annual basis (Sartori, Napolitano, & Voss, 2012). For both the nearly zero energy building and the NZEB, the production of on-site renewable energy is mentioned; which in most cases results in the installation of active solar energy technologies. Currently, there is a lack of knowledge of how much solar energy can contribute to the production of on-site renewable energy to cover the energy demand of buildings in cities. Also, there is a lack of knowledge how urban planning decisions may affect the solar potential of future buildings.

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1.1. Towards NZEBs in Sweden

As an EU member state, Sweden will have to follow the EU directive on nearly Zero Energy Buildings, even though a clear definition of the nearly Zero Energy is currently lacking. The concept of the similar NZEB has gained much attention lately, for instance in the IEA SHC Task 40 / EBC Annex 52 and in literature (Aelenei & Gonçalves, 2014; Berggren, Wall, Flodberg, & Sandberg, 2012; Hall, Geissler, & Burger, 2014; Marszal et al., 2011; Sartori et al., 2010). How the different concepts relate to each other in the Swedish context is illustrated in Figure 1.

The least ambitious energy goal for a building in Sweden is by complying with the current Swedish Building regulations BBR (Boverket, 2013a). The Swedish National Board of Housing, Building and Planning, which issues the building regulations, considers the current energy demands (90 kWh/m^{2}a for heating and common electricity in the South of Sweden) as nearly zero (Boverket, 2013b). Interestingly, only the energy demand side is included in the current building regulations, not the production side.

One rank higher is the passive house, defined by the Swedish Passive House Standard, setting stricter requirements for the energy demand of building, although not on on-site renewable production. The next step is the NZEB, which uses as much energy as it produces. The highest ambition energy goal is the plus energy building, which produces more energy as it needs over a year.

In this study, a nearly zero energy building is considered to be a NZEB, but without the requirement to balance the *entire* energy demand. Only the energy demand of heating, DHW and common electricity is taken into account (excluding plug load).

Only limited literature is available on how to actually build NZEBs in Sweden (Berggren et al., 2012; Flodberg, 2012) and these studies focused on office buildings. Other literature shows often the achievement of a net zero energy balance in single-family houses and offices (Cellura, Guarino, Longo, & Mistretta, 2014; Gallo, Molina, Prodanovic, Aguilar, & Romero, 2014; Mohamed, Hasan, & Sirén, 2014; Pikas, Thalfeldt, & Kurnitski, 2014). Only some studies focus on buildings in denser environments like city centres (Hachem, Athienitis, & Fazio, 2014; Hachem, Fazio, & Athienitis, 2013), where access to solar energy might be limited due to shading of other buildings.

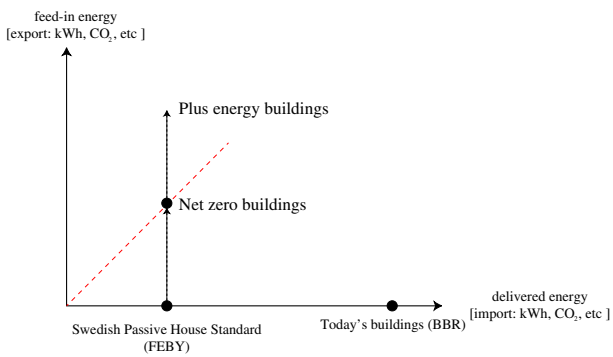


Figure 1. Visualisation of different energy concepts (adapted from Igor Sartori et al. (2012)).

1.2. The influence of urban planning on solar energy access

Since the majority of our future buildings will be built in cities, it becomes very important that proper conditions for these buildings are assured during the urban planning process; especially for solar access since this has effect on both the energy use and a possible energy production. IEA SHC Task 51 called Solar Energy in Urban Planning has commenced last year with the objective to provide support for urban planners to increase the implementation of solar energy in cities. Sweden is a member of this task; hence collaboration was set up between the urban planning departments of the cities of Lund and Malmö (South Sweden) and the Swedish participants of Task 51. Short workshops and meetings were held with local urban planners, where it became clear that urban planners are willing to implement solar energy, but it is unclear for them how to reach this goal. This is partly caused by the fact that the urban design phase is both dependant on the decisions taken on a national level and decisions taken in a later phase (building design and implementation phase); a process illustrated in Figure 2.

The Swedish zoning plan determines the density of cities, the shape of buildings, the height, inclination of roofs, roof types, function, etc. Conditions for solar energy – both passive and active – are therefore indirectly set by the design of such a plan, which could lead to further constraints in the design phase if buildings e.g. get too much shaded (Kanters, Dubois, & Wall, 2012). Besides, the fact is that urban planners – often unconsciously – design the conditions for solar energy, municipality and city administrations, and hardly have any legal instruments to require the implementation of solar energy. For example, Swedish city administrations are not allowed to prescribe a certain technology to use as renewable energy source, like solar or wind energy, but they are limited to set neutral energy type recommendations. Only if the municipality or city owns the land where future urban districts or buildings are planned, they are allowed to set additional energy requirements. Furthermore, some voluntary initiatives like the 'climate contract' in Hyllie, Malmö were born to stimulate all involved actors to work towards an increasing share of locally produced renewable energy.

To help energy planners to set realistic energy goals for future buildings and for urban planners to understand their impact on solar energy conditions, the objectives of this study are partly to examine the limitations of solar powered NZEBs and partly to look into the effect of early urban planning design decisions – mainly density, orientation, roof type and form.

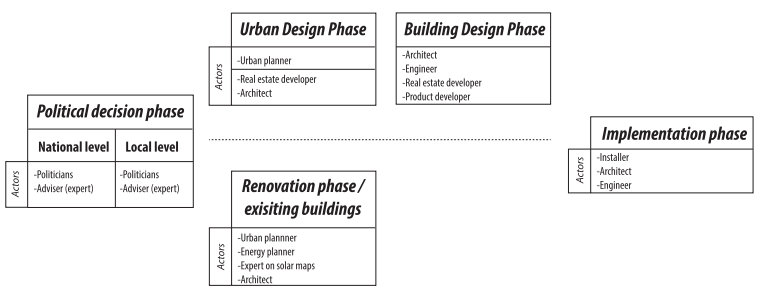


Figure 2. An overview of the different phases in the urban planning process and involved actors.

2. Method

In order to analyse the effect of design decisions, simulations were performed with the program DIVA4RHINO (Jakubiec & Reinhart, 2011); a program which is able to simulate the solar irradiation within a CAD environment. The simulations were run with climate data from Lund (Sweden) generated from the Meteonorm program (METEOTEST, 2009). DIVA4RHINO uses Radiance to simulate the solar irradiation. Table 1 shows the Radiance settings used in the simulations. Results from the simulations were exported and post-processed.

2.1. Geometry set-up and parameters

Four different design parameters were explored in this study: the design of the urban building blocks, the orientation, roof type and density.

In collaboration with the urban planning departments, four typical *building block designs* were identified. They can be seen in Figure 3 with their respective names: Strip 50 × 50 m, Closed 80 × 0 m, Closed 50 × 50 m and U-form 50 × 50 m. The metres are referring to the width and length of the plot. All building blocks had a depth of 12 metres.

The studied roof types are shown in Figure 3 and are called flat, gabled and lean-to. In the zoning plan, urban planners can set the roof type or they can specify the boundaries of the roof of buildings. These three roof types are rather common in the zoning plans developed in the early phase and were therefore included in this study.

The parameter *density* is an important parameter in urban planning. The Floor Space Index is often used to express the density of an urban district, but can however be defined in different ways. In Swedish urban planning, a metrics called 'building block index' is used, which is the total floor area of the building divided by the plot area + ½ of the surrounding street area. In this study, this metric is called Floor Space Index (FSI_{bbi}). In all simulations, the streets are considered to be 15 metres wide. The density is varied by adding and/or removing floors in order to reach a 'target FSI_{bbi}' of .5, 1, 1.5, 2 and 2.5 (a rather common range for Swedish cities).

The fourth parameter is the *orientation* seen from South, which varied from 0°, 15°, 30°, 45°, 60° and 75° towards East (see Figure 3).

2.2. Load matching

Most studies focus mainly on the production side of solar energy in cities. Energy policy-makers and real estate owners are however interested in which contribution renewable energy can deliver in relation to the consumed energy, called load matching. The term Solar Fraction is used when the energy is produced with active solar systems. The first step needed for determining the load match is the calculation of the heat and electricity need. The current Swedish building regulations (BBR) were taken as the first set of requirements for the energy demand. The second alternative was the FEBY voluntary criteria for low-energy buildings from the Swedish Centre for Zero Energy Buildings. Both the BBR and FEBY provide the required energy demand, but do not specify the

Table 1. Settings of radiance.

Nodes offset	10 mm	Ambient super samples	20
Ambient bounces	3	Ambient resolution	500
Ambient divisions	2048	Ambient accuracy	.1

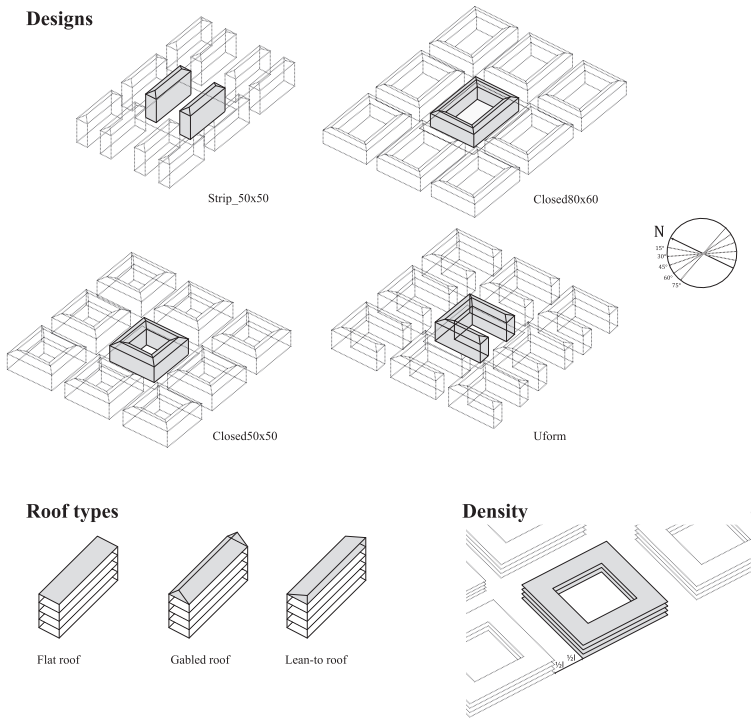


Figure 3. The used geometries and parameters.

division between heating and electricity. This is done to provide flexibility when designing the energy system in the building. In this study, the following electricity and heating demands were used (Table 2).

For every simulation option, the floor area was calculated, resulting in the total electricity and heating demand according to BBR and FEBY.

The second step was simulations with DIVA4RHINO of annual irradiation on the building envelope, which was divided in a 1×1 m grid (both façades and roof). The simulations resulted in a list of surfaces with their respective area and irradiation level. The surfaces were then divided into four categories: unsuitable, reasonable, good and very good. Surfaces were designated into one of these categories based on their collected amount of annual irradiation; these amounts are displayed in Table 3.

Table 2. Electricity and heating demand according to the two standards BBR and FEBY (values in kWh/m^{2}a).

	FEBY	BBR
Electricity	10	10
Heat (space + DHW)	35	80

Table 3. Threshold values for different categories (values in kWh/m^{2}a).

	Unsuitable	Suitable		
		Reasonable	Good	Very good
Façades	0–650	651–900	900–1020	>1020
Roof	0–800	800–900	900–1020	>1020

These threshold values were based partly on categories used in a local solar map (Kraftringen, Lunds kommun, Lunds Tekniska Högskola, & Solar Region Skåne, 2012), but are also based on previous studies by the authors (Kanters & Horvat, 2012; Kanters, Wall, & Dubois, 2014; Kanters, Wall, & Kjellsson, 2014). In this study, the PV panels and ST collectors were assumed to be parallel to the actual roof/façade. For every simulation option, the surface area (in m^2) and the total amount of irradiation (kWh) was summarised per category. Then, the produced energy was calculated from the total irradiation. For ST, an efficiency of 40% was taken, for PV an efficiency of 15% was taken. A 25% reduction of surface areas was applied to all suitable areas due to fenestration on the façade and installations on the roof. The division between PV and ST area was considered to be 50–50%. The final load matching was then calculated by dividing the annual production of solar energy systems with the annual energy demand. It should be noted that a load matching of 100% could be reached. This might not always be considered as realistic: if owners of a solar energy system do not have the possibility to store the energy or deliver it to the grid, then the produced energy is wasted. In Sweden, only some electricity providers accept solar electricity in their grid and reward producers financially for that. There are hardly any district heating companies willing to accept solar heat in their grid. The load matches in this study therefore provide more of a theoretical boundary than a very realistic scenario today.

3. Results and discussion

This section will first present a discussion about a new metric for solar potential and then discuss the results of the simulations.

3.1. *SAFAR$_n$: a new metric for the solar potential*

There are ambivalent definitions for the 'solar potential' of buildings in literature. Compagnon defined it as 'the percentage of building envelope which receives an amount of solar radiation greater than or equal to the preset thresholds' (Compagnon, 2004), while others define it as the potential energy which can be produced (Araya-Muñoz, Carvajal, Sáez-Carreño, Bensaid, & Soto-Márquez, 2014; Kodysh, Omitaomu, Bhaduri, & Neish, 2013; Lukač, Žlaus, Seme, Žalik, & Štumberger, 2013; O'Brien, 2010). These two definitions differ a lot; the first one defines more the performance of the design of a building, not so much *how much energy* is produced and is in that sense a more qualitative metric.

This metric can therefore be seen as a first 'quick' metrics for expressing the solar potential of a building. Nault, Rey, and Andersen (2013) used Compagnon's metric to evaluate the urban solar potential of six urban projects and noted some drawbacks of it: (1) the binary nature of the metric (a certain threshold is met or not), (2) lack of relation between potential production and expected needs and (3) the set thresholds are

technology-dependent. Not only are the thresholds for active solar energy technology-dependent, it should also be noted that they are dependent on the location. Since annual irradiation differs per location, thresholds should differ too. Local thresholds are important but have proven hard to set; something which is shown in an analysis of the threshold values used in solar maps, which often were based on 'experience in the field' rather than, for instance, on payback time (Kanters, Wall, & Kjellsson, 2014).

The balance between possible production and expected needs is an important link to the discussion of NZEBs. Compagnon's metric is related to the façade area, not the floor area; which normally determines the energy need. Therefore, an alternative metric is introduced in this article called $SAFAR_n$ (Suitable Area to Floor Area Ratio), with the n to be the threshold value in kWh/m^{2}a (Equation (1)).

$$SAFAR_n = \frac{A_s}{A_{fl}} \tag{1}$$

where $SAFAR_n$ = Suitable Area to Floor Area Ratio; A_s: Suitable Area (Area receiving an amount of solar radiation greater than or equal to the preset threshold n) (m^2); and A_{fl}: Floor Area of the considered building (m^2).

The $SAFAR_n$ can be more than 100% (for example, in the case of a villa where the roof area and suitable parts of the façades together are bigger than the floor area).

If we compare the metrics of Compagnon (active solar potential) and $SAFAR_n$ in the case of one design with four different roof types (averaged for all orientations), significant differences can be seen (Figure 4).

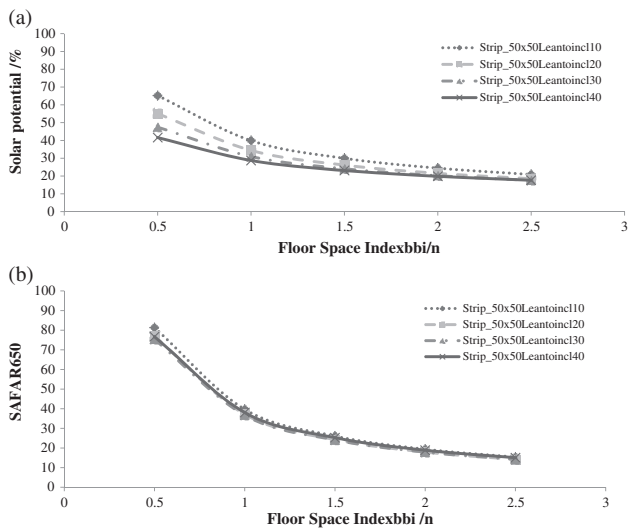


Figure 4. Solar potential as the percentage of building envelope which receives an amount of solar radiation greater than or equal 650 kWh/m^{2}a (after Compagnon (2004)). Solar potential as the percentage of the building envelope which receives an amount of solar radiation greater than or equal 650 kWh/m^{2}a related to the floor area ($SAFAR_{650}$).

By taking Compagnon's metrics (Figure 4(a)), the roof type with the lowest roof inclination outperforms the options with the highest roof inclination. The $SAFAR_n$ metric hardly shows any difference between the four options. The reason why Compagnon's metric show a higher potential for the lowest inclination is the fact that by increasing the angle, the larger the North façade gets (Figure 5); leading to a lower solar potential. Since the $SAFAR_n$ is linked to the floor area, not the façade area, the metric changes.

For all design options, the $SAFAR_{650}$ is plotted against the density in Figure 6.

The $SAFAR_{650}$ graph shows a graph similar to a power function. One reason to use the $SAFAR_n$ metric is that it might be a way to prepare a Swedish zoning plan for solar energy. Since urban planners are not allowed to prescribe a certain use of a technology in the zoning plan, it should be possible to use the $SAFAR_n$ metric, since it is officially energy-neutral (although its threshold are indirectly based on active technologies). It could be compared to the 'Green Area Factor' used in the city of Malmö, which is an instrument to ensure vegetation, openness and permeability of ground surface in new areas in Malmö (Lindberg, 2012). The Green Area Factor is a useful instrument which assures urban planners, but mostly real estate owners and architects to think and discuss the green areas in and around future buildings.

3.1.1. Sensitivity analysis

During workshops and meetings with urban planners, it came forward that urban planners were only partly aware of their influence on the conditions for solar energy in urban environments. In the following sections, the results of the parametric study – concerning density, roof type and orientation – are shown. The influence of design decisions of the urban building blocks is indirectly apparent. For each parameter, the implications on urban planning are discussed.

3.2. Density

The results of a fitted quadratic model showed that the FSI was the most sensitive parameter. Since the electricity demands according to the BBR and FEBY standard are similar (Table 2), the load matching is similar. The results of the load matching for electricity and the requirements of BBR and FEBY are shown in Figure 7 (averaged for all orientations, 50% ST, 50% PV and all suitable area is used).

The results for the heating load matching for FEBY and BBR are shown in Figures 8 and 9 (note the difference range on the solar fraction axis).

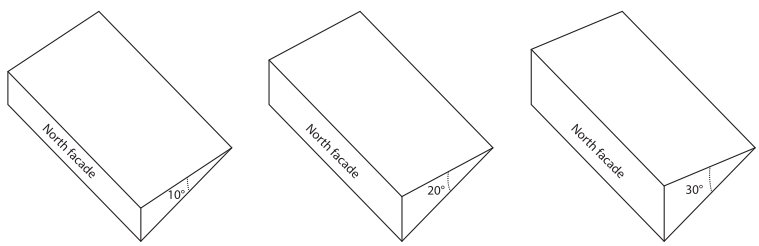


Figure 5. Increasing the inclination of the roof enlarges the North façade.

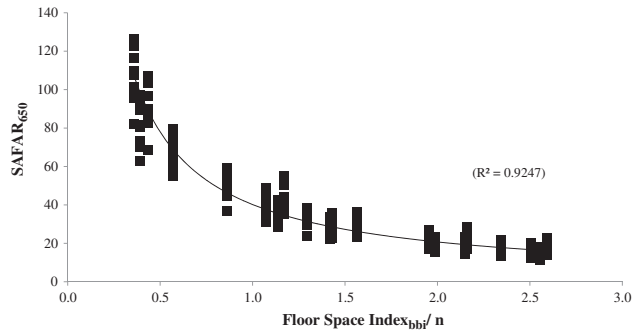


Figure 6. $SAFAR_{650}$ for all design options (averaged for all orientations).

The results displayed in Figures 7–9 show roughly the same pattern. The line showing the average of all options displays a power function; a notion which will be further elaborated in the next subsection. There is a clear relationship with the $SAFAR_{650}$ graph in Figure 6, since they are connected through the suitable area, efficiency of the active solar technologies, floor area and energy demand.

A 100% electricity load match can be reached for the BBR and FEBY standards at low densities. At densities higher than ~2.25, most of the building block configurations do not reach a 100% load match anymore. The highest electricity load match is achieved for the option Uform50 × 50flat, while at roughly the same density, Closed80 × 60gabled returned only 50% of the load match of Uform50 × 50flat, which is a very significant difference. Especially for the lower densities, the differences between the design options are the largest; at higher densities, the differences are almost neglectable.

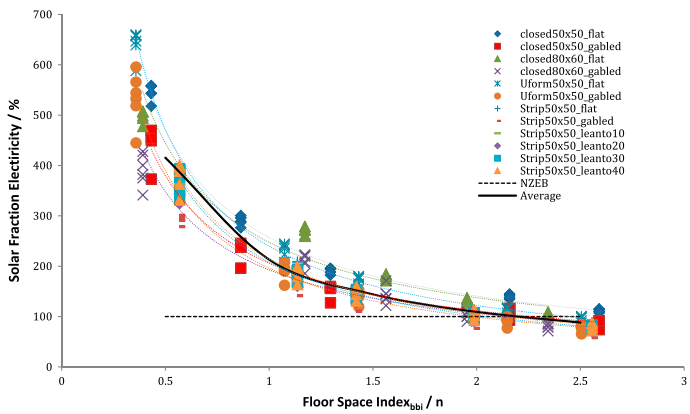


Figure 7. FEBY/BBR load matching for electricity demand.

For the heating load matching, the same pattern is visible for Figures 8 and 9, although the absolute values differ. With the FEBY standards, a density lower than 1.5 achieves a load match of at least 100% (Figure 8). Uform50 × 50flat also performs best here at a density of ~.4, while Closed80 × 60gabled performs worst around this same density. Also here, differences between the design options get smaller at higher densities. With the current BBR requirements, it is hard to achieve a 100% load match for heating (Figure 8); the density would need to be below .5.

3.2.1. Generalisations of results

To plan for energy efficient cities, it would be beneficial for energy and urban planners to work with rules of thumb. To produce such rules of thumb, the average value for the load matching for heating and electricity for all design options and orientations was plotted in Figures 7–9. The equation of these lines were explored; taking the following parameters into account: the ratio PV-ST, the electricity and heating demand, and the density. The orientation was averaged per option and density, and is therefore not part of these equations. This resulted in the following set of equations:

$$R_{PV} + R_{ST} = 1 \tag{2}$$

$$L_{PV} = \frac{4258.6}{Q_{electricity}} * R_{PV} * d^{-0.964} \tag{3}$$

$$L_{ST} = \frac{11356.4}{Q_{heat}} * R_{ST} * d^{-0.964} \tag{4}$$

where R_{pv} = Ratio of Photovoltaics [-]; R_{st} = Ratio of Solar Thermal [-]; L_{PV}: Electricity load matching with photovoltaic systems [%]; $Q_{electricity}$: Annual electricity demand [kWh/m^2]; d = Density (Floor Space Index) [-]; L_{ST}: Heating load matching with photovoltaic systems [%]; Q_{heat} = Annual heat demand [kWh/m^2]; d = Density (Floor Space Index$_{bbi}$) [-].

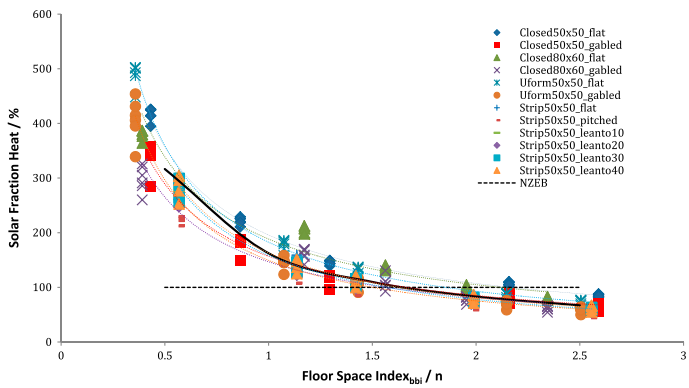


Figure 8. FEBY load matching for heating demand.

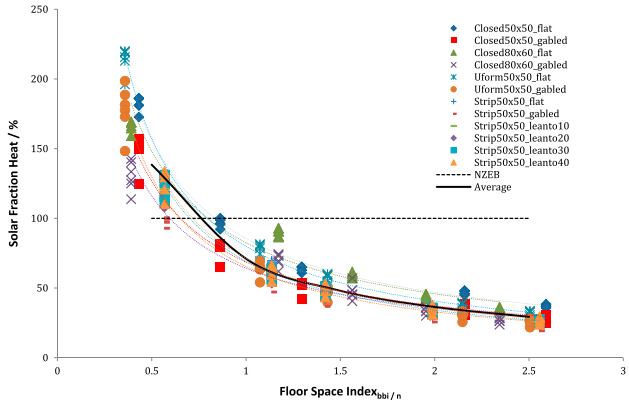


Figure 9. BBR load matching for heating demand.

In Figure 10, the generalised load matching for electricity is drawn (note that the blue line is similar to the line in Figure 7).

In the load matching for electricity, the plug load was not included. The FEBY and BBR standards only set requirements on the electricity for the mechanical equipment, e.g. fans and pumps. When planning for new residential buildings, an additional 30 kWh/m^{2}a is taken as a template value used for the plug load (SVEBY, 2012). The red line in Figure 10 illustrates that, by taking the plug load into account, it is very hard to reach a 100% load matching, even for the lower densities.

In Figure 11, it can be seen that energy reduction for heating is a valid strategy since it is hard to reach a 100% cover for heating for higher densities.

3.2.2. *Consequences for urban planning*

Current density levels in Malmö and Lund range between 1.0 and 2.0 (Larsvall, 2010): a selection of some urban districts with their densities can be seen in Figure 12.

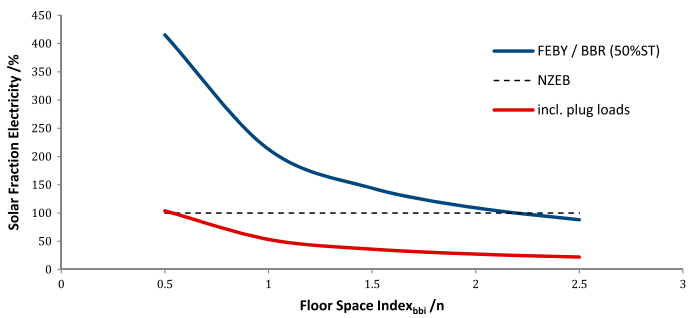


Figure 10. Load matching for electricity demand (generalised).

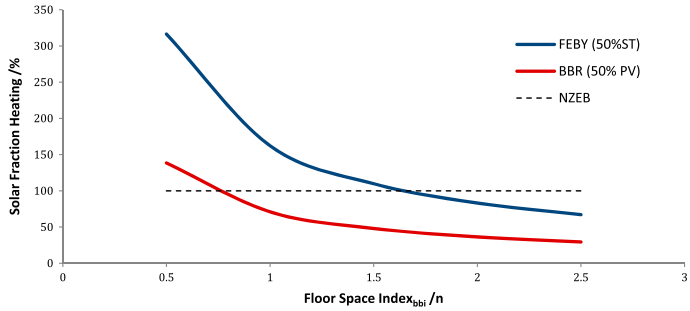


Figure 11. Load matching for heating demand (generalised).

How dense can we plan our future sustainable cities? Energy use is not the only factor when planning for sustainable cities, although earlier studies describe that energy demand of buildings has by far the most influence on the environmental improvement factor (van den Dobbelsteen & de Wilde, 2004). Another study demonstrates that the urban density is negatively correlated with urban private transport energy use (Liddle, 2013). Reducing buildings' energy demand and make expertly plans for the urban development seem to be a good and important strategy ahead.

3.3. Roof type

In this section, the effect of the roof type is analysed. The load match for heating according to the BBR standards is taken as a basis to compare the effect of roof types. For every option displayed in Table 4 the maximum value was normalised and the other options were related to this maximum.

The results show that in the majority of the cases, the flat roof returns the highest value. This is interesting since it was expected that in most cases, the lean-to roofs would generate the highest production. The strip option consists of two strips (see Figure 3); Roofs with a high inclination will therefore shade the stroke behind the first



Davidshall: FSI$_{bbi}$: 1.966. Västra Hamnen FSI$_{bbi}$: 1.1 **R**osengård **H**errgården FSI$_{bbi}$: 0.9.

Figure 12. Densities of some districts in Malmö.

Table 4. Relative difference for the Strip options. The option label is built as following "Design type", "density" and "orientation", e.g. Strip_0.5_0.

Option	Flat	Gable	Leanto10	Leanto20	Leanto30	Leanto40
Strip_0.5_0	95.74	73.34	96.53	97.69	98.04	100.00
Strip_0.5_15	97.81	74.25	97.71	98.53	98.07	100.00
Strip_0.5_30	99.54	75.70	99.74	99.21	98.36	100.00
Strip_0.5_45	100.00	70.88	94.34	96.08	95.97	98.92
Strip_0.5_60	100.00	95.77	95.77	90.24	91.56	95.69
Strip_0.5_75	100.00	95.06	94.90	94.69	98.81	96.70
Strip_1_0	100.00	76.54	96.26	92.32	92.86	96.90
Strip_1_15	100.00	76.31	95.74	91.67	91.86	95.30
Strip_1_30	100.00	76.27	95.55	91.98	91.99	94.95
Strip_1_45	100.00	69.78	91.60	90.49	90.64	95.29
Strip_1_60	100.00	94.75	94.07	88.67	91.87	94.83
Strip_1_75	100.00	94.61	94.90	95.26	99.75	97.31
Strip_1.5_0	100.00	76.62	96.52	93.14	94.26	98.58
Strip_1.5_15	100.00	75.81	96.04	92.11	93.27	97.28
Strip_1.5_30	100.00	75.80	96.23	92.11	92.83	96.92
Strip_1.5_45	100.00	69.49	89.97	91.03	91.62	96.97
Strip_1.5_60	100.00	94.09	94.52	88.82	92.73	96.79
Strip_1.5_75	98.67	94.10	93.54	95.39	100.00	97.48
Strip_2_0	99.03	75.03	95.88	93.42	94.56	100.00
Strip_2_15	100.00	75.10	96.48	92.85	94.01	99.39
Strip_2_30	100.00	74.90	96.71	93.27	94.13	99.11
Strip_2_45	100.00	68.81	90.85	91.87	92.27	98.70
Strip_2_60	100.00	94.12	94.44	89.40	93.73	98.27
Strip_2_75	97.28	92.86	92.75	95.57	100.00	97.74
Strip_2.5_0	97.80	73.50	95.36	92.80	94.48	100.00
Strip_2.5_15	99.45	74.82	96.06	93.54	94.50	100.00
Strip_2.5_30	100.00	74.43	96.58	93.36	94.16	99.48
Strip_2.5_45	100.00	*67.54*	91.66	92.27	93.01	99.59
Strip_2.5_60	100.00	93.21	94.49	88.53	94.34	98.40
Strip_2.5_75	97.24	91.48	92.56	95.60	100.00	97.60

stroke more. The biggest relative difference between the different roof types was 32%. Furthermore, it can be seen that the gabled roof never has the highest load match, although in some cases it is rather close to the maximum. This means that in reality, the well-oriented parts of the gabled roof receive a higher amount of solar radiation, but that a large part of the roof receives less than the threshold value due to its orientation. However, the investment costs per m^2 of installed solar system are lower since the irradiation per m^2 is higher.

Table 5 shows the relative differences between flat and gabled roofs in case of other design options: Closed50 × 50, Closed80 × 60, and Uform50 × 50 (Figure 3). In none of the cases, the gabled roof had a higher load match. The biggest difference was 36%.

3.3.1. *Consequences for urban planning*

The results show that a flat roof often produces the highest load match, while in some cases the lean-to roof was better. In this study, the PV panels and ST collectors were assumed parallel to the actual roof/façade. A flat roof however raises the question of how to set up a PV system efficiently (row distance and inclination); an issue which can significantly determine the production of the whole system (Kanters & Davidsson, 2013).

Table 5. Relative differences between flat and gabled roofs. The option label is built as following "Design type", "density" and "orientation", e.g. Closed50 × 50_0.5_0.

Option	Flat	Gabled		Flat	Gabled		Flat	Gabled
Closed50 × 50_0.5_0	100.00	86.65	Closed80 × 60_0.5_0	100.00	83.82	Uform50 × 50_0.5_0	100.00	92.55
Closed50 × 50_0.5_15	100.00	84.14	Closed80 × 60_0.5_15	100.00	75.17	Uform50 × 50_0.5_15	100.00	88.52
Closed50 × 50_0.5_30	100.00	84.15	Closed80 × 60_0.5_30	100.00	75.27	Uform50 × 50_0.5_30	100.00	90.67
Closed50 × 50_0.5_45	100.00	66.81	Closed80 × 60_0.5_45	100.00	67.19	Uform50 × 50_0.5_45	100.00	67.49
Closed50 × 50_0.5_60	100.00	84.29	Closed80 × 60_0.5_60	100.00	83.09	Uform50 × 50_0.5_60	100.00	80.82
Closed50 × 50_0.5_75	100.00	83.54	Closed80 × 60_0.5_75	100.00	86.58	Uform50 × 50_0.5_75	100.00	80.19
Closed50 × 50_1_0	100.00	86.00	Closed80 × 60_1_0	100.00	83.58	Uform50 × 50_1_0	100.00	92.10
Closed50 × 50_1_15	100.00	83.10	Closed80 × 60_1_15	100.00	75.55	Uform50 × 50_1_15	100.00	87.83
Closed50 × 50_1_30	100.00	82.85	Closed80 × 60_1_30	100.00	74.67	Uform50 × 50_1_30	100.00	88.25
Closed50 × 50_1_45	100.00	65.36	Closed80 × 60_1_45	100.00	66.68	Uform50 × 50_1_45	100.00	66.99
Closed50 × 50_1_60	100.00	81.85	Closed80 × 60_1_60	100.00	81.17	Uform50 × 50_1_60	100.00	78.82
Closed50 × 50_1_75	100.00	83.03	Closed80 × 60_1_75	100.00	85.90	Uform50 × 50_1_75	100.00	79.42
Closed50 × 50_1.5_0	100.00	85.73	Closed80 × 60_1.5_0	100.00	82.93	Uform50 × 50_1.5_0	100.00	92.10
Closed50 × 50_1.5_15	100.00	83.27	Closed80 × 60_1.5_15	100.00	74.93	Uform50 × 50_1.5_15	100.00	87.37
Closed50 × 50_1.5_30	100.00	82.13	Closed80 × 60_1.5_30	100.00	73.97	Uform50 × 50_1.5_30	100.00	87.40
Closed50 × 50_1.5_45	100.00	64.88	Closed80 × 60_1.5_45	100.00	66.02	Uform50 × 50_1.5_45	100.00	66.53
Closed50 × 50_1.5_60	100.00	81.62	Closed80 × 60_1.5_60	100.00	80.63	Uform50 × 50_1.5_60	100.00	79.19
Closed50 × 50_1.5_75	100.00	82.84	Closed80 × 60_1.5_75	100.00	100.00	Uform50 × 50_1.5_75	100.00	78.84
Closed50 × 50_2_0	100.00	85.65	Closed80 × 60_2_0	100.00	83.14	Uform50 × 50_2_0	100.00	91.81
Closed50 × 50_2_15	100.00	83.17	Closed80 × 60_2_15	100.00	75.12	Uform50 × 50_2_15	100.00	87.89
Closed50 × 50_2_30	100.00	81.34	Closed80 × 60_2_30	100.00	73.45	Uform50 × 50_2_30	100.00	87.24
Closed50 × 50_2_45	100.00	64.14	Closed80 × 60_2_45	100.00	65.67	Uform50 × 50_2_45	100.00	65.52
Closed50 × 50_2_60	100.00	81.09	Closed80 × 60_2_60	100.00	80.35	Uform50 × 50_2_60	100.00	78.29
Closed50 × 50_2_75	100.00	83.46	Closed80 × 60_2_75	100.00	86.40	Uform50 × 50_2_75	100.00	79.04
Closed50 × 50_2.5_0	100.00	85.46	Closed80 × 60_2.5_0	100.00	82.90	Uform50 × 50_2.5_0	100.00	91.45

(*Continued*)

Table 5. (*Continued*).

Option	Flat	Gabled		Flat	Gabled		Flat	Gabled
Closed50 × 50_2.5_15	100.00	83.30	Closed80 × 60_2.5_15	100.00	74.81	Uform50 × 50_2.5_15	100.00	87.75
Closed50 × 50_2.5_30	100.00	80.98	Closed80 × 60_2.5_30	100.00	73.01	Uform50 × 50_2.5_30	100.00	86.23
Closed50 × 50_2.5_45	100.00	64.00	Closed80 × 60_2.5_45	100.00	65.26	Uform50 × 50_2.5_45	100.00	65.18
Closed50 × 50_2.5_60	100.00	80.74	Closed80 × 60_2.5_60	100.00	79.90	Uform50 × 50_2.5_60	100.00	78.00
Closed50 × 50_2.5_75	100.00	83.12	Closed80 × 60_2.5_75	100.00	86.23	Uform50 × 50_2.5_75	100.00	79.06

The results show that the type of roof affects the possibilities for utilising solar energy significantly. In this study, the gabled roof and the lean-to roof were options, but in reality, the consequences for some of these options would be significant. A lean-to roof with an inclination of 40° and a building with a width of 12 m would result in a height of 10 m (see Figure 13) which resembles multiple stories.

A more reasonable inclination would be one floor height, e.g. 3 or 4 m (Figure 13). This would result in an inclination of 14° and 18°, respectively. A lean-to roof with a lower inclination (10° or 20°) would not produce the highest amount, but in some cases, it produces more than a flat roof.

3.4. Orientation

Table 6 shows the effect of the orientation of building blocks on the load match. The results were normalised per option.

Table 6 shows that there is no apparent optimal case, except that the maximum is often achieved at orientations between 15° and 60°. The worst performance was in this case the Closed80 × 60_gabled roof with an orientation of 30°, with almost 29% difference.

3.4.1. Consequences for urban planning

Designing zoning plans with closed urban building blocks ease the importance of choosing which orientation should prevail. By rotating the building block slightly, all façades get access to solar energy. Also, daylight conditions get more equal on all façades.

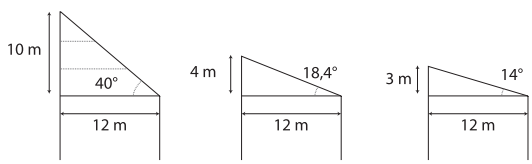


Figure 13. Consequences of roof types on building height.

Table 6. Orientation sensitivity analysis.

		Orientation					
	FSI	0°	15°	30°	45°	60°	75°
Closed_50 × 50flat	0.5	92.71	97.25	99.79	100.00	99.77	97.19
	1	91.95	96.15	98.58	100.00	98.49	95.47
	1.5	93.05	96.23	99.45	100.00	99.18	95.96
	2	93.02	95.36	98.91	100.00	98.27	94.93
	2.5	92.98	95.37	98.65	100.00	98.46	95.05
Closed_50 × 50gabled	0.5	95.52	97.29	99.86	79.44	100.00	96.54
	1	96.81	97.83	100.00	80.02	98.70	97.05
	1.5	97.67	98.10	100.00	79.44	99.12	97.34
	2	99.04	98.59	100.00	79.73	99.05	98.47
	2.5	99.46	99.44	100.00	80.11	99.50	98.89
Closed_80 × 60flat	0.5	94.05	98.24	99.94	100.00	99.69	97.28
	1	94.06	97.39	100.00	99.86	97.98	92.95
	1.5	95.06	97.72	100.00	99.95	97.56	92.79
	2	94.57	97.06	99.51	100.00	97.26	92.43
	2.5	94.43	96.84	99.62	100.00	97.15	92.30
Closed_80 × 60gabled	0.5	93.60	87.68	89.31	79.78	98.34	100.00
	1	98.45	92.15	93.52	83.39	99.61	100.00
	1.5	84.95	78.91	79.71	*71.11*	84.78	100.00
	2	98.47	91.31	91.54	82.24	97.87	100.00
	2.5	98.37	91.03	91.39	82.00	97.53	100.00
Uform50 × 50flat	0.5	89.22	96.93	99.65	100.00	99.97	98.10
	1	84.99	91.41	96.35	99.12	100.00	98.09
	1.5	85.69	91.60	97.25	99.57	100.00	98.49
	2	86.92	91.13	97.49	100.00	99.43	97.87
	2.5	87.00	91.21	97.26	100.00	99.47	97.26
Uform50 × 50gabled	0.5	91.40	94.98	100.00	74.70	89.43	87.08
	1	92.06	94.43	100.00	78.09	92.70	91.63
	1.5	92.85	94.16	100.00	77.94	93.17	91.35
	2	93.84	94.18	100.00	77.04	91.54	90.96
	2.5	94.86	95.43	100.00	77.72	92.50	91.69
Strip_50 × 50flat	0.5	96.03	99.02	100.00	99.19	95.72	86.50
	1	97.87	100.00	99.83	97.08	90.58	80.63
	1.5	97.85	99.67	100.00	97.26	91.00	80.61
	2	97.99	99.95	100.00	98.00	91.96	81.22
	2.5	97.29	99.09	100.00	97.47	91.65	81.48
Strip_50 × 50gabled	0.5	80.25	82.00	82.96	76.69	100.00	89.69
	1	87.28	88.92	88.72	78.93	100.00	88.89
	1.5	87.56	88.25	88.53	78.94	100.00	89.78
	2	85.78	86.73	86.54	77.91	100.00	89.57
	2.5	85.58	87.26	87.12	77.05	100.00	89.72
Strip_50 × 50Leanto 10	0.5	96.64	98.73	100.00	93.39	91.50	81.93
	1	98.41	100.00	99.63	92.89	89.00	79.93
	1.5	98.14	99.47	100.00	90.94	89.38	79.41
	2	98.11	99.71	100.00	92.06	89.80	80.07
	2.5	98.22	99.10	100.00	92.50	89.67	80.30
Strip_50 × 50Leanto 20	0.5	98.23	100.00	99.91	95.54	86.59	82.10
	1	98.41	99.84	100.00	95.68	87.47	83.66
	1.5	98.94	99.67	100.00	96.12	87.74	84.61
	2	99.12	99.51	100.00	96.53	88.14	85.55
	2.5	98.88	99.83	100.00	96.32	86.91	85.80

(*Continued*)

Table 6. (*Continued*).

		Orientation					
	FSI	0°	15°	30°	45°	60°	75°
Strip_50 × 50Leanto 30	0.5	99.06	100.00	99.53	95.88	88.27	86.08
	1	98.94	100.00	99.96	95.79	90.58	87.55
	1.5	99.21	100.00	99.86	95.85	90.76	87.87
	2	99.41	99.83	100.00	96.06	91.57	88.70
	2.5	99.82	100.00	100.00	96.28	91.83	88.99
Strip_50 × 50Leanto l40	0.5	99.08	100.00	99.23	96.92	90.48	82.62
	1	99.51	100.00	99.46	97.07	90.13	82.33
	1.5	99.48	100.00	99.96	97.28	90.84	82.13
	2	99.61	100.00	99.77	97.37	90.97	82.14
	2.5	99.84	100.00	99.85	97.42	90.52	82.08

3.5. Share of roof and façade

Façades are also valuable areas to place PV or ST, especially in cases when we want to exploit the sun to its full potential. In all simulations, division was made between roof and façades, and both façades and roofs were categorised by means of the threshold values shown in Table 3.

Focusing on the irradiation on all suitable areas, it can be seen that the share of suitable roof and façade changes per option (Figure 14).

Figure 14 shows that especially the options of the Strip_50 × 50_gabled/flat design have a higher share of suitable façade area than other options. This type also gives the largest variations. Furthermore, it can be seen that options in the Strip_50 × 50_leanto design have some very high shares of suitable roof area, and even in some cases when the share is 100%, i.e. no façade area was found suitable.

In Figure 15, the share of the roof of the total irradiation vs. the density is displayed. For all densities, it could be seen that the range varies significantly, depending on the design. It should be noted that this graph only shows the share of the roof of all irradiation (and indirect the façade) of all suitable areas.

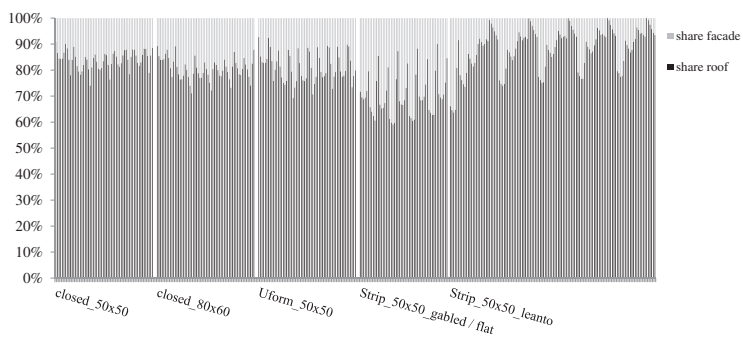


Figure 14. The share of irradiation on all suitable areas (roof and façade) per design type.

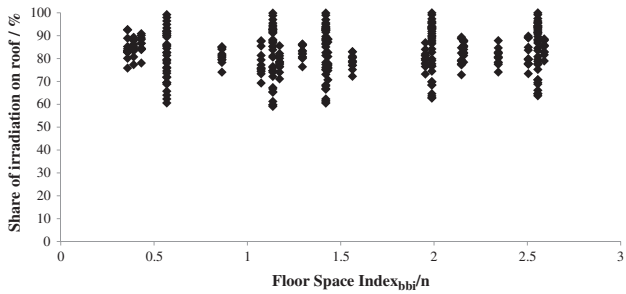
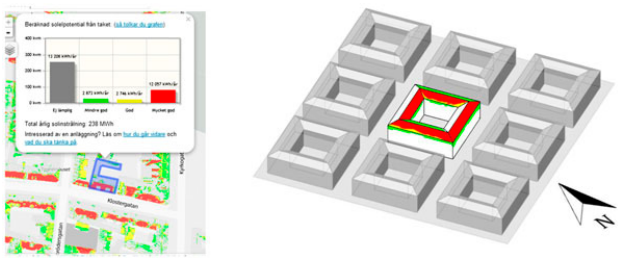


Figure 15. Share of irradiation on roof vs. density.



Solar map fo Lund *Output of a siimulation*

Figure 16. The same categorisation and colours were used in the simulation results of building blocks as in the solar map.

3.5.1. Dissemination of results: website

Within the Swedish part of the project Task 51, our goal is to inform urban planners about the role solar energy could play in the urban planning process as well as the impact on future energy supply of cities. Therefore, a website (www.solarplanning.org) was set up where urban planners could enter and compare different design alternatives with each other. Per simulation option, a picture was exported and the same categorisation and colours were used as a local solar map (Kraftringen et al., 2012) (Figure 16). The website is an additional communication channel to urban planners.

4. Conclusions

Designing buildings that are energy efficient and even energy producing requires a high competence level amongst architects and urban planners. The zoning plan developed in the early urban planning stage already frames the conditions for solar energy for buildings in the urban context. The shape of building blocks, density, roof shape and orientation are the main design decisions that urban planners take and which are determined in the zoning plan. This study examines the effect of these design decisions on the active

solar potential of buildings in the urban context, while also looking at the boundaries for net zero energy solar buildings in the Swedish context.

The concept of the NZEB has been a way to market, design and construct buildings that in general are more energy efficient than regular buildings. NZEBs often implement solar energy as a provider of local, renewable energy. This study shows the possibilities and limitations of reaching a net zero energy balance in buildings placed in an urban context. Access to solar is more restricted in cities and the available suitable area per square metre living area is also limited. Reducing the energy demand in buildings will increase the possibilities to reach a net zero balance, especially if we need to take plug loads into account.

Results from this study show that the urban density is the most sensitive parameter. Also, it is shown that the relation between the load matching level and the urban density can be described as a power function. For lower densities and for the electricity load, urban densities had to be lower than FSI = 2.5 to reach a 100% load match, while for heating, it was harder to meet a net zero energy balance. In many of the building blocks, flat roofs instead of pitched roofs resulted in a higher load match, while gabled roofs never resulted in the maximum load match. This is due to that although parts of the roof get a higher solar irradiation, other parts get more shaded. A sensitivity analysis of the parameter *orientation* resulted in a less clear pattern, but roughly it can be said that orientation between 15° and 60° returned the highest load match. This study shows that the contribution of façades is rather limited in size, and since they receive less irradiation than the roof, also have a limited contribution in production. However, façade areas might be a feasible place to install solar energy systems if roofs are (partly) shaded, or to produce additional solar energy at those times that the optimally placed? solar systems are not producing at their peak.

In this article, the $SAFAR_n$ metric is introduced, which is intended to provide Swedish urban planners an instrument to assess how well a zoning plan performs regarding the solar energy potential. The metric enables to set requirements on the design of a zoning plan within the legal framework in Sweden. The $SAFAR_n$ metric has the objective to drive urban planners, architects and real estate developers to make well-informed solar energy decisions. Even though the real estate market has increased interest in implementing solar energy in buildings, the metric $SAFAR_n$ will elucidate the solar potential and motivate involved actors to discuss how solar energy can be implemented in future building.

Another important point is the consequences of the considered time resolution on the NZEB concept. Even though a building might have an annual net zero energy balance, it often does not reach a net zero energy balance for every month of the year. This is especially true in the Northern European climate, where the highest energy need is mainly during winter, when the contribution of solar obviously is very limited. This requires an energy network that can provide “storage” and energy supply at the times when it is needed. The fictive energy network storage is depending on that there is an energy need somewhere else within the same timeframe as a local overproduction is fed into the network. Not reaching a net zero energy balance within the boundaries of the building or a group of buildings also asks for a discussion on what possibilities exist to achieve a net zero energy balance in another way. One example might be that inhabitants could invest in external solar fields, e.g. as the “BürgerInnen Solarkraftwerk” in Vienna (Wien Energie, 2012).

One of our goals in the project is to support urban planners, meaning that the knowledge gained in research needs to find its way to the common urban planning practice.

One way to facilitate this is by setting up a website which provides a platform for urban planners to gain more knowledge about the results of this study. Further work and collaboration is needed in order to understand the needs, barriers and drivers for implementing solar energy in the urban planning process. This is part of the work within IEA SHC Task 51 Solar Energy in Urban Planning (see http://task51.iea-shc.org/).

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Article PR 5

A planning process map for solar buildings in urban environments

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Abstract:

Our future built environment will not only consume energy, it will also produce (partly) it's own energy need. Solar energy has been proven to be a valid strategy for producing on-site renewable energy. Planning for integrating solar energy in buildings involves many actors and decision-making. In this article, a process map defining which decisions regarding solar energy needs to be discussed in which design stage, is presented. With the help of this process map, more informed decisions should facilitate the implementation of solar energy in buildings.

Keywords: solar energy, urban planning, architecture, real estate developers, urban planner, architect

1. Introduction

Our way of thinking about energy and buildings is changing; was the building solely considered to be energy-consuming, future buildings will be need to consume less energy while producing (part of) their own energy [1]. One way to produce renewable energy on-site is by means of active solar energy. By doing so, buildings will reduce the impact on the environment and reduce the dependence on imported energy. Current legislation is already directing towards such energy efficient and energy producing buildings, with the European directive for the energy performance of buildings [2] as the clearest example.

The installed effect of solar energy is growing rapidly (average annual growth rate of 40% (PV) [3], 12% for ST (from 2000-2010 in Europe) [4]), mainly due to dropping solar energy system prices and favourable political conditions. Solar energy has become more and more accessible for a larger group of people. Technically, solar energy, especially PV, has developed a lot since its invention. Starting with a PV efficiency of 15% in the 1950s, to 17% in the 1970s, towards 28% nowadays [5]. However, most common PV systems commercially available still have an efficiency between 12-15% [5]. Even though more efficient solar cells and panels will become available on the market in the future, other factors are slowing down a wide implementation of solar energy. A lack of knowledge amongst decision-makers in the urban planning and building design process is one of these factors. Urban planners and architects are important decision-makers as regards to the planning, design and eventually construction of buildings with embedded solar energy; a key driver to achieve an energy-efficient built environment. Without adequate knowledge amongst decision-makers, suboptimal decisions might be taken. The final decision regarding solar energy is in many cases taken by real estate developers, whose decisions are often based on a financial basis. Therefore, economic feasibility studies and financial information are a key issue during the whole design process. However, this does currently not have a high priority in the planning process, partly because it is unclear whose task it is to provide such information. Until now, it has mainly been the sole domain of the real estate developer. Preferably, information should come from different actors, supported data obtained from relevant tools.

The main aspects of integrating solar energy (technical, economic, political, and social), have been subject to many studies. However, a comprehensive compilation and overview of relevant decisions and actions, used tools, and involved actors in chronological order of the planning and design process is absent. The objective of this work is to bridge this gap; providing an overview of relevant decisions and actions, used tools and involved actors supported by relevant literature. The outcome of this study is a process map per design and planning phase.

This study is limited to buildings making use of solar energy in the urban context. Also, most focus is on the active utilisation of solar energy.

2. Method

The objective of this study was to develop a process map for the planning for solar energy for buildings in the urban environment. This process map is based on previous research conducted by the authors as well as by an additional literature review.

1. Research by authors

The authors were involved in Task 41: an IEA Solar Heating and Cooling Programme project focusing on the integration of solar energy in architecture. The goals of the task were to "help achieving high quality architecture for buildings integrating solar energy systems, as well as improving the qualifications of the architects, their communications and interactions with engineers, manufactures and clients" [6]. Work was done in three main topics: a) architectural quality criteria for solar energy systems, b) tool development for early design stage consideration and c) integration examples. In the light of this research project, the authors conducted qualitative interviews with Scandinavian architects [7], investigated the role of tools used by architects for solar design [8], the solar potential of building blocks [9], and developed a Façade Assessment and Design Tool for Solar Energy [10]. All common publications of Task 41 can be found on task41.iea-shc.org.

Results of research performed in IEA SHC Task 41 made clear that, in the case of buildings in urban environments, much of the conditions for solar energy are already determined by zoning plans, although urban planners might not be fully aware of their role of creating conditions for solar energy in buildings. The IEA SHC Task 51: solar energy in urban planning was started to "provide support to urban planners, authorities and architects to achieve urban areas and eventually whole cities with architecturally integrated solar energy solutions" [11]. Work will be done in four main topics: a) Legal framework, barriers and opportunities for solar energy implementation, b) Development of processes, methods and tools, c) Case studies and action research, and d) Education and dissemination. In the framework of this research project, collaboration was set up between the authors and the local urban planning department of the Swedish cities Malmö and Lund, focusing on two new urban districts Hyllie and Brunnshög. This collaboration can be seen as action research; the current working method is observed and analysed, while the involved researchers are contributing to the actual case. Until now, the authors investigated the role of design decisions on net zero energy solar buildings in Sweden [12] and analysed solar maps as a knowledge base for solar energy use [13].

2. Literature review

The material of the literature review comprises peer-reviewed research articles published in international journals. Earlier research by the authors [6, 7] as well as other IEA Task 51 members has pointed towards critical issues regarding solar energy in the building design and planning process. In the literature review, articles were selected from 1990s onwards. A search was done in the electronic databases of ScienceDirect and LUBSearch (an EBSCO search engine), with a focus on the terms *solar energy*, *urban planning* or *architecture* in the keywords, titles and abstracts. The articles from the search 'solar energy and architecture' and 'solar energy and urban planning' were then filtered and divided from type of aspect (economical, technical, social, political) to chronological aspect (which design stage).

3. Literature review and process map

In this section, first the process map is presented (3.1), followed by a detailed description per phase.

3.1. Process map

The planning process map for solar buildings in urban environments is shown in Figure 1.

The whole planning and design process is divided into the following different phases:

a) Political decisions phase: this is the phase where decisions are made regarding the political context of solar energy on a large scale (administrations on European Union, national and local level). This also implies the indirect consequences of political decisions, e.g. the lack of political decisions,
b) Urban design phase: in this phase, proposals for new urban district are materialised and/ or the possibilities of integration solar energy into existing urban districts are explored,
c) Building design phase: the design for a building is being developed as well as the architectural integration of solar energy,
d) Renovation phase: decisions are taken how to implement solar energy in existing buildings,
e) Implementation phase: here, the active solar system gets installed and used.

The renovation phase is parallel to the building process phase, since renovation projects do not have the same priorities and possibilities as new buildings. Per phase, decisions and actions, used tools, documentation and methods are described.

The map itself does not have a direction with parts that have higher priorities than others. Decisions taken in all stages of the planning process are important; while political decisions might have a bigger impact in general, a non-attractive integrated solar energy system might lead to less acceptance of solar energy.

Figure 1. Process map

3.2. Detailed description of the process map

In this section, the process map will be described in detail.

3.2.1. Political decision phase

3.2.1.1. National level

The ratification of the Kyoto protocol was the first global step towards a cut of CO_2 emissions [14]. However, recent re-negotiation of the protocol has not led to a continuation of the protocol. On European level, member states agreed on common environmental goals, which is partly put into force by means of directives; e.g. the European directive on the Energy Performance of Buildings [2]. This agreement provides a framework on a European level, leaving space for every member state to concretise these goals into national energy decisions, thereby taking into account the energy availability (like hydropower, solar, and wind) and other geographic constraints (land use, available land). The national plans are important means to reach the national goals. Since solar energy clearly is a significant source of renewable energy, it is important to shape the political context to accelerate the implementation of solar energy.

Decisions and actions

Political decisions taken at the national level shape a political climate for solar energy, which may be either beneficial or disadvantageous. The main political instruments defining the political climate for solar energy are:

- Feed-in tariffs,
- Subsidies,
- Building regulations.

Feed-in tariffs

The feed-in tariff system, an obligation for utilities to purchase electricity generated by any renewable source at a set price, is in place in many European countries. The advantages and disadvantages of the feed-in tariff system were identified by Rowlands [15] as:

Advantages	Disadvantages
1. It effectively promotes the expansion of renewable energy capacity, 2. The use of installed capacity is encouraged by its payment structure, 3. More geographical locations can benefit from the system, 4. It can encourage technological learning, 5. Flexible, fast and easy to establish.	1. There is hardly any competition amongst generators of renewable electricity, 2. Prices of renewable energy systems are higher in countries with feed-in tariff systems than in countries without, 3. Setting an optimal tariff for every renewable technology was found to be very difficult

Subsidies

Another way to accelerate the generation of renewables is by providing subsidies for installing renewable capacity. Sandén [16] identified the following conditions for providing subsidies:

1. Subsidies should promote a self-sustained growth, driven by dynamic learning and scale effects,
2. The subsidised technology should fulfil the needs of the future market.

If the two conditions are met, the subsidies should decrease over time.

Building regulations

In many countries, building regulations set requirements for indoor climate, functionality and often energy use. However, these requirements often focus on the energy demand, not energy production. Future building regulations will most probably include such demands, making it legally binding for new buildings to produce renewable energy on site [17, 18].

Targets

What are realistic targets on a national level, what are the advantages and disadvantages of setting up these targets, and how can solar energy play a role in these targets?

Delucchi and Jacobson [19] studied the possibility to produce all global energy by wind, water, and solar power, even at the same level of costs for energy as the costs for energy today. They identified that the barriers to a 100% conversion to wind, water, and solar power are primarily social and political, not technological or even economic [19]. It would be very beneficial if every country, region or city performs an analysis which renewable energy sources are at hand and feasible given the context of that country. An example of such an analysis is done for New York State by Jacobson, Howarth [20]. Their proposal was to reduce the power demand, followed by installing the following renewable energy sources, of which a significant part was provided by active solar energy [20]. Another example is the proposal for a Zero Carbon Britain [21] which is a national action plan to first 'power down' and then 'power up'. From such national and / or regional analyses; national, realistic, targets for both PV/ST can be extracted.

Tools and documentation

Although political decisions are taken by politicians, external actors (e.g. the industry and non-governmental organisations) could still be powerful. They do not have that many official instruments to their disposal to affect political decisions, but an example of an important instrument in the political design phase is the technology roadmap; a long-term planning tool to 'forecast the direction of future markets and developments in technology and help make strategic decisions providing a critical link between technology investment decisions and business planning and providing a structured approach for mapping the evolution and development of complex systems' [22]. An example is the roadmap for PV developed by the International Energy Agency [3]. Besides an overview of the latest figures and facts about the PV market (e.g. installed effect, price development), it also pinpoints the key actions for the next years; a) Policies should support long-term investment in solar energy, taking away any uncertainties for investors by creating favourable political conditions, b) Grid operators, utilities and the PV industry have to develop strategies how to integrate large amounts of PV electricity into the grid, c) The effort in research and development needs to be increased to reduce costs of PV, as well as international collaboration to accelerate the learning process, d) More should be invested in the rural electrification in emerging countries and e) National and/or local governments should try to remove any non-economic barriers like planning delays, lack of coordination between different authorities and long permission granting time [3].

3.2.1.2. Local level

National targets on solar energy and the potential of a city set a framework for the city administrations to apply them on the local level. A tailor-made environmental analysis of the city's possibilities would provide a foundation how to comply with the national targets.

Decisions and actions

Mainly, there are two important factors which need to be considered on the city level:

- Translation of national goals into local (and possible additional) targets for renewable energy
- Local, additional, demands on energy use in buildings

As on all levels, it is important to look at energy reducing measures as well as local, renewable energy production and to define a reasonable strategy for reaching both goals. In a study by Grewal and Grewal [23], the energy future of Cleveland (USA) was studied. Different scenarios and their costs are presented to facilitate the choice of the right future scenario; the presentation of such scenarios provides cities with tangible, quantifiable data making it easier to base decisions upon. Besides the potential for renewables, the existence of energy grids and energy production and / or planning of new energy networks (urban district heating, smart electricity grid) is seen as an important factor in the analysis.

Urban planners and city administrations have currently a limited possibility to legally enforce solar energy. Azevedoa, Delarueb and Meeusa described different instruments for pursuing goals [24]. There are policy mechanisms known as *tambourines* "whose main objective is to raise awareness among on what is expected from them and how they can achieve it", *carrots* are policy mechanisms that "enable different stakeholders to act by providing incentives", and finally *sticks* which are about "regulating the performance of stakeholders, as well as sanctioning the lack of it" [24]. Right now, the possibility to use the stick might be limited as a way to 'force' real estate developers to implement solar energy in their buildings. What is left is *tambourines* and *carrots*. Urban planners might be limited –at least in Sweden- to the principle *tambourine*.

Tools and documentation

City administrations require simple tools to see the impact of decisions on the future climate goals. On the one hand, different parameters for reducing energy will need to be studied; on the other hand, different options for generating renewable energy need to be studied.

3.2.2. Urban Design phase

Decisions and actions

The term *urban design* is in this study interpreted as "place-making; creating a vision for an area and then deploying the skills and resources to realise that vision" [25]. The urban design phase mainly consists of the development of a zoning plan for either new or existing urban districts. Zoning is one of several tools urban planners use to control "the physical characteristics of developing landscapes by imposing restrictions on variables such as maximum building height and density, extent of impervious surface and open space, and land use types and activities" [26]. In most of the cases, the zoning plan is designed and developed by the local planning authorities, sometimes it is first subject to a competition and later transformed into a zoning plan, making it legally binding.

Urban design can affect the energy use and energy production in cities; more dense settlements will reduce the amount of energy used for transportation [27], while data showed that savings in energy cost of 20-50% are possible through integrated planning with carefully considered site orientation and passive strategies [28]. However, some authors identified that the urban scale has been neglected in the debate on energy consumption and climate change [28, 29]. Although limited in numbers, there are studies which have focused on the layout of the zoning plan and the urban canyon. Those studies have shown that the zoning plan has a considerable impact on energy use in buildings, daylight penetration, and available solar radiation [30-34]. Okeil [35] developed a model to evaluate the relationship between urban built form and energy efficiency. A new urban building block design was developed and results show that this new model allowed the maximum potential of passive utilisation of solar energy in buildings, and combined this high solar exposure with the functional, spatial, social and visual advantages.

In the PhD thesis of Montavon [31] entitled 'optimisation of Urban Form by the Evaluation of the Solar Potential', actual and theoretical urban forms were compared in order to explore the diverse effect of daylighting and solar potential on dense sites. In this study, sites in Switzerland and Brazil were analysed, as well as Le Corbusier's Contemporary City of Three Million Inhabitants. Simulations were performed with Radiance and PPF and thresholds were specified to compute the potential contribution to solar energy and were based on threshold values set by Compagnon [32]. Important factors that influence the implementation of solar energy into urban planning were found to be: financial aspects, environmental aspects, energy-efficiency of buildings, comfort, ambience, and protection. Other findings in the thesis were that implementing PV panels on facades in a dense urban area might not be that feasible and that reorganising the layout of building blocks (without reducing the usable floor area) allows more favourable conditions for solar energy utilisation.

Van Esch et al. [34] discussed the effects of urban and building design parameters on solar access and solar heat gains. Buildings with three different roof shapes and two different orientations were simulated in order to see the effect on solar access and solar heat gains. The results showed that the street width had a significant influence on the global radiation of the canyon: the wider the street, the higher the global radiation yield. Increasing the street width was also preferable from the point of view of maximising the solar gain of dwellings in the winter, although decreasing the street width would result in limiting overheating in summer as well as increasing density in cities. Maximising solar exposure of the building envelope in the winter can best be done in the east-west street direction, since the radiation yield of dwellings in east-west canyons is larger in winter compared with north-south streets. For canyons in east-west direction, single-pitched roofs produced the highest yield. Increasing the amount of transparent facade openings will not always improve the solar performance of the dwelling and will often lead to overheating in summer.

Kanters & Wall [12] assessed the effect of design decisions –form, density, orientation and roof type- on the solar potential of building blocks typically used in Swedish urban planning. Results showed that density was the most influential parameter, while the effect of orientation was not that clear. In the framework of this study, the website www.solarplanning.org was launched, where urban planners can compare the performance of different building blocks.

Implementing solar energy systems within new and existing buildings also requires an approach for how well these systems should be architecturally integrated. One method is proposed by Munari

Munari Probst and Roecker [36], who defined sensitivity (the quality of the architectural environment) and visibility (close and remote visibility of the proposed system). Together with the socio-political context, different levels of integration quality of solar systems were specified.

In the process map, the following parameters were specified having influence on the solar energy potential and / or the passive use of solar energy (daylight):

- Building dimensions:
  - Orientation,
  - Heights.
- Number of inhabitants, business, industry,
- Functions.

During the design of a zoning plan, it is preferable that first, a solar energy potential quantification of the developed zoning plan is conducted; providing the active solar energy potential (Suitable area (m^2)) and production (kWh)), and shading patterns identifying those places on the building envelope that get shaded or not. Preferably, different design alternatives should be simulated, optimised and re-simulated in an iterative way.

Furthermore, it should be clearly defined in what way active solar energy systems should be architecturally integrated into buildings; both for existing buildings and for new buildings.

Tools and documentation

Several types of tools are used to conduct the design tasks within the urban design phase; reports, written guidelines for the zoning plan, Computer Aided Architectural Design (CAD) programs, physical models, and Geographic Information Systems (GIS) tools. As regards solar energy, Gadsden [37] mentioned the lack of tools that can help city planners to make informed decisions. In the past, assessment of the solar potential in urban conditions has been difficult because of the complexity of modelling the 3D urban geometry due to need for computer power [29].

One prominent solar energy tool used in urban planning is the solar map; a GIS system providing the annual solar irradiation on building surfaces, mostly accompanied by information of the output of solar thermal or photovoltaic systems. There are several ways to produce a solar map. The most common methodology to produce a solar map was described by Lukač et al. [38]; first, LiDAR data and a digital elevation model is obtained, then the data gets prepared. The next step is the calculation of irradiance on all surfaces as well as shading, and in the final step, a filter is used to categorise surfaces in different categories e.g. reasonable, good and very good. A growing number of cities are obtaining LiDAR data, making it in theory possible for these cities to produce a solar map. One important aspect in the method of producing a solar map is the calculation method, both for the solar irradiation and the output of the solar technology (PV / ST). Jakubiec & Reinhart (2013) note that 'limited attention has been paid to the assumptions and calculation methods underlying solar maps' [39]. In their analysis of North American solar maps, it was found that the most used calculation method was the constant irradiation level method, which is predicting that every point on the rooftop receives the same irradiation. Since this assumption decreases accuracy in many cases, Jakubiec & Reinhart used Radiance and Daysim as calculation method.

Kanters, Kjellsson and Wall [13] analysed 19 different solar maps. They concluded that the studied solar maps can be classified in three categories; basic, medium and advanced. The *basic* solar map is a solar map with basic information: the irradiation level. Preferably, irradiation levels are also categorised (e.g. in 'reasonable, good and very good'). Such a solar map is the base for the *medium* and *advanced* solar map, of which features are all based on the analysis of annual solar irradiation of surfaces. The *medium* solar map provides the energy output of the suitable areas as PV / ST. The most advanced solar map is not only providing quantitative data, but also provides information about what to do next when people want to install PV or ST.

Although solar maps give architects and urban designers valuable information about the suitability of existing buildings to harvest solar energy, it is not developed yet to be used as a design tool. One important design, non-computerised, tool for solar urban planning was developed by Knowles, and is called the 'solar envelope' [40]. The solar envelope is a 3D surface, on a given site, that does not obstruct more than *n* hours of sun onto the adjacent site [41] and which is visualised as a 3D volume.

Later, Knowles' idea was extended into *solar rights envelopes* and *solar collection envelopes* by Morelli and Ratti [41]. The solar right envelope is the same as the solar envelope, while the solar collection envelope is defined as a 3D volume examining the total number of sun-hours collected. These envelopes facilitate the calculations of solar envelopes over complex urban sites easier, providing the actual irradiation and illumination. Jakubiec and Reinhart [42] incorporated the solar envelope into the 3D CAAD environment of designers [41].

Compagnon [32] developed a method for quantifying the potential for passive solar utilisation, PV electricity production and daylighting of facades and roofs located in urban areas. The simulation engine used in this study was Radiance. The output of the simulations provided the fractions of the total facade or roof area that are suitable for various kinds of solar energy technologies. A very important aspect of this study was the setup of threshold values for daylight and active solar systems (*Table 1*), which have served as a basis for many later studies.

Table 1. Threshold value used in the study by Compagnon (2004)

Technology	Threshold value / facades	Threshold value / roofs
Passive thermal heating	216 kWh/m² during heating seasons	Same as for facades
PV systems	800 kWh/m²a	1000 kWh/m²a
Daylight systems	10 klx mean daylight illuminance during office hours (8-18h)	Same as for facades
ST systems	400 kWh/m²a	600 kWh/m²a

Compagnon's method enables urban planners and architects to assess and compare different design alternatives with each other by quantifying passive and active solar potential.

In search for other ways of calculating energy aspects in urban environments, Ratti et al. [29] used digital elevation models (DEM); a 2D matrix of elevation values storing 3D information. The DEMs facilitate the possibility to predict the annual heating, lighting, ventilating and cooling energy use,

also by taking into account the impact of overshadowing by surrounding buildings. An interesting aspect in this study is the use of the obstruction sky view (OSV) angle, which is used to quantify the luminance of the obstructing facades as a function of their view of the sky. Instead of the Obstruction Sky View angle, Cheng et al. [30] used the Sky View Factor (SVF) which defines the openness of a surface: a SVF of 1 means an unobstructed view of the sky and a SVF of 0 means a completely obstructed view of the sky. The SVF facilitated the examination of the relationship between built forms, density and solar potential by means of three design criteria: openness at ground level, the daylight factor on the building facade and the PV potential on the building envelope using Compagnon's method [32].

3.2.3. Building Design phase

The building design phase is the phase where the design of a building is developed and consists mainly of three phases: concept design, schematic design, and detailed design.

The process of designing, constructing and managing a building is fragmented and involves many participants interacting in complex ways over a longer period of time [43]. The design process is different for every building, although a general course of the design process can be identified. The majority of architects follows what is called a traditional design process [44], in which the following stages can be distinguished: briefing, pre-conceptual design, conceptual design, preliminary design, detailed design, and design documentation [45]. This linear process has proved its value in the last decades, but it has often led to undesirable design features like a limited exploitation of the potential advantages offered by solar gain during the heating season, a possible exposure of the building to high cooling loads during the summer, a non-utilisation of a building's daylighting potential, an exposure of occupants to severe discomfort, and a lack of computer simulations of predicted energy performance [44]. In order to deal better with the constraints of the traditional design process, the Integrated Design Process (IDP) was developed; a process which considers and optimises the building as an entire system including its technical equipment and surroundings and for the whole lifespan. It has proven to be more effective in producing high-performance and environmentally-friendly buildings [44], and buildings were found to be performing better and more cost-effective compared with the ones designed according to a traditional design process [46]. In general, the IDP will have the following sequence [44]:

1. Establish performance targets for a broad range of parameters, and then develop preliminary strategies to achieve these targets;
2. Minimise heating and cooling loads and maximise daylighting potential through orientation, building configuration, an efficient building envelope and careful consideration of amount, type and location of fenestration;
3. Meet these loads by an optimum use of solar and renewable technologies and a use of efficient HVAC systems, while maintaining performance targets for indoor air quality, thermal comfort, illumination levels and noise control;
4. Iterate the process to produce at least two, and preferably three, conceptual design alternatives, using energy simulations as a test of progress, and then select the most promising of these for further development.

The most notable difference with the traditional design process is that the design becomes a collaborative effort of the design team [43]. The American Institute of Architects [47] defined an

architect's guide to integrating energy modelling in the design process. The report says that all architects should be 'leaders in energy modeling for the building industry, taking responsibility as designers for assuring that buildings perform to high standards'. The report also provides a guideline how to integrate energy modelling in the design process, for instance by defining which decisions needs to be taken.

All stakeholders have a crucial role to play in altering the way the built environment performs in term of energy performance [48]. Not only the involved architects and engineers play an important role, also clients. Nässén, Sprei [49] performed an interview study where most of the interviewees identified the clients as the most important actors to drive change in the building sector. Feige et al. [48] identified key stakeholders and their main concerns in the design process (Table 2). Different main concerns might lead to issues in reaching a common goal. This was also confirmed by Lützkendorf, Fan [50], who looked at the role of the financial sector in the energy-efficient real estate. By engaging in sustainable property development, financial stakeholders are exposed to moderate risks but gain on their image building.

Table 2. Involved stakeholders and their main concerns (after Feige et al., 2001)

Key stakeholders (internal)	Investor	Manufacturer /supplier	Banks/financial institutions	Contractors	Planners/designers	End user/owner	Public authorities
Main concerns	Return of investment, economic feasibility, corporate social responsibility, regulation, personal belief, company image	Energy supply, availability of natural resources, economic feasibly, regulation, personal belief, company image	Return of investment, company image	Materials and energy supply, economic feasibility, cost-efficiency, workforce, corporate social responsibility, regulation, personal belief, company image	Knowledge, creative and efficient application of technologies, cost-efficiency, corporate social responsibility, regulation, personal belief, company image	Well-being, economic feasibility, lifestyle, personal belief, company image	Regulations and control, well-being
Key stakeholders (external)	Non-governmental organisations	Research and education	Media	Environment	Future generations		
Main concerns	Social equity, access to information, well-being	Technology and knowledge	Democratic share of information	Permanent degradation	Social equity, well-being		

3.2.3.1. Concept Design phase

Decisions and actions

In this phase, the architectural design starts and is being developed. The main aspects of the building are getting designed. As regards the conditions for the implementation of solar energy in buildings, the following aspects are crucial:

- Orientation of the building,
- Height,
- Fenestration,
- Material,
- Dimensions,
- Choice of solar products

Integrating solar energy into buildings needs to be taken care of from the first design phase. Hestnes [27] described several case studies where solar systems became part of the general building design. Eight buildings were discussed, with special focus on the integration of solar systems into the building; place, size, problems of integration, colour and material of solar systems and their architectural features were evaluated. It was found that designers of these buildings should have a good and common understanding of how to design buildings where energy systems are an integral part of the whole, which Hestnes called the holistic approach. Designers needed help when applying this approach in choosing the right solar system. If solar elements replaced other building elements, their architectural integration became better: they served dual functions and thus reduced total costs. Architects have discovered that solar elements can be used to enhance the aesthetic appeal of a building, and their clients have discovered the positive effect of advertising their use of solar

energy. In most cases, the key to success in solar building projects was the use by architects of the approach of aesthetic compatibility rather than of invisibility. Lundgren and Torstensson [51] analysed the architectural integration of solar energy in buildings in Scandinavia and the Netherlands through cases studies. All the involved architects found PV interesting as a building material. In some case study buildings, PV was introduced late in the process, resulting in a less attractive integration compared with those buildings where PVs were integrated from the beginning of the project. Furthermore, architects experienced the financial factors as limiting. Henemann [52] described building integrated photovoltaics (BiPV) as an important product which can change the perception of solar energy since they are more attractive and adaptable than regular systems. Some of the advantages mentioned were that the modules can be integrated into non-ventilated facades of new buildings, in ventilated facades to increase the appeal of old buildings; they replace other building materials, can be used as balustrades, and function as a screen against noise, wind, sun, etc. Kosoric et al. [53] described the building integration of PV on a demonstration site in Singapore. In the design process, which was divided into three phases, eight design alternatives were created which all had to be innovative, functional, successfully integrated into the architecture and have a good performance considering both costs and energy output. In design phase 1, suitable places for the PV were selected. In phase 2, design alternatives were generated and optimised, and in phase 3, the eight design alternatives were assessed by multi-criteria decision-making (MCDM) in order to pick the best alternative. The use of such a MCDM method was seen as successful since it reduced subjectivity, but special attention should be devoted to the determination of weighting coefficients

Quesada et al. [54] performed a detailed literature review of solar facades, with a special focus on opaque solar facades. The review concluded that BiST is a relatively simple technology, but not yet fully optimised and understood and that BiPV have many advantages since they do not only produce energy, but can also reduce cooling loads when the air flow behind the panels is utilised efficiently. Hybrid ST /PV systems were seen as improving the economic return of the system by combining the two technologies. The most developed system is the thermal storage wall or Trombe wall, which can reduce the heating load by about 40-50%.

Munari Probst and Roecker [55] conducted a survey on the perception of the integration quality of Building Integrated Solar Thermal (BIST) systems. The web-based survey's target group were architects, engineers and facade manufacturers from different climatic European areas. Results showed a clear ranking of BISTs by architects, and another ranking by engineers. Architects agreed on the value of the integration quality of the objects, while engineers and facade manufacturers were generally less demanding regarding integration quality. It was found that some specific system characteristics had a significant impact on the integration quality; size and position of the collector field, shape and size of the modules, type of joining, collector material and surface texture, and absorber colour.

One of the client's main priorities is to perform a financial study on the costs and benefits of solar energy. Clients should define a budget for renewable energy in this phase. In order to make well-founded decisions, clients should be aware of the latest prices for solar products, latest energy prices, and support system (feed-in tariffs and / or subsidies). It might also be useful to be aware of the latest business models on renewable energy. To support the financial study, the following actions should be executed:

- Assessment of the active solar energy potential,
    - Suitable area (m^2)
    - Possible production on suitable area (kWh)
- Assessment of ratio PV / ST,
- Assessment of shading patterns,
- Assessment of best suitable location for PV/ST,
- Search for suitable products for best architectural integration,
- Estimation of a rough system size.

Tools and documentation

Most architects and engineers use CAAD programs for their daily work. CAAD programs have evolved from replacing much of the hand drawing into a working platform by the introduction of the so-called Building Information Model-programs (BIM): a digital building environment containing form, behaviour and relations of parts and assemblies (Eastman, 1999). Architects and engineers can work together on a 3D building model and can exchange information about the building and building components. When assessing the building's energy performance, Building Performance Simulation (BPS) tools are used in the design process. Such tools are whole-building energy simulation programs, providing key performance indicators such as energy demand (and/or production), temperature, and humidity [56]. Over the past 50 years, hundreds of building energy programs have been developed. Because of the large number of BPS tools, it is hard for architects and engineers to know which program will fit their working method best. Another complicating factor is the fact that developers of simulation programs all use their own language when describing their products, which makes it harder for architects to choose [56].

Attia et al. [57] conducted a survey amongst architects in order to compare several BPS tools for their architect-friendliness. The authors mentioned that most of the current users of those BPS tools were researchers and experts, not architects. An analysis of the different tools showed that only three of the tools were classified as architect friendly.

Holm [58] wrote that the designer's approach, working from the whole towards the detail, is contrasted with the way analytical models are typically structured, which has led to the development of a number of simulation tools which overlook the real needs of the industry. Schlueter and Thesseling [59] claimed that nowadays, still no tools exist which could seamlessly integrate performance assessment into the design process or support the design and decision-making of the architect or building designer. However, Hensen and Augenbroe [60] discuss that over the past two decades, the building simulation discipline has matured into a field that offers better methods and tools for building performance evaluation. Several CAAD embedded plug-ins were launched recently integrating energy simulation tools into the everyday drawing environment of the architect. Another trend amongst architects and researchers in architecture is called parametric design; the use of parameters to define a form [61]. In order to analyse the performance of several design alternatives, the user needs to produce a script which makes this possible. Including BPS tools in the scripting environment makes energy simulations easier accessible.

Most BPS tools focus on the consumed energy of buildings and on indoor comfort, while solar energy is not always part of such tools. Dubois and Horvat [62] provided an overview of the available

digital tools used for solar design, dividing the digital tools into three categories: 1) CAAD (computer-aided architectural design), 2) visualisation, 3) simulation tools. It was found that most tools were more suited for later (detailed) design phases than for the EDP. In addition, Horvat et al. [63] also carried out an international survey on digital tools used by architects for solar design within the framework of IEA SHC Task 41 Solar Energy and Architecture. The web-based survey focused on identifying current barriers preventing architects from using existing methods and tools for solar building design, and to identify important needs and criteria for new or adapted methods and tools to support architectural design and integration of solar components at the EDP. Results showed that architects did not rate their skills of digital tools as very advanced (Figure 2).

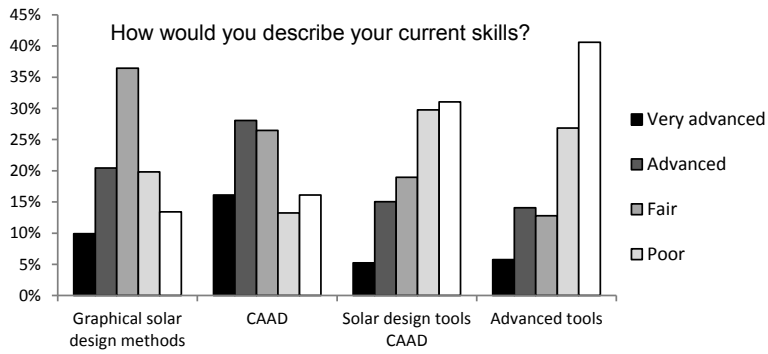

Figure 2. Current skills of architects regarding digital tools (Horvat et al. 2011)

Results showed furthermore that architects have different needs for tools in every different design stage.

Ibara and Reinhart [64] compared six commonly used distribution methods of solar irradiation. The six methods were: 1) Daysim DS, 2) Daysim DDS-s, 3) GenCumulativeSky, 4) Ecotect tiles, 5) Ecotect Points, and 6) a manual method in Excel. Two test cases were compared with each other; in one case, measured data was compared with the six different methods, and the second case represented a tower in a complex surrounding urban fabric. In case 1, where the measured data was taken as a reference, the biggest relative errors were made on the north side with the manual calculation in Excel and with Ecotect Points. In case 2, the Daysim program was taken as a reference. Compared with Daysim, the biggest relative errors were seen, on average, with the Ecotect Tiles method. The results in this study have shown that Radiance-based programs made the smallest relative errors under these conditions. Furthermore, the authors demonstrated that differences in results between the different methods significantly influence the design recommendations.

Kanters, Wall and Dubois [10] developed a tool that can be used to assess the solar potential of façades in complex environments. Besides providing the energy output of PV / ST on an hourly basis, it is also possible to obtain the economic value of this energy production.

3.2.3.2. Schematic design

When the involved actors agree on the concept design, the next stage starts. In practice, this transition might hardly be noticeable. In the schematic design phase, the layout of the building gets more detailed.

Decisions and actions

In this phase, the following architectural design decisions have an influence on the conditions for solar energy:

- Detailed architectural design
  - Outer walls,
  - Characteristics of solar products,
    - Dimensions,
    - Colour,
    - Rhythm,
    - Texture.
  - Roof material
    - Dimensions,
    - Colour.
- Structural design decisions

A proper architecturally integrated system is 'the result of a controlled and coherent integration of the solar collectors simultaneously from all points of view: functional, constructive, and formal (aesthetic) [65]. In this design phase, the following actions should be taken to assure a good (architectural) integration of solar energy:

- Detailed layout of the system (strings, series / parallel),
- Exact dimensions of system and system components (tanks etc.),
- Detailed layout of joints and materials,
- Detailed financial evaluation,
- Mutual shading of rows PV / ST ,
- Rough baseline energy mod,
- Provide annual energy use charts for baseline vs. proposed,
- Detailed budget for renewable energy (detailed) / payback.

Although the architectural integration of solar technology should have been present from the very beginning, this phase is a crucial phase since the integration concept will get materialised. In the report *solar energy systems in architecture* developed within the IEA SHC Task 41, different levels of integration put forward are: added technical element, added technical element with double function, free-standing structure, part of surface composition, complete façade / roof surface, and form optimised for solar energy [65].

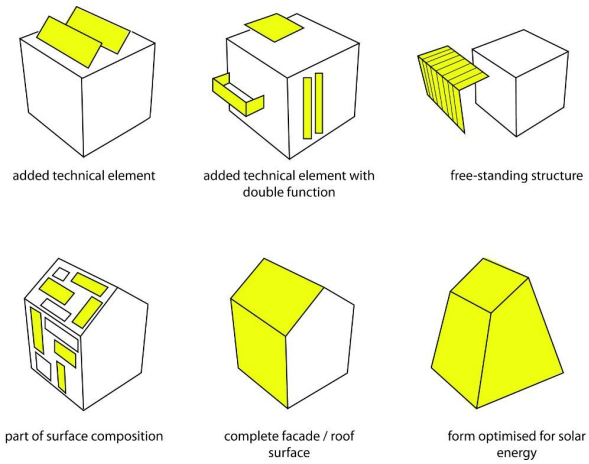

Figure 3. Categories of integration (Farkas et al., 2013)

Compared to a traditional façade and roof design, a well-integrated solar system might require more design work. On the other hand, new solutions and architectural elements can be found, as well as it will results in better aesthetics and lower costs compared to a later installation when the building is already constructed.

Tools and documentation

Simulation software supports the involved actors to perform a full assessment on the technical and financial issues, as is shown in earlier studies [66-68]. Common output of such tools is the annual, monthly and even hourly output, the size of the system components (mostly inverters), and an estimation of losses. Both mutual shading and shading due to surroundings have often been missing in the simulation software, but newer versions often allow to assess shading. Tools supporting the architectural integration of solar systems are very scarce. One example is a CAD object tool which uses a library with common PV cells and enables users to visualise the solar energy system [69].

3.2.3.3. Construction documents

In the last phase of the design process, final details of the building and the embedded solar energy system will be designed and documented.

Decisions and actions

In this phase, the construction details of the integration of solar products will be designed and documented. It is important to get the right details of solar products from the manufacturers in order to get a good integration of the products. Furthermore, the final design model has to be prepared, as well as the final documents for code compliance.

Tools and documentation

In this phase, detailed simulation software for solar energy systems are used, similar to those used in the previous phase.

3.2.4. Renovation phase

To reach targets on renewable energy production, it is crucial to not only focus on new buildings, but also on existing buildings. Real estate owners might either choose to renovate the building and implement solar energy while renovating or they might chose to add solar energy on top the existing building envelope, resulting in a non-integrated solar energy system. Voss [70] described fourteen demonstration projects initiated in IEA SHC TASK 20 Solar Energy in Building Renovation, focusing on the technical, economic, and building physics issues of solar collectors, glazed balconies, and solar walls. The case studies showed that when buildings undergo renovation, solar energy can play an important role in contributing to decreased energy use and in producing energy if it is considered at an early phase. However, solar concepts were rarely discussed in renovation strategies. Solar concepts in renovation can increase comfort and save energy, but were still considered as being too expensive.

Decisions and actions

The following decisions and actions have to be taken in the renovation phase –some of them overlap with the schematic design phase-:

- Map the active solar potential of existing buildings (solar map)
- Map and define integration issues in existing buildings
    - Sensitivity (heritage), material, colour, reflections
- Prepare for building permissions
- Detailed layout of the system (strings, series / parallel),
- Exact dimensions of system and system components (tanks etc),
- Detailed layout of joints and materials,
- Detailed financial evaluation,

Tools and documentation

The mapping of the active solar potential can be done by means of solar maps as described earlier. For the detailed technical evaluation, the same detailed simulation software as for the schematic design phase can be used.

One important tool in the process is construction documents, where the architects and engineers determine how solar energy is implemented and how the constructor and installer should prepare the existing building for the next phase: the implementation phase.

3.2.5. Implementation phase

In this phase, the actual solar energy system gets installed. The final installation of the system could affect the performance of a system. With a good preparation and experience, installations flaws could be avoided.

Decisions and actions

- Install the solar energy system on the building
    - Actual jointing, installation
- Follow-up of system's performance

Tools and documentation

Construction documents are the main tools used in this phase. They also assure a transfer of knowledge from one actor to another. Preferably, the performance of an installed solar systems should be assessed as well as registered.

4. Conclusions

A process map for implementing solar energy in the urban planning and building design process has been presented. The process map is based upon previous research by the authors, a literature review and ongoing research within the framework of IEA SHC Task 51. Instead of focussing on the technical, social, political and financial aspect of solar energy, this process map focusses on the chronological aspect within the planning process as well as on the actors taking the major decisions regarding solar energy.

The process map distinguishes the following phases of the design process: political decision phase, urban design phase, urban design phase, building design phase, renovation phase, and implementation phase. Within these phases, the following aspects were discussed: decisions and actions, tools and documentation and actors.

The presented process map underlines that every actor in the design process has the power to influence the final decision to install solar energy on buildings either directly or indirectly, although the amount of power differ per actor.

The process map highlights some critical points in the design process;

1) Having the right information to base decisions upon. Decision-makers might take decisions based on their own experience even though their knowledge might be incomplete and / or outdated. This is especially true for real estate developers, whose decisions often are based on return-on-investment calculations; not taking into account the latest prices and developments on the energy market might lead to a wrong picture of solar energy.

2) The legal framework for solar energy is very much dependent on the political context in a country, which might be change heavily for every political term. A long-term political will to create favourable conditions for solar energy will decrease uncertainties for investors in solar energy and are therefore more likely to invest.

3) All actors need to take responsibility to increase the uptake of solar energy. The design process is a long process stretching over years with many actors involved. Until now, there is not a clear way how solar energy should be handled throughout the design process. Often, the final decision to install solar energy is driven by personal belief or financial benefit (or both). This position could influence all involved actors.

4) Tools play an important role for decision-making during the design process. Different levels of details of tools are necessary to provide useful information. The level of detail needed in the described phases are increasing throughout the design process.

The integration of solar energy in buildings might be increased with the right information in the hands of the right actor at the right time. Based on the process map, guidelines can be set to facilitate the implementation of solar energy in buildings within the urban context:

Step 1: Develop a strategy (pre-zoning plan phase)

- Determine early goals: what role do we want solar energy to play in our future urban district?
  - Can we set any reasonable energy targets: how much should solar energy contribute in the new urban district?
  - How does solar energy relate to the rest of the energy mix?
- How can we ensure that these goals will be achieved and maintained?
  - (Swedish) urban planners do not have that many legal instruments to put demands on real estate developers; so solar energy needs to be part of an early dialogue with future real estate developers, architects and other relevant actors. However, non-descriptive ways to focus attention on solar should be looked after.

Step 2: Assess the zoning plan (urban planning phase)

- How can we 'design with solar energy' within the urban planning department? Do we have the right level of competence?
- Perform an assessment of the zoning plan (at least once):
  - Assessment of solar potential (total amount of kWh/a and m2 of suitable area)
  - Daylight conditions: ensure that public spaces receive enough daylight
- Can we improve the zoning plan for solar energy (without decreasing the overall quality of the zoning plan)? This requires an iterative process; an assessment of a design might lead to an improved design, which needs to be assessed again.
- How do we transfer the information of early assessments to the building developer and their team?
- How do we ensure the architectural quality of the integration of solar energy?
- How can we ensure the use of solar energy while protecting the quality of the urban environment (heritage)?

Step 3: Follow-up in the building design phase

- How can we as municipality / city administration follow the process of implementation of solar energy into the architecture of the new building blocks?

Step 4: Register the final results

- How can we learn from the obtained results? Are there lessons to be learnt?

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Mutual shading of PV modules on flat roofs: a parametric study

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Abstract

In order to make cities more resilient, our urban environment should not only consume energy, it should also become energy producing. Flat roofs are highly suitable for the placement of PV systems to produce renewable energy, but the assessment of its exact energy potential is not straightforward. Important configurations parameters of PV systems are the inclination and row distance, both leading to mutual shading. This study examined the technical and economic consequences of mutual shading of PV systems. In the first part, a comparison is performed between an unshaded module and a shaded module with different row distances and inclinations; in the second part, the energy output as well as payback times of a PV system on a flat roof were simulated. A significant decrease in energy production was seen due to mutual shading, while the configuration to achieve the maximum energy output was at an inclination of 0° and a row distance of 0 metres. Payback calculations showed that, when electricity prices rise in the future, more options concerning inclination and row distance became feasible.

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Keywords: mutual shading; solar resource assessment, PV

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1. Introduction

Cities are home to more than half of the world population [1] and consume the majority of total global energy [2]. Smart planning of new urban districts will help cities to reach their goals of both energy reduction and local energy production; in such a way that they could become more self-reliant [3]. Roofs are the most important part of the building envelope to transform valuable solar irradiation to renewable energy, but calculating the solar potential assessment of roofs is not always straightforward. Placing PV modules on a flat roof always ask for a strategy; are panels to be placed in such a way that, together, they will generate as much energy as possible annually, or in such a way that they receive the highest irradiation level per solar panel? Mutual shading between the PV modules will result in lower outputs than when modules are unobstructed. Even though mutual shading is a well-known effect, there are hardly any programs taking into account the effect of mutual shading on the output of a PV system [4].

Effects of mutual shading has been recognised as an important parameter in several studies [4-7], although its effect was often estimated rather than calculated. The effect was sometimes assumed to be 15% over the year [6] or it was simply stated that 'shading is one of the major loss mechanisms in photovoltaic energy production' [4] without further quantification. Mutual shading depends on the shading of objects in the vicinity, but its effect also depends on the layout of both the modules and the system; e.g. the placement of bypasss diodes and serial / parallel connection.

The goal of this study is to explore the effect of different parameters on the total solar potential of PV modules installed on a flat roof.

2. Method

The parametric study was performed using the simulation program DIVA-for-Rhino [8]. This is a Radiance based Building Performance Simulation program embedded in the CAAD program Rhinoceros and using the GenCumulativeSky sky model [9].

A common type of solar modules was taken as reference, having 3 strings of 20 cells with bypass diodes, like common solar modules sold on the market [10] (Figure 1). In this study, it was assumed that the cell with the lowest solar irradiation determines the output of the whole string; e.g. the lowest irradiation was in the middle of the panel, as is shown in the hatched cells in Figure 1. That means in this case that the total output of the module was calculated as:

the lowest irradiation level of the 1st row x area of the 1st and 2nd row
+
the lowest irradiation level of the 3rd row x area of the 3rd and 4th row
+
the lowest irradiation level of the 5th row x area of the 5th and 6th row
} x efficiency of the cell (15%)

The 1st, 3rd and 5th row always returned the lowest values due to the mutual shading. Later, the output of the modules was divided by the area of the module. When calculating the output of the module, the temperature effects of the cells were omitted. It was assumed that by comparing relative differences between shaded and unshaded panels, temperature differences would be almost similar. In reality, there will be a temperature difference due to shading mostly in winter. No other system losses were taken into account.

In DIVA-for-Rhino, two identical rows of PV panels were constructed and simulated. One row consisted of five panels and dimensions of the modules were 1m * 1.666m (Figure 1).

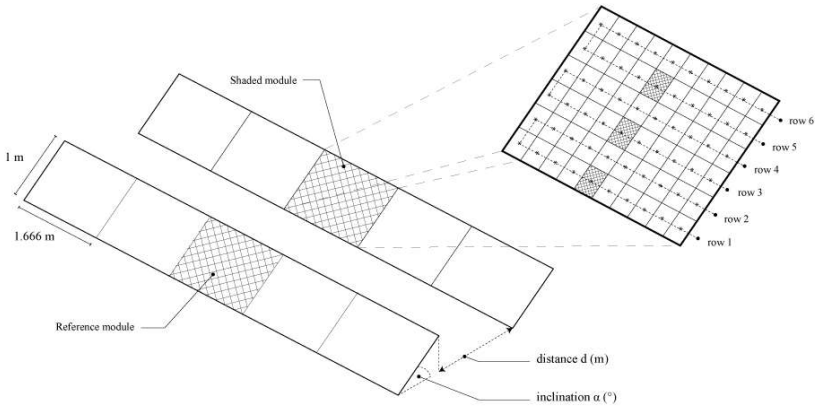

Figure 1. Layout of the two simulated rows, layout of panels / strings

The middle module of the first row always served as the reference module; the middle module of the second row served as the analysed module. In this way, the effect of mutual shading could be quantified. By taking the middle row out of a row of five modules, side effects were considered to be absent.

The following parameters were studied:

- Distance between rows *d* (0.5; 1; 1.5; 2; 2.5m)
- Inclination α (0°, 15°, 30°, 45°, 60°, 75°, 90°)
- Location (Lund, Sweden (55°42′N 13°12′E); and Miami, USA (25°47′N 80°13′W))

These parameters were considered to have a considerable effect on the mutual shading, as well as they determine the final size of the whole system; an important issue for financial calculations. Note that the combination inclination 90°, row distance 0m is not possible and therefore not mentioned in the results.

The results of the simulations of the reference and shaded modules in Lund and Miami affect the system design. In the second part of this study, a rooftop, 1 metre * 100 metres was taken to understand the consequences of the simulations (Figure 2). The rooftop is facing south.

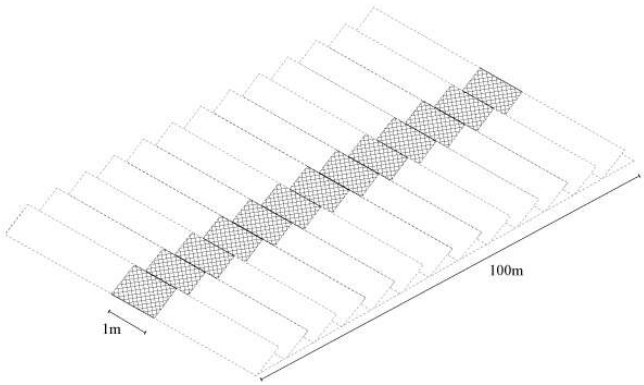

Figure 2. The rooftop

In the rooftop simulations, the same parameters 'Distance between rows *d* (0.5; 1; 1.5; 2; 2.5m)' and 'Inclination *α* (0°, 15°, 30°, 45°, 60°, 75°, 90°)' were varied. For every option, the first row was always unshaded, the rest of the rows were partially shaded. The total area of modules is shown in Table 1.

Table 1. Total area of modules (m^2)

	0m	0.5m	1m	1.5m	2m	2.5m
0°	100	67	50	40	34	29
15°	103	68	51	41	34	29
30°	116	73	54	42	35	30
45°	141	83	59	45	37	31
60°	200	100	67	50	40	34
75°	386	133	80	57	45	37
90°	x	200	100	67	50	40

3. Results

3.1 Lund

Results of the annual output of a 1 m^2 module in Lund are shown in Figure 3.

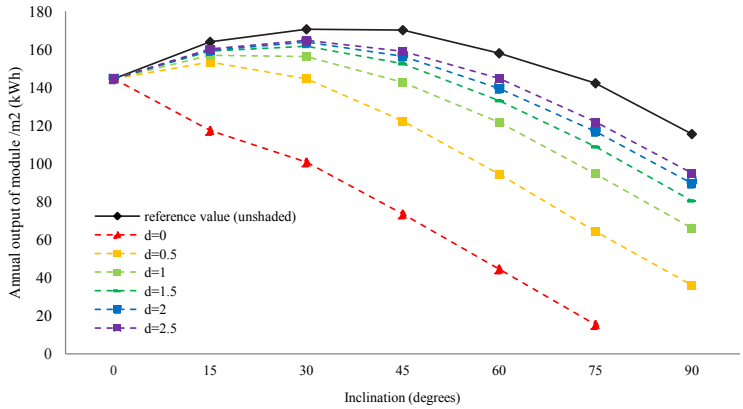

Figure 3. Output of the reference module and the shaded module in Lund.

Figure 3 shows that the maximum output of the reference module is at an inclination between 30° and 45°. Table 2 gives the output of the shaded panels in relation to the maximum output. When the inclination of the rows is 0°, the effect of mutual shading is absent. When the row distance is 0 metres, the effect of mutual shading is the largest; when rows are placed further away, the impact of mutual shading became less.

Table 2. Relative output compared to maximum output, Lund

	Reference module	Shaded module					
		0m	0.5m	1m	1.5m	2m	2.5m
0°	85%	85%	85%	85%	85%	85%	85%
15°	96%	69%	90%	92%	93%	93%	94%
30°	100%	59%	85%	92%	95%	96%	97%
45°	100%	43%	72%	84%	89%	92%	93%
60°	93%	26%	55%	71%	78%	82%	85%
75°	83%	9%	38%	55%	64%	69%	71%
90°	68%	x	21%	39%	47%	53%	56%

3.2 Miami

The results of the simulations of Miami are shown in Figure 4.

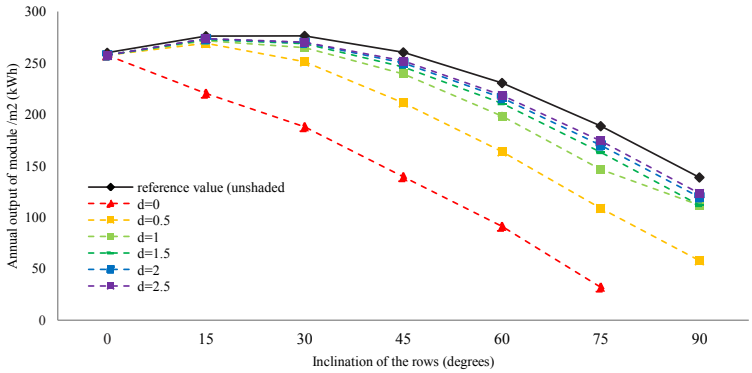

Figure 4. Output of the reference module and the shaded module in Miami.

The reference module in Miami has a maximum output at 30°. In Table 3, the relative output is shown in relation to the maximum output. The effect of mutual shading caused by a short row distance was not so significant at low inclinations, which is caused by the high solar position in Miami.

Table 3. Relative output compared to max output, Miami

	Reference module	Shaded module					
		0m	0.5m	1m	1.5m	2m	2.5m
0°	93%	93%	93%	93%	93%	93%	93%
15°	100%	80%	97%	98%	99%	99%	99%
30°	100%	68%	91%	96%	97%	98%	98%
45°	94%	50%	76%	87%	89%	90%	91%
60°	83%	33%	59%	72%	76%	78%	79%
75°	68%	12%	39%	53%	59%	62%	63%
90°	50%	x	21%	40%	40%	43%	45%

Comparing the results of Lund and Miami, it is visible that the effect of mutual shading is less in Miami than in Lund. Mostly, this is due to the difference in solar altitude at the two places; in Lund, the altitude of the sun ranges from 11° (Jan) to 58° (July), in Miami, the altitude of the sun ranges from 41° (Jan) to 87° (July). Furthermore, it might also be that the ratio between direct and diffuse radiation is having an impact on the results, although Table 4 shows that only in winter months there is a significant difference in the two places.

Table 4. Diffuse / Global radiation values for Lund and Miami [11, 12]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Miami	0.41	0.40	0.42	0.41	0.47	0.54	0.52	0.52	0.52	0.48	0.45	0.42	0.47
Lund	0.73	0.69	0.52	0.43	0.45	0.46	0.52	0.50	0.52	0.58	0.68	0.78	0.50

3.3 The rooftop

3.3.1 Energy output

The simulations described in section 3.1 and 3.2 have provided important information when designing a system, especially for the parameters *inclination* and *row distance*. On their turn, these parameters affect the amount of rows which fit on a roof surface.

The output of the whole system was calculated by: output of 1 unshaded row + output of *n* shaded rows (n is dependent on how many row fit on the rooftop). Table 1 shows an overview of the total area of the system at different parameters. The output of the whole system is shown Table 5, with the highest output highlighted (highest output of the system = 1).

Table 5. Relative output of the whole system:

Lund	0	0.5	1	1.5	2	2.5
0°	**1.00**	0.67	0.50	0.40	0.34	0.29
15°	0.83	0.71	0.55	0.45	0.37	0.32
30°	0.80	**0.72**	**0.58**	0.46	0.39	**0.34**
45°	0.71	0.70	**0.58**	**0.47**	**0.40**	**0.34**
60°	0.62	0.65	0.56	0.46	0.38	**0.34**
75°	0.41	0.59	0.52	0.43	0.36	0.31
90°	x	0.50	0.45	0.37	0.31	0.26

Miami	0	0.5	1	1.5	2	2.5
0°	**1.00**	0.67	0.50	0.40	0.34	0.29
15°	0.88	0.70	0.53	**0.43**	**0.36**	**0.31**
30°	0.84	**0.71**	**0.55**	**0.43**	**0.36**	**0.31**
45°	0.76	0.68	0.54	**0.43**	**0.36**	0.30
60°	0.71	0.63	0.51	0.41	0.33	0.29
75°	0.48	0.56	0.45	0.36	0.29	0.25
90°	x	0.45	0.43	0.29	0.23	0.19

In both Lund and Miami, it is most favourable to place the PV modules with a 0° inclination, 0 metres row distance. Even though a 0° inclination decreases the yearly output with 15% (Lund) and 7% (Miami) compared to the optimal inclination, the fact that rows do not get shaded (i.e the effect of mutual shading is 0) play a very beneficial role. When row distances gets bigger, it can be noticed that the most favourable inclination is the optimal inclination in both cases (30-45° in Lund, 30° in Miami). When running solar irradiation analyses on city level, the solar potential of flat roofs is often calculated by multiplying the surface area with the irradiation level of this area. This is however only partly right; it is only valid when the row distance could be 0. With a row distance of 0.5, the total output of the system decreased by (28% in Lund and 30% in Miami in comparison to 0° inclination, 0 metres row distance).

The energy output of large PV systems is not the only important aspect to evaluate; investors are interested in both the investment costs and payback times. As can be seen in Table 4 and Table 1, configurations with a short row distance (or 0) return more kWh but require more module area (and thus higher investment costs). A calculation of the payback time will take both aspects –value for the produced energy and investment costs- into account. A system design with a short payback time often does not lead to a setup where the maximum energy output of the system can be reached.

3.3.2 Costs and revenues of the system

Costs of PV system depend on the application (residential, commercial, and utility) and on the system size. Figure 5 shows the prices of installed PV system [13]. The economy-of-scale effect is clearly visible (all four lines are a logarithmic function). In this study, the costs of PV system was calculated by taking into account the size of the system, as well as well as its application (commercial).

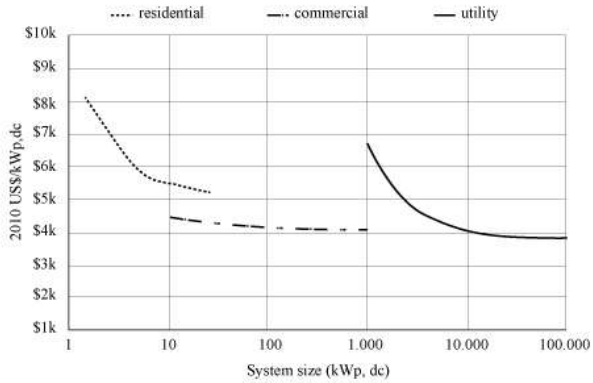

Figure 5. Residential, commercial, and utility scale PV system prices (installed) [13]

A large scale PV system is most likely to feed-in its electricity output to the grid. Medium-scale systems, for instance on apartment blocks, are most likely to feed-in partly to the building, partly to the grid. An overview of some of the electricity prices in Europe (highest in Denmark, lowest in Estonia) and USA [14] (Table 6) is needed to calculate the annual revenues and the payback time. By using annual net-metering (a system that allows customers with PV systems to reduce their electric bills by offsetting their consumption with PV generation, independent of the timing of the generation relative to consumption [15]), it is easy to quantify the amount of saved energy in money. In the case of selling all electricity to the grid, an overview of current feed-in tariffs is provided in Table 6 [16].Note that it was assumed that no interest had to be paid on the investment costs of the system.

Table 6. Electricity prices in Europe and USA (left), Feed-in-tariffs (right) (Euro / kWh) [14, 16]

Country	Euro per kWh Electricity
Estonia	0.10
United States	0.10
Sweden	0.20
Denmark	0.30

Country	Feed-in-tariff per kWh
Austria	5 kW-20 kW = €0.39
	>20kW = €0.3388
Denmark	€0.0831 /kWh
Germany	0-10kWp = €0.20
	10-40kWp = €0.19

To find the optimal design for a PV system in Lund, Table 7 provides an overview of the payback times of the rooftop system with different parameters.

Table 7. Payback times of system in Lund

Payback time (yrs) by price 1 kWh=0.2 Euro

Lund	0m	0.5m	1m	1.5m	2m	2.5m
0°	16	16	16	16	16	16
15°	20	15	15	15	15	15
30°	23	16	15	15	**14**	**14**
45°	31	19	16	15	15	15
60°	50	24	19	18	17	16
75°	144	35	24	21	20	19
90°	x	63	35	29	26	25

Payback time (yrs) by price 1 kWh=0.5 Euro

Lund	0m	0.5m	1m	1.5m	2m	2.5m
0°	6	6	6	6	6	6
15°	8	6	6	6	6	6
30°	9	6	6	6	6	6
45°	12	8	7	6	6	6
60°	20	10	8	7	7	7
75°	57	14	10	9	8	8
90°	x	25	14	12	10	10

When the electricity prices are at their current level in Lund (1 kWh = 0.2 Euro), the shortest payback time can be reached by putting rows at a distance bigger than 2 metres, inclination 30° . If the electricity price and / or feed-in tariff would get higher (1 kWh = 0.5 Euro), then multiple options are providing the same results.

Because of its higher irradiation levels, Miami will be more favourable for installing PV systems than Lund. Table 8 shows the payback times of a system with different parameters in Miami. Both with the current electricity price as well as with a higher price, it is most favourable to put the PV modules with a 15° inclination at a distance of at least 0.5 metre from each other.

Table 8. Payback time of system in Miami

Payback time (yrs) by price 1 kWh=0.1 Euro

Miami	0m	0.5m	1m	1.5m	2m	2.5m
0°	18	18	18	18	18	18
15°	21	17	17	17	17	17
30°	24	18	18	18	18	18
45°	33	22	19	19	19	19
60°	50	28	23	22	22	22
75°	138	42	32	29	28	27
90°	x	78	41	42	39	38

Payback time (yrs) by price 1 kWh=0.5 Euro

Miami	0m	0.5m	1m	1.5m	2m	2.5m
0°	4	4	4	4	4	4
15°	4	3	3	3	3	3
30°	5	4	4	4	4	4
45°	7	4	4	4	4	4
60°	10	6	5	4	4	4
75°	28	8	6	6	6	5
90°	x	16	8	8	8	8

4. Discussion

When designing a solar system, the effects of mutual shading are not negligible. The issue however is that by increasing the row distance the effect of mutual shading is decreased and thus the production will increase, but it will also limit the number of rows that can be installed on a roof top. This leads to the question: what is more important; a short payback time or as much output as possible (or a balance between those two)? Electricity prices tend to increase over years; Table 7 and 8 show that when electricity prices go up, inclination and row distance become less important. In that sense, there is no longer a need to make a choice: those setups of the system that deliver a high output also have become feasible. Results also showed that it would be most favourable to install the PV modules horizontally and a row distance of 0 metres, but a row distance of 0 metres is quite hard to achieve in reality, since a certain space to install and maintain the panels needs to be accounted for.

A further development of this study is desirable. It would be useful to look at the monthly output of the whole system and to value the output differently for every month, since electricity prices in Sweden differ per month. Such a study might lead to a different setup (inclination and row distance) of the system. Furthermore, the development of a script in Grasshopper (the environment where Rhino is connected to DIVA-for-Rhino) might be useful to determine the best inclination and row distance of a specific roof. This would make it easier for architects to make decisions during the design process.

5. Conclusion

This study examined the technical and economic consequences of mutual shading of PV systems. In the first part, a comparison is performed between an unshaded module and a shaded module with different row distances and inclinations. Results show that row distance smaller than 1metre significantly reduces the output of a module. Modules placed with a higher row distances produce still less output than unshaded ones, but are less affected by mutual shading (less than 10%). The effect of mutual shading was more significant in Lund than in Miami, mostly due to higher sun altitudes all year round.

In the second part of this study, the energy output as well as payback times of a PV system on a flat roof of 1m*100m were simulated. Results have shown that the solar potential of a flat roof cannot simply be calculated by multiplying the roof area with the irradiation level on that flat roof, but that a conversion factor also needs to be taken into the equation. This conversion factor (Table 5) is dependent on a) the inclination of the modules, b) the distance between the rows, and c) the location, and conversion factors range from 0.26-1. This conversion factor also implicitly takes into account the fact that a higher row distance increases the output of a single row, but decreases the amount of modules that can be placed on a roof. The most favourable configuration of the system is an inclination of 0° and a

row distance of 0 metres. On small roofs, it might be possible to work with a 0 metres row distance because all solar cells can be reached, on larger roofs, it might be needed to divide the roof in sections with a small row distance between the sections. Besides the energy output of a system, the payback time of the system on a flat roof was studied. The revenue of the produced electricity was calculated by either the amount of saved energy costs or the amount of money received for delivering electricity to the grid. With the current electricity prices in Europe and the US, shortest payback time are reached with a inclination of 15° in Miami and 30° in Lund. Increasing electricity throughout the years will however make it the parameters less sensitive, i.e. several set-up of the system (inclination and row distance) will return the same payback time. Making the right decisions concerning the inclination and row distances of big systems on flat roof are crucial and not always straightforward.

Acknowledgements

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Solar energy as a design parameter in urban planning

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Abstract

By the end of 2020, all EU member states need to ensure that all newly constructed buildings consume 'nearly zero' energy and that their energy needs are produced locally as much as possible and with renewable sources; a concept called nearly Zero Energy Buildings (ZEB). At the same time, more and more people live in cities, where the access to local renewable energy sources –wind and solar- is limited. Planning for such ZEBs in cities is therefore a difficult task since urban planners often do not have the technical knowledge to quantify the contribution of solar energy in their urban plans. This study shows an exploration of geometrical forms of urban blocks and the potential of solar energy to the local production of energy. Simulations were performed with the program Ecotect for the city of Lund in southern Sweden. It was found that the impact of the geometry form on the potential of solar energy was significant (up to twice as much) and some forms were found to be less sensitive for different orientations. When the urban blocks were surrounded by other geometry, which resembles the situation of a dense city, the contribution of solar energy decreased by 10-75%.

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Keywords: Solar energy; solar zoning; urban plannin; urban morphology; architecture; insolation; parametric study

1. Introduction

More and more people are living in cities and this development seems to continue in the future [1]. In Europe, cities are home to nearly 80% of the population, resulting in the production of 75% of all CO_2 emissions [2] . The urban scale has often been neglected in the debate of energy consumption and climate change [3-4], although data showed that savings in energy cost of 20-50% are possible through integrated planning by carefully considering site orientation and passive strategies [3]. An extensive utilisation of solar radiation in urban areas appears to be essential and a practicable strategy but has a big impact on the

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formation of cities in order to be fully effective [5-6]. Another challenge is that, in Europe by the end of 2020, all newly constructed buildings need to consume 'nearly zero energy' and that their needed energy needs to be produced locally as much as possible and with renewable sources [7]. This requirement might be hard to meet in dense cities, where access to local renewable energy sources is limited. In addition, often urban planners do not have the technical knowledge to quantify the potential of solar energy the design process.

Being able to understand the solar potential is also important for architects when designing buildings in urban environments. Integrating solar energy on the building level, with roofs and facades as the most logical places to harvest solar energy, needs to be carefully considered as it significantly affects the architecture. When the integration of active solar technologies is taken into account early in the design process, it is more likely to lead to more attractive solutions [8-10]. The early integration might be made easier when architects are aware of locations where most energy can be produced. The solar potential can also function as an important tool for real estate developers, who can directly see the amount of energy which can be produced on the building envelope.

In order to aid urban planners and architects in their design process, a broad set of guidelines needs to be developed. This parametric study may be the first step in that direction, as it analyses different types of urban blocks and their potential contribution to locally produced energy. By this, the study will attempt to quantify the role of solar energy as a renewable energy source in various urban morphologies.

2. Method

This parametric study consisted of a range of four urban blocks, each with a different design (A, B,C, D). In order to see the impact of density in urban plans, the Floor Space Index (FSI) / Plot Ratio of the urban blocks ranged from 1-5. Both the design options A,B,C,D and the FSI range can be seen in Figure 1.

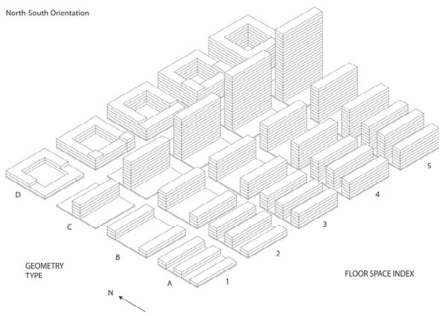


Fig. 1. Overview of geometry types in North-South orientation

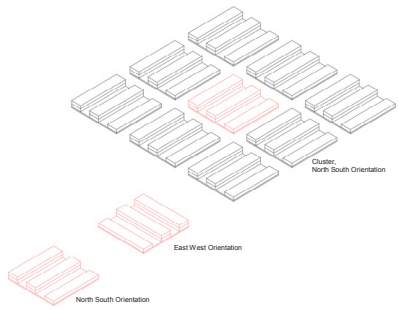


Fig. 2. Overview of changes of direction and environment

Besides changing the form and the density of the blocks, orientation and environment was also changed: first, blocks were simulated in North-South (NS) direction, then in East-West (EW) direction. In the third case, blocks were placed North-South direction within surrounding buildings with the same density (Cluster / CL) (Figure 2).

All geometry was drawn in 3D in AutoCAD and imported into the Building Performance Simulation tool Ecotect [11] with all floors 10 metres wide and 3 metres high. Ecotect 2011 was chosen as the main simulation tool, since it enables the user to export a large amount of data to Excel, and the visual user interface was experienced to be easy to use. Another reason to use Ecotect was the fact that it is used extensively by the industry [12-13]. However, the authors were aware of the lack of transparency of Ecotect's calculation methods and reported possibility of errors as mentioned by Ibara and Reinhart [13], where the Building Performance Simulation tools Ecotect and DIVA with measured data were compared. DIVA is a Radiance-based simulation program which works which the CAAD program Rhinoceros. In this parametric study, a comparison between DIVA and Ecotect was performed to see how much the values differed by using the two different calculation methods.

In Ecotect, a solar access analysis was run using 'medium' settings, looking at the incident solar radiation over a whole year on the building envelope of the urban block, for the location of Lund, Sweden (N55.705, E13.191). Then, within Ecotect, surfaces with an annual solar radiation above 650 kWh/m2/year were identified and selected. This value was chosen because they can produce around 100 kWh/m2/year with a 15% efficient PV cell; for Solar Thermal it would roughly mean a production of 250 kWh/m2/year. Furthermore, the solar panel area was considered to be 75% of the facade area, leaving 25% for fenestration. The value of 25% for fenestration is realistic since too much fenestration can lead to visual problems and overheating [14]. The same ratio was chosen for the roof, since a certain portion of the roof surface is needed for maintenance of the building and building service installations. In this study, the solar panels were considered to be PV cells, but a similar method can be used for Solar Thermal. The electricity use of the buildings was considered to be 50 kWh/m2/year. Out of that, 30 kWh/m2/year is taken as an indication for the average household electricity used annually in Sweden. The remaining 20 kWh/m2/year was assumed to cover the shared energy use, like for the whole-building ventilation system, etc. The electricity coverage was calculated by dividing the annual solar produced electricity in a building by the annual electricity demand in the building. The incident solar radiation was simulated annually, meaning that the problem of seasonal imbalance between energy production and need was not taking into account here. The production and need for domestic hot water (DHW) was also not considered in this research.

3. Results

3.1.Comparison Ecotect and DIVA.

First, a comparison was made between the simulation programs Ecotect 2011 and DIVA-for-Rhino 2.0 [15], similar to a study performed by Ibara and Reinhart [13]. This comparison was done to test how both simulation programs perform and how the output of the program is facilitated. Two models were tested for the annual solar insolation; one block North-South orientated, FSI=5, and design C (Figure 1), the other block was North-South orientated, FSI=5, and design A. The results are shown in Table 1.

Table 1. Difference in reference point on surfaces (values in kWh/m^2/year)

North – South orientation, FSI = 5, design option = C (E=Ecotect, D=DIVA, Diff.= Absolute value difference Ecotect-DIVA / relative difference)

South			North			East			West			Roof		
E	D	Diff.	E	D	Diff.	E	D	Diff.	E	D	Diff	E	D	Diff.
670	780	**-110 / 16,4%**	293	221	**+72 / 24,5%**	487	482	**+5 / 1%**	453	500	**-47 / 10,4%**	985	976	**+9 / 0,9%**

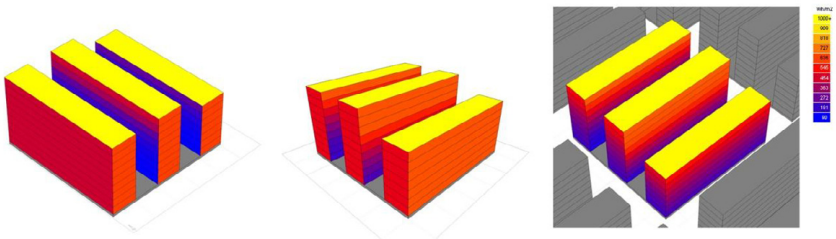
North-South orientation, FSI = 5, design option = A

South			North			East			West			Roof		
E	D	Diff.	E	D	Diff.	E	D	Diff.	E	D	Diff	E	D	Diff.
669	741	**-72 / 10,8%**	292	220	**+72 / 24,7%**	487	482	**+5 / 1,0%**	453	500	**-47 / 10,4%**	967	970	**-3 / 0,3%**
604	571	**+33 / 5,5%**	220	244	**-24 / 10,9%**									
512	354	**+158 / 30,9%**	192	189	**+3 / 1,6%**									
247	183	**+64 / 25,9%**	138	105	**+33 / 23,9%**									

Results show that the simulations done in both Ecotect and DIVA differ significantly for mostly the South and North, with relative differences of ~10-30%. Surfaces directed towards East and horizontal surfaces had the lowest differences. These differences are due to the difference in calculation methods in the two programs.

3.2. Results of the simulations

In this section the simulation results of the building blocks are presented. Figure 3 presents the visual results of some of the simulations in Ecotect for some of the building blocks.



NS5A EW5A NSCL5A

Fig. 3. Graphical output of annual solar insolation in Ecotect

The solar performance of the blocks are divided into two parts: a) The PV potential –the percentage of building envelope which receives an amount of solar radiation greater than or equal to a preset threshold [16]- and b) the electricity coverage –the annual solar produced electricity in a building divided by the annual electricity need, a unit which has been used in similar studies by Izquierdo et al., Wiginton et al., Jeppesen and Ordóñez et al. [17-20]. Figure 4 shows the PV potential of the different building blocks in different settings.

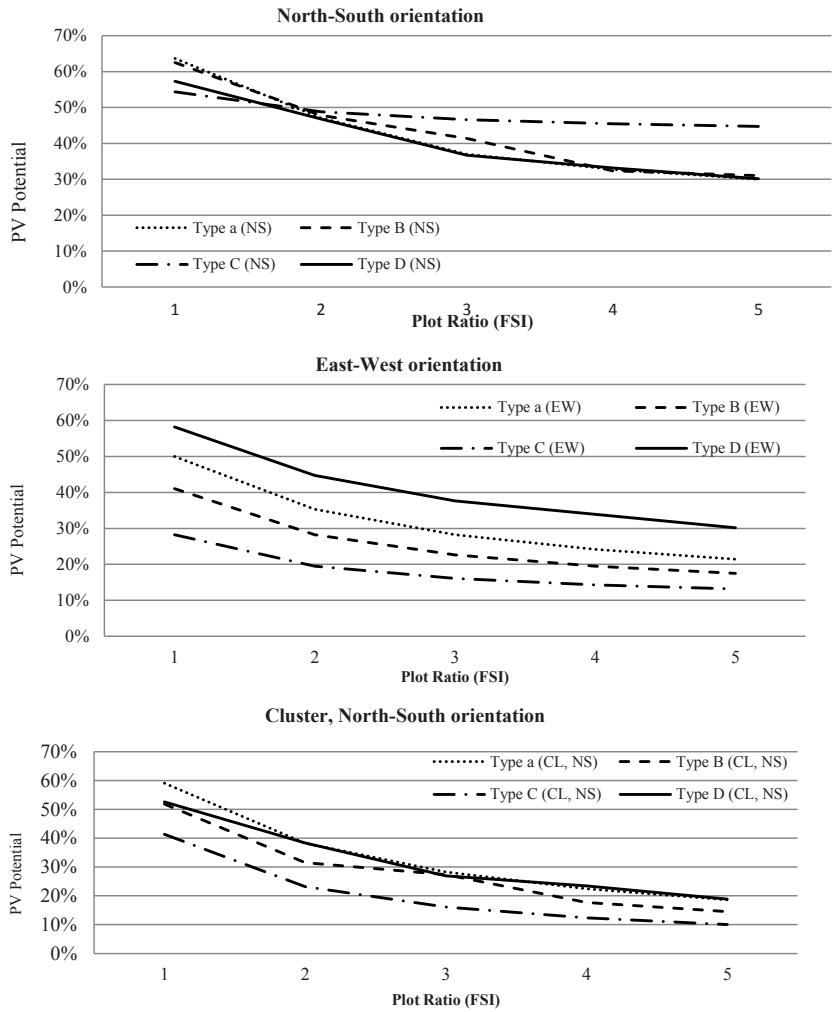


Fig. 4. PV potential of the blocks

Although the start values are not the same due to the design, it can be seen that, in general, the decline of the PV potential per case is the same, except for the Type C, in the NS orientation.

Type B in the cluster setup also shows different behaviour. Even in cases of a high FSI (5), still 30-45% of the facade receives more than the threshold annually in case of the NS orientation. In the case of the EW orientation and FSI=5, the PV potential is still 15-30%. This implies that a relative big part of the facade can be used to generate energy on the building, which will have its impact on the architecture. Furthermore, increasing the FSI from 1 to 5 in the EW orientation will decrease the PV potential by 50%. Increasing the FSI from 1 to 5 in the NS orientation will also decrease the potential by 50%, except for Type C. In the situation with surrounding geometry, the PV potential dropped by 70-75% when FSI increased from 1 to 5, a much higher decline compared to the two other cases without surrounding geometry.

The electricity coverage of the buildings blocks are displayed in Table 2.

Table 2. Annual Electricity Coverage of photovoltaic cells in the buildings (in %)

	Type A					Type B					Type C					Type D				
FSI	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
NS	169	93	65	54	46	134	81	63	47	43	90	68	60	57	54	149	85	59	48	43
EW	141	75	53	42	35	97	53	39	31	27	53	31	24	20	18	154	80	61	47	43
Cluster	159	79	53	40	32	115	57	44	29	23	71	36	24	18	14	139	73	47	36	30

When calculated annually, in 8 out of 60 cases (13%), the electricity need can be met with locally produced electricity with the preset assumptions. In order to become Net Zero Energy Buildings, heat and DHW will also need to be provided by local sources. In all other cases, the electricity demand cannot be met with the solar cells. The range of coverage is rather wide: the highest coverage is 169%, while the lowest coverage is 14%.

Results show that the impact of geometry on the solar potential was significant: Type C gave in most cases the worst coverage while Type A gave the best performance. Type D was relatively less sensitive for rotating from North-South to East-West direction. This was obviously due to the design of Type D, which has almost equally much surface area to East, West, North, and South. Interestingly, Type D outperformed Type B when it comes to electricity coverage.

When the urban blocks were surrounded by other geometry, the coverage decreased by 6% to 74% due to shading of the adjacent geometry. Figure 5 shows the influence of surroundings on the electricity coverage; in the graph, the difference between the NS model and the cluster model represents this influence. The graph shows that Type C is very sensitive when it is placed in a dense built environment, especially with a high density. Type B is the second most sensitive design, while Type A and D show almost the same increase when placed in a dense built environment.

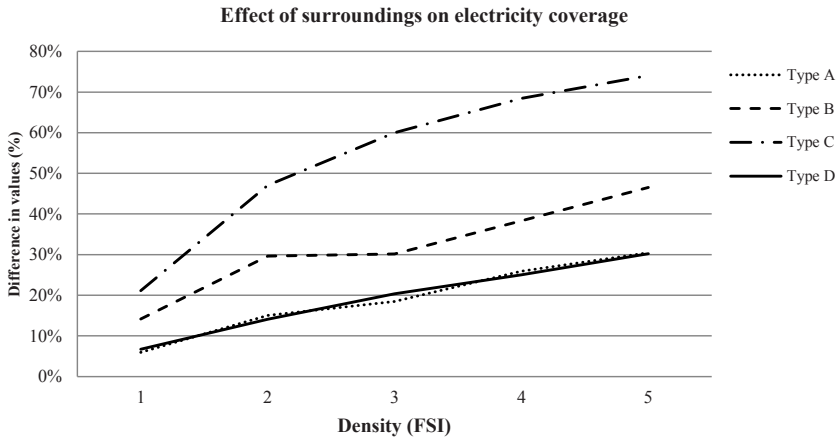


Fig 5. Effects of surroundings on electricity coverage of the simulated models

3.3. Implementation and future work

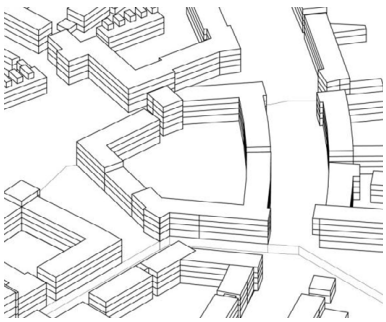
This parametric study represents a start of the development of a working method which ultimate goal is to implement solar energy into the daily practice of urban planners and architects. The next step was to understand how this could fit into the current design practice of urban planners. In order to do so meetings were set up between the authors and the planning departments of the cities Malmoe and Lund, located in the south of Sweden. Both cities expressed a will to implement more solar energy into future buildings planned to be built in the near future. The cities provided all proposals' documentation and 3D digital models for the newly planned urban districts.

The used method in the cases of both cities Malmoe and Lund can be seen in Figure 6. The building blocks were simulated in Ecotect directly to get numerical results. In order to get a better integration in the daily workflow of designers, the graphical output of the annual solar radiation analysis was performed by connecting the CAAD program Rhinoceros through the GECO plug-in to Ecotect[21]. The method consists of five steps: 1) a design alternative is developed and drawn in 3D, 2) the annual solar insolation is simulated, 3a and 3b) by setting a certain threshold (in this case 650 kWh/m2/year), a certain part of the building envelope is selected as the most appropriate for harvesting solar. This is both visualised graphically and numerically. Step 4 is the evaluating phase: does the design alternative live up to the expectations? If not, than another design alternative is performed and will go through step 1-3, otherwise the process goes on to step 5. In step 5, both the graphical and numerical output of the solar potential is given to the architects who will design the building in detail. It is important that this is the knowledge transfer is done properly so that this information is not lost in later design phases. In such a way, design alternatives can be compared with each other for their solar potential and performance.

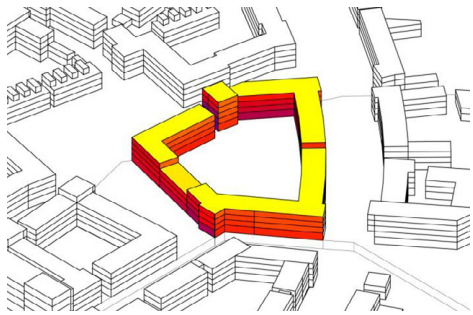
However, certain issues need to be addressed first so the method can become more versatile:

Solar Thermal needs to be implemented in the method. This is a rather simple adaptation of the calculation method. By doing so, the tool can take into account both DHW / heat, and electricity.

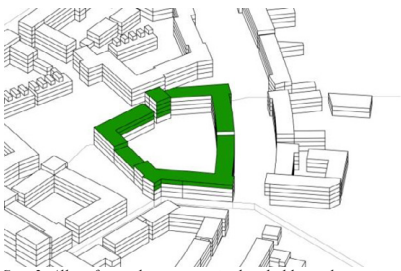
- Giving an overview of the costs and benefits of implementing active solar harvesting would provide an extra factor to take decisions upon.
- The threshold value should be discussed. With the threshold of 650 kWh/m^2/year as it is taken now, parts of the facades and roofs were selected. If the threshold was instead set much higher, only roof areas would be valid for placing PV cells.

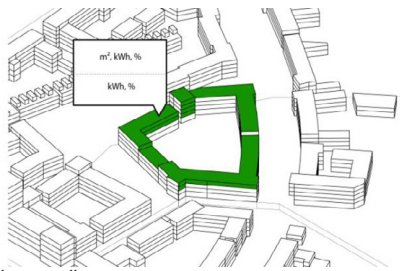


Step 1. Design alternative is developed, building is available in 3D.

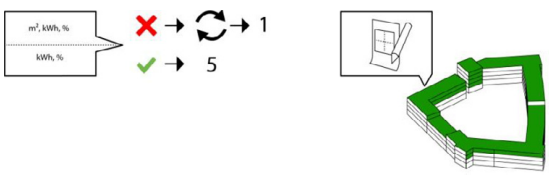


Step 2. A simulation is run for the annual solar insolation





Step 3. All surfaces above a certain threshold are shown visually and numerically



Step 4 and 5. If the design alternative performed as planned, information is given to the architects. Otherwise, back to step 1.

Fig. 6. Visualisation of a possible working method for urban planning

4. Conclusions

The results of the simulations done in this study show that taking solar energy into account when designing new urban district can provide a significant contribution to the local production of renewable energy. Also, solar zoning [22] can contribute to solar access for solar energy in denser cities.

Certain designs of building blocks performed better than others in the simulations, especially when the blocks were surrounded by a dense built environment. When the plot ratio / FSI was 1, almost all design options were able to meet the energy need with energy produced by solar energy. When the FSI was increased, building blocks were not able to meet all the energy need with locally produced energy. In one case, the solar potential decreased by 75% when it was placed in dense built environment, which meant that the electricity coverage of this design was very low.

Urban planning is a process in which many factors play a role. Solar energy is just one of these components which urban planners have to take into account. Urban planners should be informed about the consequences of building blocks' layout on the solar potential. In an ideal situation, one actor in the design process should perform the simulations and calculations regarding the solar potential as described in this article. This actor could be an external consultant, an urban planner or an architect. The further in the design process, the more detailed the solar potential analysis can be done. Important issues in these analysis are: the production of the active solar systems (kWh), the production over the year, the ratio between PV and ST, architectural integration issues (colour, texture, dimensions) etc.

It is also important that real estate developers are well-informed about the latest technology and prices, since they are a very important factor in the decision process. In the two cities of Lund and Malmoe, the urban planning department has set up meetings with real estate developers to talk about sustainability issues, of which solar energy is an important contributor.

In general, the production of electricity did not meet the electricity need. In this study, only the electricity need was taken into account, not the heat / DHW need. If those two components will be taken into account, the question whether to produce heat or electricity on which places in the building will become very actual. Furthermore, the fact that the annual solar energy production is not able to meet the energy need of buildings in cities leads to the issue if it is right to force future all buildings to generate all their energy locally within cities. Another conflict of using the whole roof is the competition with the green roofs.

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Typical values for active solar energy in urban planning

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Abstract

There is an urgent need to start generating energy within cities in order to pave the way for a more sustainable and resilient society. Renewable energy by means of active solar energy systems (solar thermal, ST and/or photovoltaics, PV) can be generated using roofs and facades of buildings. In this study, the annual solar energy potential of typical Swedish city blocks was analysed in order to develop guidelines for urban planners and architects. The results show that the design of the city blocks has a significant effect (up to 50%) on the total annual solar energy production. The study also shows that the contribution from active solar energy can be significant even in the urban environment, but shading by adjacent buildings may greatly limit the total amount of energy produced.

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Keywords: urban planning; solar energy; simulations; solar architecture; density; orientation; urban design

1. Introduction

Cities are home to more than half of the world population [1] and consume the majority of global energy [2] and resources. Future cities will be faced with the necessity to reduce their energy demand significantly while shifting to local urban energy production systems. Political instruments, such as the energy performance of buildings directive (EPBD) [3], are already in place to prepare for net zero-energy buildings, and eventually, net zero-energy communities and cities in the European Union. An increased use of active solar energy as well as an awareness of the passive use of solar energy -by solar gains and daylight- is needed to reach sustainable solutions. Smart planning of new urban districts will help cities to reach their goals of energy reduction and energy production; in such a way that urban districts could become more self-reliant [4].

The urban design process is a complex one with a range of stakeholders taking various decisions at each stage of the process. Solar energy is just one of the many parameters affecting this process [5], but paradoxically, the energy

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yield of solar systems is very dependent on design decisions made in the early stages of the design process. Besides the design of the cityscape, other key issues to accelerate the implementation of solar energy in the urban environment are: legal framework, processes, methods and tools, good examples, and further education [6].

Architects and urban planners are amongst the actors shaping new urban districts and by making right and informed decisions, future buildings can be both energy efficient and energy self-reliant. Building Performance Simulation (BPS) tools can support the decision-making process regarding solar energy [7-11] as will be demonstrated in this study.

1.1. Density

The layout and density of urban districts are two of the most important parameters to consider in the early design phase. The density of the urban fabric is expressed by the Floor Space Index (FSI), Plot Ratio or Floor Area Ratio (called FSI in the rest of this article). Formerly defined, the FSI is the ratio of a building's total floor area in relation to the size of the plot on which it is built, see Figure 1. A plot with no buildings on it has a FSI of 0. Building the same amount of floor area as the plot area results in a FSI of 1; two floor slabs covering the entire plot results in FSI=2 etc. The same FSI can thus be reached by adjusting the ground floor area and the amount of floors in a building, as shown in Figure 1. Also, a site with a large unoccupied space and a high FSI will results in tall buildings. Table 1 shows the FSI of different cities. Note that in some cases, the maximum allowed FSI is per plot, and that the FSI is only per building plot, not including streets, which explains why some cities are known to be very spread (like e.g. San Francisco compared to Amsterdam or Paris). Note that is difficult to provide an overview of FSI of cities in the world due to differences in calculation methods.

Table 1. Overview of FSI in different cities [12]

City	Floor Space Index	City	Floor Space Index
New York	10-15 (centre)	San Francisco	9 (maximum)
Central Amsterdam	2	Hong Kong	12
Paris	3	Los Angeles	13 (centre)
Bangkok	8 (maximum in centre)	Singapore	2.8 (maximum)

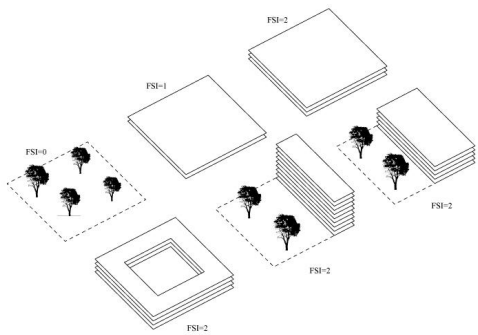

Figure 1. Principle of Floor Space Index (FSI).

1.2. Solar energy potential

Every building has a solar energy potential, which is the amount of energy that can be produced using building surfaces covered with photovoltaics (PV) or solar thermal (ST) systems. In this research, a parametric study was carried out, based on typical layouts and densities of Swedish urban city blocks in order to investigate the effect of the urban layout and density on the solar energy potential. The results of this analysis will provide guidelines for urban planners when designing new urban districts.

2. Method

Four typical Swedish city blocks designs were modelled based on city blocks in the Southern cities of Malmö and Lund (Figure 2); two of them based on existing city blocks (Rörsjöstaden and Norra Fäladen), and two of them based on planned city blocks (Hyllie and Brunnshög). As can be seen in Figure 2, the three designs Rörsjöstaden, Hyllie and Brunnshög are relatively similar and generally present a rectangular "donut" shape. Note however that Hyllie is more square than Rörsjöstaden and Brunnshög. In Rörsjöstaden, the buildings have a pitched roof while all other designs have a flat roof. In Norra Fäladen, the buildings are scattered differently on the plot.

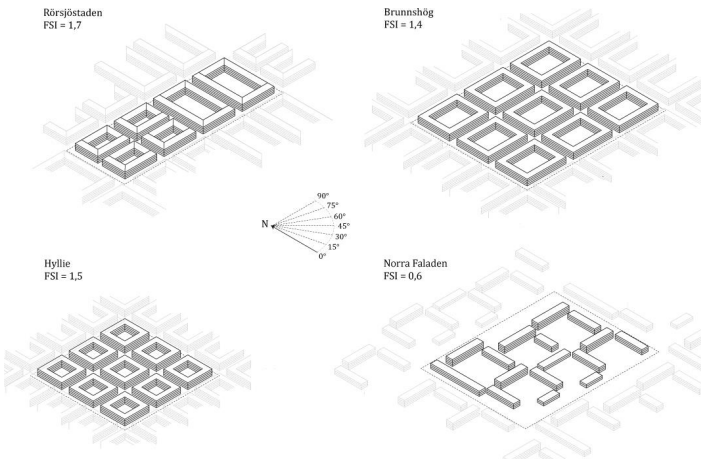

Figure 2.The four simulated city blocks and their actual FSI.

In addition to studying the impact of urban design layout on solar energy production, this study analysed the effect of 'rotation' and 'density' of the city block on annual solar energy production. The rotation of the city blocks varied from 0° to 90° counter clockwise (with 15° increments) with respect to South (Figure 2). The density ranged from 0.5 to 2.5 FSI. The four modelled city blocks had an existing density (as displayed in Figure 2), but for the present study, the FSI was virtually altered by adding or deleting floors in the 3D models (Figure 3). Important to notice is that the city blocks are modelled with equally dense adjacent city blocks, streets and courtyards similar to the real world situation.

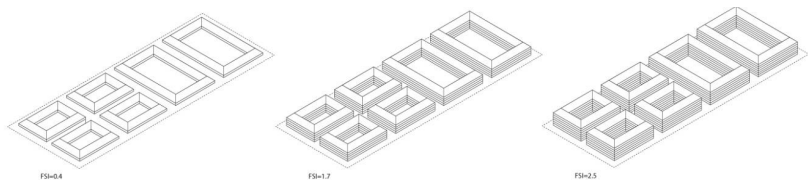

Figure 3. Alternation of density (FSI) of Rörsjöstaden

The four city blocks were modelled in Rhinoceros [13] with the help of information from the urban planning departments of Lund and Malmö. The annual solar irradiation analysis was performed in DIVA-for-Rhino (D4R), a Radiance based program [14] embedded in the CAAD program Rhinoceros using the GenCumulativeSky [15] model for solar radiation. Settings for these simulations were as presented in Table 2. Many of these parameters are default values in the DIVA-for-Rhino program and will be used in the Radiance engine for performing the simulation. The ambient bounces setting – the maximum number of different bounces computed by the indirect calculation- was however altered to increase the accuracy. The reflectance value was set to resemble the reflectance of surfaces, roofs, and ground.

Table 2. Settings of DIVA-for-Rhino

Parameter	Setting	Parameter	Setting
Ambient bounces	5	Start date	01 01
Ambient divisions	1000	End date	12 31
Ambient super-samples	20	Hour range	00 24
Ambient resolution	300	Geometric density	100
Ambient accuracy	0.1	Reflectance of facades and roof	35%
Weather data	Lund (Meteonorm)	Reflectance of ground plane	20%

The next step consisted of comparing the total annual solar irradiation with the energy demand of the buildings. The surfaces on the roof and façade which received an annual solar irradiation superior to 650 kWh/m²a were considered suitable, which is justified in an earlier study [16]. This threshold is dependent on many parameters; a study by Compagnon [10] suggested a value of 800 kWh/m²a for PV, but in this case 650 kWh/m²a was selected to achieve a shorter payback time than the life time of the system in the Swedish context.

Furthermore, the suitable area was considered to be split into photovoltaic (PV) systems (80% of the surface, 20% efficiency) and solar thermal (ST) systems (20% of the surface, 40% efficiency). Solar thermal and PV systems behave differently if they get shaded: if ST systems get shaded partly, in most cases, the output will decrease accordingly. For PV systems however, the output drops more than proportionally. In this case, the difference in behaviour between the two different technologies was omitted. Windows, lift shafts, and other installations were considered to cover 25% of the suitable area. The electricity need of the buildings was considered to be 50 kWh/m²a, consisting of 20 kWh/m²a for common electricity use [17] and 30 kWh/m²a for household electricity [18]. The space heating demand was set at 20 kWh/m²a, which can be reached in Sweden with a very low energy design [19]. Taking these assumptions into consideration, the heating coverage (amount of heat produced / heat demand) and the electricity coverage (amount of electricity produced / electricity demand) was calculated.

Two hypotheses were tested: 1) the Norra Fäladen design will perform poorly compared to the other designs due to self shading and 2) the Rörsjöstaden will perform better than the Brunnshög design due to its pitched roofs.

3. Results

The computer tool D4R can provide both graphic and numerical results. In section 3.1., graphical results are presented while section 3.2. provides numerical results.

3.1. Graphical results

The direct embedding of D4R into the CAAD program Rhinoceros is advantagous since it does not require extra translations or additional programs to show results and it is possible to analyse the results interactively, i.e. the user is able to use the results in various ways. One way is simply to show the annual solar radiation on the analysed geometry (Figure 4, top).

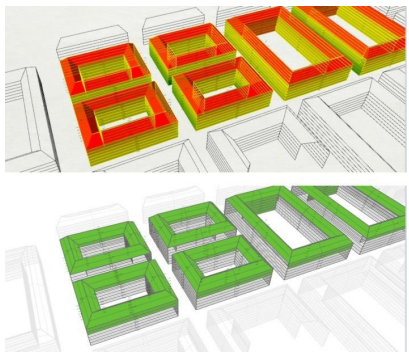

Figure 4. Interactive use of results

Another way to display the results is by using a filter. An example of such a filter is shown in Figure 4 (bottom), where the green surfaces represent surfaces that receive an annual solar irradiation superior to 650 kWh/m²a. By applying such a filter, architects and urban planners get direct feedback about the most valuable surfaces for the design.

3.2. Numerical results

In this section, the focus is on the annual electricity coverage, followed by the annual heating coverage, and the annual energy coverage. Figure 5 shows the annual electricity coverage of the four building blocks. A 100% coverage means that the annual electricity produced by PV equals the annual electricity use.

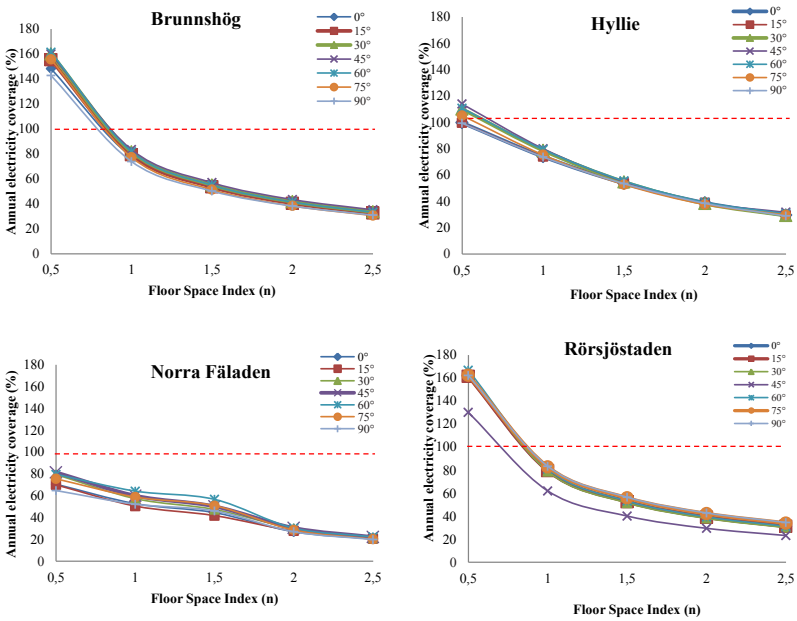

Figure 5: Annual electricity coverage at different densities

The four graphs in Figure 5 show that there is a significant difference in annual electricity coverage due to the layout of the city blocks, especially for the lowest densities. In general, it can be seen that for the higher densities (>1.5), the absolute differences between the different layouts are less significant. The reason for this can be explained by the decreasing suitable area (roof area plus suitable facade) per floor area. At lower densities, the amount of suitable area is relatively high compared to the floor area, while at higher densities, this ratio decreases. The patterns of Brunnshög and Rörsjöstaden are almost identical, also at lower densities. Hyllie does not follow the same pattern as Brunnshög, although their geometry is quite identical (Brunnshög is a bit more rectangular). The irregular pattern in the results obtained for Norra Fäladen is most likely caused by its special “scattered” geometry increasing the impact of self shading.

Furthermore, the rotation of the building blocks did not have as much impact in the Brunnshög, Hyllie and Rörsjöstaden layouts as expected, except for the Rörsjöstaden 45° rotation, which provided less energy covering for all densities. This is due to the fact that, at exactly 45°, a big part of the roof received slightly less than the threshold due to shading at the place where the two sloped roof surfaces meet.

The results also show that rotation has a larger impact in the Norra Fäladen layout compared to the other layouts. Note, in addition, that differences between orientations also became less significant at higher densities.

Figure 6 shows the heating coverage of the building blocks.This figure shows similar patterns as in Figure 5, which was expected since the only difference lies in another efficiency of the solar technology and energy demand. The only difference is thus found in the absolute values.

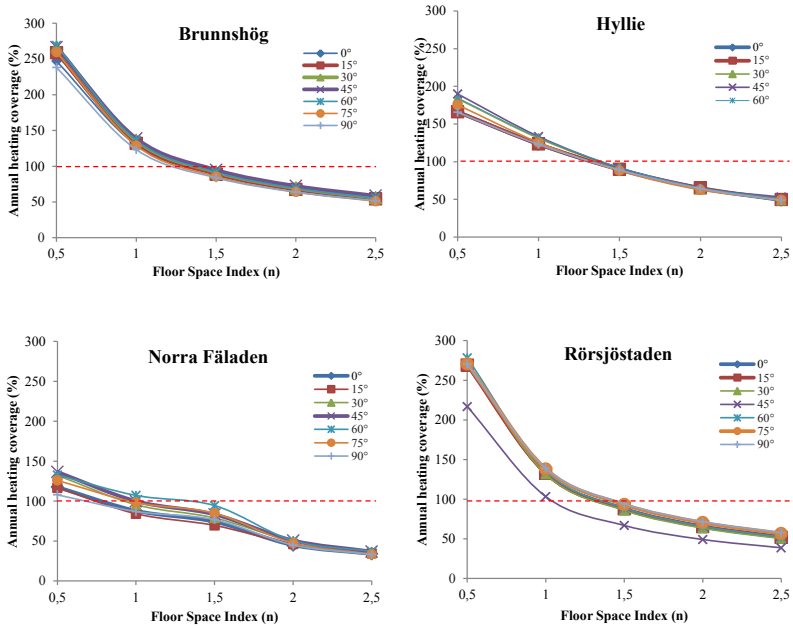

Figure 6: Annual heating coverage at different densities

The annual energy coverage can be calculated for the different building blocks by summarising the produced electrcity and heat, divided by the total energy need of the building blocks. Summarising heat and electricity is often done by taking conversion factors into account, but for the sake of simplification, this is not done in this study. Figure 7 shows the annual energy coverage, in which the average of all rotations is calculated per layout.

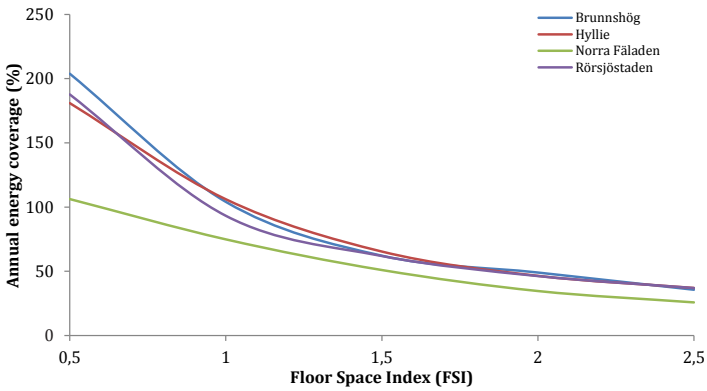

Figure 7. Annual energy coverage

It becomes clear that Brunnshög, Rörsjöstaden, and Fäladen have almost identical values and patterns. The pattern which clearly stands out is the one of Norra Fäladen. Table 3 shows the normalised energy coverage of all building blocks per FSI (0.5; 1; 1,5; 2; 2,5) (the maximum energy coverage per FSI is underlined) and emphasises the differences between the different layouts, orientations and densities.

Table 3. Annual energy coverage per city block (%)

FSI	Brunnshög	Hyllie	Norra Fäladen	Rörsjöstaden
0.5	**1.00**	0.89	0.52	0.92
1	0.98	**1.00**	0.71	0.88
1.5	0.95	**1.00**	0.78	0.95
2	**1.00**	0.95	0.71	0.94
2.5	0.96	**1.00**	0.70	0.99

Table 3 shows that the maximum energy coverage for FSI=0.5 is for the Brunnshög design. For FSI=1 and 1.5, it is the Hyllie design, for FSI=2, it is the Brunnshög design, and for FSI=2, it is the Hyllie design. The differences between the Brunnshög, Rörsjöstaden, and Norra Faladen design were minimal especially for the higher densities, often within a range of 10%. The biggest differences were seen at the Norra Fäladen design, differing at a maximum of 48% for FSI=0.5, similar to the heating coverage and electricity coverage as shown in Figure 5 and 6.

4. Discussion and conclusions

A parametric study was carried out to evaluate the solar energy potential of four common designs of city blocks in Sweden. In addition to design layout, the evaluated parameters were density and rotation. Surfaces on the building envelope -roof and facade- were considered to be suitable when they received more than 650 kWh/m²a. The solar energy potential of the city blocks was simulated with DIVA-for-Rhino and was expressed as the energy coverage, i.e. the energy produced by solar energy divided by the amount of energy used in the building blocks. Two hypotheses were stated at the beginning of the study: 1) the Norra Fäladen design will perform poorly compared with the other designs and 2) the Rörsjöstaden will perform better than the Brunnshög design due to its pitched roofs.

The first hypothesis was confirmed. In none of the cases did the Norra Fäladen design return the highest energy coverage. This configuration also proved to be more unpredictable than the others, i.e. the energy coverage varied in a "chaotic" way for different densities and rotations. The design of the Norra Fäladen design consisted of various scattered building blocks, resulting in strong mutual shading effects.

The second hypothesis was infirmed. The building blocks with a pitched roof did in most cases not return much higher energy coverage, as expected. The Rörsjöstaden design was comparable to the Brunnshög and Hyllie design, which basically had the same design but with flat roofs. The design of a roof solar system should obviously be kept in mind; a flat roof can have a high potential, but the setup of the system –number of rows, row distance, and inclination- also plays a crucial role in converting these flat roofs into energy producing surfaces. In the present study, the collectors were assumed to lay flat on the roof (no inclination resulting in no mutual shading, no row distance).

Furthermore, results show that 100% coverage or higher with solar energy can be achieved only for low densities (FSI<1.25) for the studied conditions in Sweden. This study thus confirms the fact that a significant contribution could come from active solar energy but that solar energy systems need to be supplemented by rigorous energy conservation measures and other renewable energy sources like wind, geothermal energy, waste heat, etc.

One great limitation of this study concerns the issue of annual versus monthly or hourly production and coverage by means of solar energy. A further study into the monthly and even hourly coverage would be very useful, since the amount of solar energy fluctuates significantly during the year and day in Sweden.

Another limitation is to ignore the difference in behaviour between solar thermal and PV systems. Also, the assumption to have 80% PV and 20% ST has a big impact on all the absolute values in this study, however, the patterns and relative differences between the designs would be the same.

Overall, this study shows that quantifying the solar energy potential of city blocks in an early design stage and providing a visualisation and quantification of the solar energy potential facilitates the comparison of design alternatives leading to a successful design. In the urban design process, it would be beneficial if this information is passed on to the architects of these buildings. Also, these solar potential studies can provide an underlying document for real estate owners who want to perform a cost and benefit analysis.

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The solar map as a knowledge base for solar energy use

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Abstract

Our existing urban environment has a significant potential to increase the use of renewable energy, mainly by using solar irradiation for heat and electricity. Quantification of the solar potential by means of a solar map is the first step in the acceleration process for using more solar energy in our urban environments. A solar map is a GIS system providing the annual solar irradiation on building surfaces, mostly accompanied by information of the output of solar thermal or photovoltaic systems. Many solar maps are already in place today; almost all of them are however using different approaches. In this paper, an analysis is done of current solar maps in order to see on which principles the solar maps were based upon.

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Keywords: Solar maps; solar cadastre; cities; tool; urban planning, solar resource assessment

1. Introduction

Cities, home to more than half of the earth's population, consume the majority of energy in the world [1]. In order to become more resilient for the future, cities need not only to reduce their energy need, but also start producing their own energy [2]. One way to generate renewable energy within our existing urban environment is by making use of solar energy. It is important to get a more detailed overview of the amount of energy we can produce with solar thermal (ST) or photovoltaics (PV) on existing buildings. One way to analyse the potential of the existing built environment is by means of solar maps [3-8]. A solar map or solar cadastre is a GIS system providing the annual solar irradiation on building surfaces (roofs and / or facades), mostly accompanied by the output of solar thermal or photovoltaic systems, and connected to a website. Many city administrations already have solar maps in place and they mainly serve two purposes: as a front-end platform to inform citizens about the potential of their own roof, and as a back-end tool for city administrations to base energy decisions upon. Current solar maps have

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different levels of advancement; the amount of information provided to users can differ a lot. Sometimes, solar maps are part of larger programs to get more renewable energy production in cities and provide users with direct information of suppliers and installers of solar systems. Other solar maps simply provide the solar irradiation to users without any further information. Furthermore, all solar maps so far take only roofs into account, not facades.

1.1. Common methodology for solar maps

The most common methodology to produce a solar map is shown in Figure 1. LiDAR data is Light Detection and Ranging data; 3D data collected by laser scanning. DEM –Digital Elevation Model- is 3D data of the terrain, and LAI –Leaf Area Index- is 3D data describing the "exchange of fluxes of energy, mass (e.g., water and CO2), and momentum between the surface and the planetary boundary layer" [9]. A growing number of cities are obtaining LiDAR data, making it in theory possible for these cities to produce a solar map. The process to obtain a solar map might be the same, but parts of the methods can be performed very differently. Maybe the most important part is the used calculation method, both for the solar irradiation and the output of the solar technology (PV / ST). Jakubiec & Reinhart (2013) note that 'limited attention has been paid to the assumptions and calculation methods underlying solar maps' [10]. In their analysis of North American solar maps, it was found that the most used calculation method were the 'constant irradiation level' method, Solar Analyst, and PVWatts, while Jakubiec & Reinhart use Radiance / Daysim as calculation method.

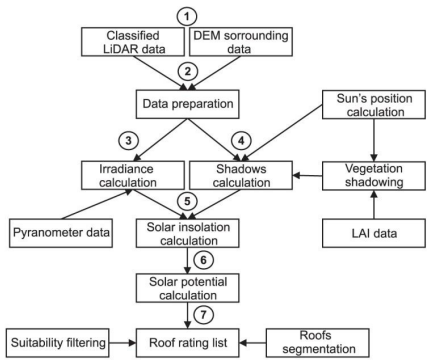

Figure 1. Methodology to produce a solar map [11]

In this study, the focus is onother parameters than the calculation method:

- which assumptions are made in the rating of the suitability of surfaces?
- which additional information is provided to accelerate the implementation of solar energy?
- how is the information provided from the solar maps used (by front- and back-end users)?

It was expected that this information would reveal the underlying status of solar energy in the cities.

2. Method

In order to get an overview of current solar maps, a simple Google search was done with the words "solar map city". Additionally, literature and scientific databases were also searched for with the same search terms. In total, 19 solar maps were identified. The authors are aware of the fact that there are more solar maps available worldwide, but many of them rely on exactly the same process (e.g. bought from the same company), and were therefore not included in the list. Table 1 shows the overview of the 19 analysed solar maps.

Table 1. Overview of analysed solar maps

	Country	City	Name	Owner
1	Austria	Graz	Solardachkataster	City of Graz
2	Austria	Vienna	Solarpotenzialkataster	City of Vienna
3	England	Bristol	Solar energy Bristol	City of Bristol
4	Germany	Aachen	Stadt Aachen Solarkataster	City of Aachen
5	Germany	Berlin	Solaratlas Berlin	City of Berlin
6	Germany	Dusseldorf	Solarkataster Dusseldorf	City of Dusseldorf
7	Germany	Marburg	Solarkataster Marburg	City of Marburg
8	Germany	Osnabrück	Sun-Area	City of Osnabrück
9	Germany	Solingen	Solarkataster Solingen	City of Solingen
10	Netherlands	Amersfoort	Zonnescan	City of Amersfoort
11	Netherlands	Arnhem	Zonatlas Arnhem	City of Arnhem
12	Portugal	Lisbon	Carta do Potencial Solar	City of Lisbon
13	Sweden	Gothenburg	SEES	Göteborg Energi
14	Switzerland	Basel	Solarpotenzial	City of Basel
15	Switzerland	Geneva	InfoEnergi	City of Geneva
16	Switzerland	Porrentruy	Cadastre Solaire	City of Porrentruy
17	USA	Boston	Renew Boston Solar	City of Boston
18	USA	Los Angeles	LA County Solar Map	LA County
19	USA	New York City	NYC Solar Map	NYC Solar America City

The owners were contacted to obtain additional information how the system was set up and what the conditions were, based on the following questions:

1. In your solar map you have different categories (good, very good, not suitable) for the assessment of solar energy. How did you choose the actual limits for the different categories? (based on financial motives, subsidies, etc.?)
2. How do you plan to work with the gained information from the solar potential map (or how do you already work with it)?
3. Is it only meant for citizens or do you use it as an instrument for urban / energy planning? (Is it used for deciding political goals for the use of solar energy?)
4. Is the total potential summarized for the city or for different areas or categories of buildings?
5. Are there analyses done for ranking or comparing areas with e.g. apartment buildings and single family buildings respectively?

Unfortunately, only 11 out of 19 answered to our short questionnaire (Aachen, Amersfoort, Arnhem, Basel, Dusseldorf, Geneva, LA County, Lisbon, NYC, Marburg, Osnabrück)

Of the different solar maps, the following parameters were analysed: (Table 2):

- Annual solar irradiation level (kWh/m^{2}a),
- Considered technologies (PV, ST),
- Total output per roof (kWh/a),
- Assumed efficiency of the technologies. In the case that the efficiency of the solar technologies was not provided, the efficiency was calculated using the total output, the area, and the solar irradiation levels (marked with a *).
- Heritage limitations (are buildings with a cultural heritage are marked),
- Threshold value per category (kWh/m^{2}a),
- Minimum surface of the solar system (m^2),
- Maximum annual solar radiation (For European cities, the maximum solar irradiation level was acquired by using PVGIS [12], even though some solar maps stated other maximum values. In USA, mainly the solar maps of NREL were used [13]).
- The percentage of maximum available annual solar irradiation level,
- Information on which parameters categories were based upon.

In Table 2, N/A means here that this data were either not specified or not elucidated in the answers. The percentage of maximum available annual solar irradiation was calculated because it makes comparisons between solar maps easier. Not all solar maps had the same categorisation. If necessary, categories were re-labelled to the common categories -very good, good, and suitable.With the information from the owners and the websites of solar maps, an inventory was made of the categorisation method used in the maps.

3. Results

In this section, first a quantitative analysis of the solar maps is provided, followed by a qualitative analysis.

3.1. Quantitative analysis

Table 2 provides an overview of all the analysed parameters. The colours in the table represent different categories:

- Blue: Reasonable
- Light green: good
- Dark green: very good
- Grey: solar maps did not divide areas in categories or did not specify –either in the documentation or in the reply- how categories were set up.

Table 2. Overview of the solar maps and their characteristics

	City	Technologies	Output / roof	Efficiency	Heritage	Categories	Thres-hold	Min. surface	Max solar rad.	% of max sol rad	Categories based on
1	Graz	N/A	No		yes	Good	N/A	12	1330	N/A	N/A
						Very good	N/A	12		N/A	N/A
2	Vienna	PV / ST	Yes	PV: 14%*	yes	Good	900	5	1300	69%	N/A
			(PV/ST)	ST: 90%*		Very good	1100	5	1300	85%	N/A
3	Bristol	PV	Yes	PV: 9% *	yes	Reasonable	880	N/A	1170	75%	N/A
			(PV)			Good	940	N/A	1170	80%	N/A
						Very good	1000	N/A	1170	85%	N/A
4	Aachen	PV / ST	Yes (PV / ST)	PV: 11.6%	no	Reasonable	800	10	1090	73%	N/A
				ST: 13.5%*		Good	870	10	1090	80%	N/A
						Very good	1020	10	1090	94%	N/A
5	Berlin	PV / ST	Yes (PV)	PV: 12%	yes	Reasonable	920	N/A	1150	80%	N/A
						Good	1035	N/A	1150	90%	N/A
						Very good	1092.5	N/A	1150	95%	N/A
6	Dusseldorf	PV / ST	Yes (PV / ST)	PV: 14%	yes	Reasonable	654	20	1090	60%	N/A
				ST: 14%		Good	872	20	1090	80%	N/A
7	Marburg	PV / ST	Yes (PV)	PV: 9-15%	no	Reasonable	825	N/A	1100	75%	Irradiation
						Good	891	N/A	1100	81%	
						Very good	1045	N/A	1100	95%	
8	Osnabrück	PV / ST	Yes (PV/ST)	PV: 15%	yes	Good	766	N/A	1090	70%	N/A
				ST: 50%*		Very good	909	N/A	1090	83%	N/A
9	Solingen	N/A	No		yes	Reasonable	N/A	N/A	1090	N/A	N/A
						Good	N/A	N/A	1090	N/A	N/A
						Very good	N/A	N/A	1090	N/A	N/A
10	Amersfoort	PV	Yes (PV)	PV: 11% *	yes	Reasonable	500	N/A	1110	45%	payback time
						Good	900	N/A	1110	81%	
11	Arnhem	PV	Yes (PV)	PV: 15%	no	Reasonable	700	11	1100	64%	N/A
						Very good	900	11	1100	82%	N/A
12	Lisbon	N/A	No		no	Reasonable	1000	N/A	1860	54%	Orientation
						Good	1400	N/A	1860	75%	
						Very good	1600	N/A	1860	86%	
13	Gothenburg		No		no	Suitable	N/A	N/A	1070	N/A	N/A
14	Basel	PV / ST	Yes (PV / ST)	PV: 15%	yes	PV good	900	N/A	1210	74%	N/A
				ST: 45%		PV very good	1100	N/A	1210	91%	N/A
						ST good	800	N/A	1210	66%	N/A
						ST very good	1100	N/A	1210	91%	N/A
15	Geneva	N/A	No		no	Reasonable	900	N/A	1400	64%	N/A

					Good	1000	N/A	1400	71%	N/A
					Very good	1145	N/A	1400	82%	N/A
16 Porrentruy	PV	Yes (PV)	PV: 12.75%	no	Reasonable	750	N/A	1250	60%	N/A
					Good	950	N/A	1250	76%	N/A
					Very good	1150	N/A	1250	92%	N/A
17 Boston	PV	Yes (PV)	PV: 11%*	yes	N/A	N/A	N/A	1307	N/A	N/A
18 Los Angeles	PV / ST	Yes (PV / ST)	PV: 18%	no	Reasonable	1204.5	N/A	1805	67%	Payback time
			ST: 64%*		Good	1460	N/A	1805	81%	
					Very Good	1789	N/A	1805	99%	
19 New York City	PV	Yes (PV)	PV: -	no	Suitable	1030	10	1456	71%	N/A

3.1.1. Categorisation

Table 3 and Figure 2 show the values of the categories 'reasonable, 'good', and 'very good' of the different solar maps. In the box plot (Figure 2), the white part of the box represents the 2nd quartile of the range, the black box the third quartile of the range.

Table 3.Median for the categories 'reasonable', 'good', 'very good' (in % of local maximum annual solar irradiation)

reasonable	65%
good	77%
very good	89%

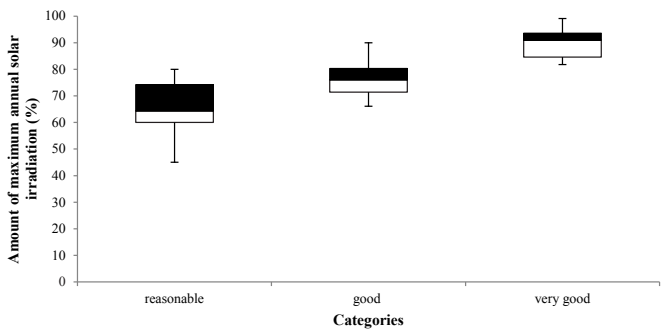

Figure 2. Box plot of categories applied in solar maps

Figure 2 shows that the categorisation of the solar maps is not straightforward. By comparing the categories as a percentage of the local maximum solar irradiation, the differences between the thresholds of the categories can only be explained from other parameters than solar irradiation, i.e. political, social, financial parameters. Interestingly,

the maximum value of the 'reasonable' category range is higher than the minimum of the 'good' category. This is also true for the highest value of the 'good' category and the lowest value of the 'very good' category. The spread of the values in the 'reasonable' category is quite high (35%), while spreading in the 'good' category is smaller (15%), and 13% in the 'very good' category. The owners were asked to clarify on which information they based their categorisation of surfaces. It was expected that they would base their categories on a certain payback time of the applied solar technologies. There was a mixture of answers: sometimes owners answered that the categories were based on the radiation level (which does not answer the question); in other cases, categorisation was done by best guesses, and only in some cases, categorisation was based on detailed calculations of payback times. The LA solar map for example based the categories on a payback time shorter than 15 years, taking into account the general electricity costs and installation costs after subsidies.

The minimum system size of the solar system was often related to the payback time of the system and / or the resolution of the data. Most solar maps did not set a requirement for the minimum surface area, while other maps had minimum requirements (this was based upon the capacity and payback time). Owners responded that only with a certain system size (kWp), a reasonable payback time could be reached.

3.1.2. Other parameters

Figure 3 and Table 2 provide an overview of the main parameters users of the solar maps can extract: Heritage limitations, Irradiation levels, PV output, and ST output. More than half of the solar maps provided an assessment of the output of a PV system installed on the roof, while less than half could provide an assessment of the output of a ST system. Half of the solar maps showed culturally / historically important buildings where the implementation of solar energy might not be allowed or needs to be considered very carefully. Also, half of the solar maps were able to show the irradiation levels on roofs, while the other half did not show the irradiation levels but rather the output of solar energy systems. This might be due to the fact that, for laymen, it is easier to relate to the output of a system and the corresponding surface area than the incoming radiation.

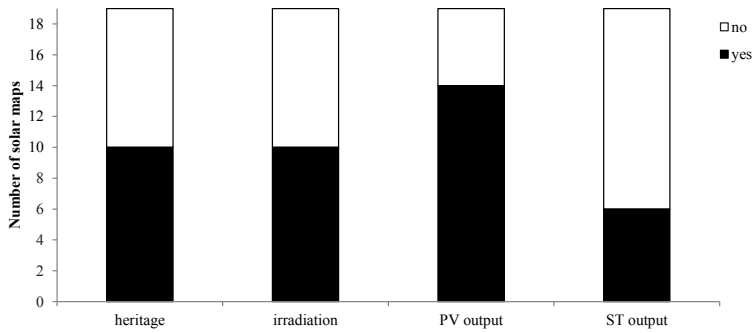

Figure 3. Main parameters of the solar maps

Many solar maps do not only focus on the quantification of the solar potential of roofs in the involved cities, but they also serve as a platform to inform inhabitants about the possibilities of solar energy. In the following section, the qualitative side of the solar maps is discussed.

3.2. Purposes of the solar maps

In general, the analysed solar maps served both as a front-end and as a back-end tool platform. Most solar maps came with a short description of what the solar energy potential is and which methods were used in order to calculate it. Many solar maps also provided a rather detailed set of assumptions which are needed to calculate the output of solar energy systems, however it is often stated that the solar potential is just a ´first estimation´, and that the owner (of the solar map) cannot be hold responsible for the calculations.

One example of how a solar map can be used both as a back- and front end tool is in case of the City of Basel, Switzerland [14]. This city launched an environmental program where they encourage people to first renovate their roofs, and then install PV –if their roofs had the right conditions; for both of the measures, the city will provide subsidies. On one website, it is explained how inhabitants should proceed. Besides that, the city also approached the owners of the 500 best roofs to implement PV.

3.2.1. Follow-up of the information gained by the user and owners

Using the solar map and obtaining the solar energy potential of roofs is often the first step in decision-making for both inhabitants and cities. Front-end users need guidance in order to understand what the solar energy potential actually means. Some of the solar maps therefore focus on two additional items:

- Finances of the system: revenues and costs
- Installations: which installers are available etc.

With this information, a founded decision can be made on the implementation of solar energy.

For the back-end users (and most often the owners of the solar maps), solar maps serve as an underlying information base for local energy decisions. In their answers, the involved cities say that they use the solar map for estimating the solar potential of all their own real estate. Some cities have underlying information about building types and year of construction. Performing such analyses takes time and money, the benefit of such an analysis was not always clear to the cities.

4. Discussion and conclusions

An analysis was done of 19 solar maps which are publically available on the internet. The solar maps were analysed, focussing on mainly the following elements:

- Annual solar irradiation (kWh/m^{2}a),
- Considered technologies (PV, ST),
- Total output per roof (kWh/a),
- Assumed efficiency of the technologies,
- Heritage limitations (are buildings with a cultural heritage marked?),
- Threshold value per category (kWh/m^{2}a),
- Minimum surface of solar system (m^2),

Besides this analysis, owners of the solar maps were asked to fill in a questionnaire, focussing mainly on:

- information on which parameters categories were based upon,
- what purposes the solar map serves.

4.1. Classification of solar maps

With the analysis of the solar maps and the results of the surveys, it is possible to classify the solar maps (Table 4). The *basic* solar map is a solar map with basic information: the irradiation level. Preferably, irradiation levels are also categorised. Such a solar map is the base for the *medium* and *advanced* solar map, of which features are all based on the analysis of annual solar irradiation of surfaces. The *medium* solar map provides the energy output of the suitable areas as PV / ST. The most advanced solar map is not only providing quantitative data, but also provides information about what to do next when people want to install PV or ST.

Table 4. Classification of solar maps

Basic	Medium	Advanced
-Irradiation levels	-Irradiation levels (not in all cases)	-Irradiation levels (not in all cases)
-Categorisation of irradiation levels (not in all cases)	-Output of solar systems (PV / ST)	-Output of solar systems (PV / ST)
	-Categorisation of suitable area for production	-Categorisation of suitable area for production
	-System effect (PV)	-System effect (PV)
		-Monthly output (not in all cases)
		-Financial considerations (investment costs, revenue)
		-Information regarding installers
		-Information about solar energy

A useful addition to solar maps could also be a feature which maps solar systems that are already installed within the city, with its according size and output.

4.2. In action

The role of solar maps as a decision support tool can be divided into three different aspects: 1) the difference in users (politicians, urban planners, investors, real estate owners), 2) scale (city, urban district, building), and 3) *soft* aspects (raise interest, vitalise the debate, get a common base for discussion).
By taking all these three aspects into account, a full deployment of solar energy in cities can be accelerated.

Acknowledgement

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Article PS 1

SOLENERGI I STADSBYGGNADSSKALAN

Solenergi har potential att globalt bli den största energikällan år 2050. För att nå dit behöver kunskapen höjas och nya användarvänliga metoder och verktyg utvecklas för att underlätta integrering av solenergi i planeringsprocessen. Forskare och praktiker redogör för planerarens förutsättningar och verktyg i planeringen av solenergi.

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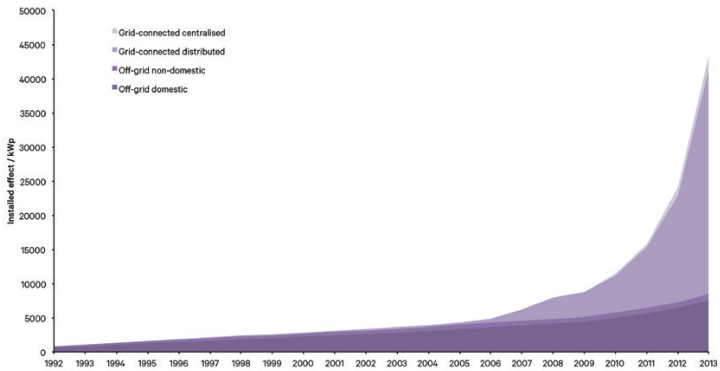
För att minska samhällets fossilberoende och klimatpåverkan pekar politiska beslut och policy mot att byggnader, stadsdelar och till och med hela städer ska vara självförsörjande vad gäller energi och samtidigt vara koldioxidneutrala. En ökad användning av solenergi är en viktig del i denna omställning.

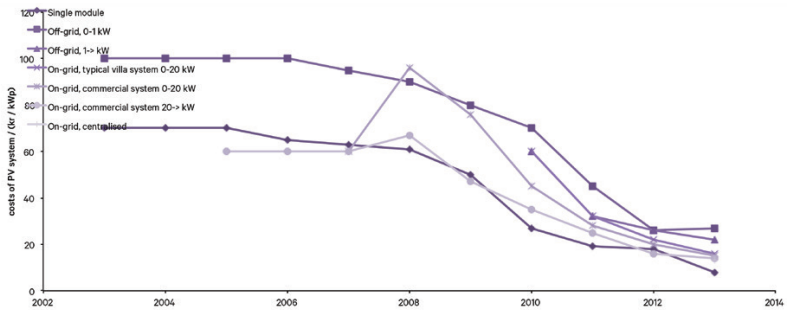
Den största utmaningen och hindret för en ökad implementering av solenergi i svenska städer är en generell brist på kunskap vilket visas i de internationella forskningsprojekten *POLIS och IEA SHC Task 41 – Solar Energy and Architecture*. Detta gäller både för kommuner, byggherrar såväl som konsulter. Det råder tveksamheter kring lönsamheten samt livslängd för solceller (som ger el) och solfångare (som ger värme) samt att det inte finns tillräckligt bra produkter på marknaden. Synen på detta är under förändring och det finns helt klart en större acceptans för solenergi idag än tidigare. Den kunskap som finns är dock till stor del begränsad till teknisk och ekonomisk kompetens för enskilda byggnader. Även om kunskapen om integration av solenergi i arkitektur har lyfts de senaste åren är den begränsad till ett antal individer. En annan begränsning är kunskapen om hur tidig planering påverkar framtida möjligheter till implementering av solenergi. Skuggstudier görs visserligen ofta men inte i syfte att utreda möjligheterna till solenergilösningar utan snarare för att utreda tillgången till soltimmar på uteplatser.

Planerare kan i sin roll fungera som möjliggörare för en högre grad av implementering av solenergi i våra städer. Förutsättningarna för aktiva solenergisystem är starkt beroende av ekonomiska aspekter som planerare inte har rådighet över; t.ex. utformning av skatter, möjlighet att sälja överskott till elnätet eller närliggande fastigheter samt prisutvecklingen av solenergiprodukter. Det planerare har rådighet över påverkar dock möjligheter både idag och i framtiden att implementera solenergi eftersom byggnadsvolymer, orientering, gatubredder, fasad- och takutformning är avgörande för mängden solinstrålning på en byggnad. Om solenergi inte beaktas idag kan planerares avväganden vara direkt hindrande för framtida implementering av solenergi när de ekonomiska förutsättningarna sannolikt är mer gynnsamma. Att planera för aktiv solenergi ökar samtidigt möjligheten för ökat dagsljusutnyttjande i våra byggnader.

Plats	Årlig solinstrålning på en optimalt vinklad yta (kWh/m2, år)	Optimal vinkel (grader) på årsbasis
Stockholm	1330	44°
Göteborg	1330	42°
Malmö	1400	41°
Berlin	1260	37°
Wien	1410	36°
Lissabon	2020	34°

Solinstrålningen på olika platser i Europa (PVGIS © European Communities, 2001-2012)





Utveckling av installationen av solceller i Sverige och prisutveckling av solceller i Sverige (Johan Lindahl / IEA PVPS Task 1)

Solenergi i Sverige

Sverige har, till skillnad från vad många tror, goda förutsättningar för solenergi. Södra Sverige har ungefär lika hög årlig solinstrålning som stora delar av Tyskland, se tabell s.19. Den stora skillnaden är att länder som t.ex. Tyskland har en mer gynnsam lagstiftning och utvecklingen har därför gått mycket snabbare än i Sverige.
Exempel på mer gynnsam lagstiftning i andra länder är feed-in-tariffsystem (nätbolag tvingas betala ett bestämt belopp när el från solenergi matas in på elnätet) eller nettodebitering (den som producerar och säljer egen el får kvitta den mot den el som köps in vid en annan tidpunkt, utan att betala energiskatt och moms). Solenergiproducenter som vill sälja sitt elöverskott till nätet tvingas idag sälja mycket billigare än vad den kostar att köpa.

Trots att Sverige inte har optimal lagstiftning ur ett solenergiperspektiv har det de senaste åren skett en positiv utveckling, framförallt för solceller. Särskilt nätanslutna anläggningar har ökat sedan 2007. Detta beror bland annat på att priserna för solceller har sjunkit med ungefär 80 procent de senaste 10 åren (se figur nedan).

Nära-nollenergi, load-matching och prosumenter

I Sverige står byggnader idag för ca 40 procent av energianvändningen. För att minska beroendet av fossila energikällor och för att minska utsläpp av växthusgaser har EU antagit ett direktiv som säger att energianvändningen i nya byggnader ska vara nära *noll* i alla medlemsstater år 2020. Detta uppnås dels genom att skärpa kraven på energianvändningen i nya byggnader samt genom att ställa krav på produktionen av lokal, förnyelsebar energi. Boverket arbetar med att utreda vad nära noll innebär i den svenska kontexten.

I framtidens energisystem kommer solenergi att spela en större roll än idag. I den nya energiförsörjningssituationen kommer *prosumenter* att växa fram - konsumenter som även är sina egna producenter. Huvudsyftet med solenergisystem på byggnader är oftast att leverera energi till dessa byggnader och inte till el- eller fjärrvärmenätet. Energibehovet i en byggnad såväl som energiproduktionen från en solenergiinstallation varierar över dygnet och året, speciellt i nordliga länder som Sverige där antalet soltimmar varierar kraftigt mellan sommar och vinter. Att mäta solenergiproduktionen på årsbasis kan då bli missvisande. Begreppet *load-matching* ämnar bemöta detta problem genom att solenergisystem utformas för att *i största mån möta det energibehov den specifika byggnaden har på månads-, dygns-, eller timbasis. Både ur prosumentens ekonomiska perspektiv och utifrån bästa samverkan mellan lokal och regional energiproduktion kommer någon form av load-matching att eftersträvas.

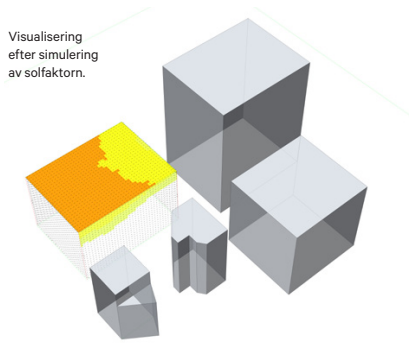
Load-matching kan även användas i ett kvarter eller kluster av byggnader istället för den enskilda byggnaden. Exempelvis genom ett solenergisystem som är utformat för att möta det totala energibehovet för flera byggnader. Detta ger även argument för blandad användning av byggnader inom ett kvarter då energibehovet under en dag varierar om det t.ex. är kontor eller bostäder - kontor har störst energibehov under dagen medan bostäder har störst energibehov under morgon och kväll.

En konsekvens av load-matching är att vi inte bara installerar solceller och solfångare i 30-45 graders vinkel mot söder - vilket ger mest energi på årsbasis med en övervägande del av produktionen under högsommaren (då vi kanske är på semester). Istället behöver vi planera och anpassa orientering och vinklar till när produktionen möter behovet.

Hjälpmedel

Lunds Tekniska Högskola och White deltar sedan 2013 tillsammans med nio andra länder i forskningsprojektet *IEA SHC Task 51 – Solar Energy in Urban Planning*. International Energy Agency (IEA) är OECD-ländernas samarbetsorgan för energifrågor och syftet med projektet är att beskriva nuläge, utveckla metoder, verktyg, processer, kunskap och riktlinjer för att skapa bättre förutsättningar att implementera solenergi i stadsplaneringen. Arbetet sker i samarbete med Malmö stad, Stockholms stad samt Lund.

I arbetet har en utvärdering av kunskapsläget visat att det idag finns idag flera verktyg som endast ser till solinstrålningen. Dessa brukar även kallas solpotentialstudier och omfattar beräkningar och



Visualisering efter simulering av solfaktorn.



I ett pilotprojekt testades en metod att utvärdera solenergin i relation till andra stadsplaneringaspekter vid planeringen av Årstafältet i Stockholm. Med hjälp av GIS kunde solpotential, marknadspotential och arkitekturpotential visualiseras. Utvecklingsarbetet bedrevs av White och Spacescape i nära samarbete med Stockholms stads stadsbyggnadskontors projektgrupp för Årstafältet.

Ovan visas överlagring av solpotential och uppskattad energianvändning för byggnader enligt strukturplan för Årstafältet. Mörkgröna byggnader är de som har potential att producera minst lika mycket energi som de använder. Syftet är att visa byggnaders olika förutsättningar för solenergi i ett stadsbyggnadsperspektiv och att miljömål bör anpassas efter de olika förutsättningarna.

visualiseringar av solinstrålning. Det saknas dock i hög grad verktyg som kan hjälpa arkitekter och planerare att värdera solenergiaspekter mot andra frågor som måste bemötas i planeringsprocessen. De flesta solpotentialverktyg som finns är heller inte tillräckligt användarvänliga och kräver en expertkompetens som ofta endast vissa ingenjörer besitter. Kunskapen om dessa verktyg är idag begränsad och de som används är inte integrerade i det traditionella planeringsarbetet. Flera verktyg och metoder är dock under utveckling med fokus på enkelhet och användarvänlighet.

På senare tid har kommuner tagit fram s.k. solkartor. En solkarta är en typ av solpotentialstudie som är framtagen för befintlig bebyggelse och som ofta är allmänt tillgänglig via webben. I dagsläget har Göteborg, Stockholm, Lund och Örebro solkartor.

Ett möjligt sätt att beakta solenergi vid nybyggnation är genom så kallad solfaktor Dvs. förhållandet mellan lämplig area för solenergi och golvarea i byggnaden. Genom en simulering ges inte bara numeriska svar men även visuell återkoppling genom olika färger som visar de areor som är mest lämpliga. Sovlfaktorn är lätt att beräkna och kan hjälpa till att jämföra förutsättningar för en byggnad i planeringsprocessen samt möjliggöra jämförelser mellan olika byggnader.

Solenergi och planerarens framtida roll

Inom forskningsprojektet IEA SHC Task 51 ämnar vi bl.a. att ge riktlinjer för vilken detaljeringsgrad solpotentialstudier behöver ha i olika skeden av planeringsprocessen. I tidiga skeden kan det räcka med att frågan lyfts upp eller att enklare studier görs som ger en fingervisning för vilka byggnader och ytor som kan vara lämpliga. I senare skeden, speciellt när enskilda byggnader börjar utformas, behövs mer detaljerade studier som kan användas för att jämföra utformningsalternativ och där placering av solceller eller solfångare baseras på energiprofilen för byggnaden samt ekonomiska förutsättningar.

Solkartor för kommuner har visat sig vara en bidragande orsak till det ökade intresset för solenergi. På stadsnivå kan solkartorna överlagras mot andra aspekter som kulturhistoriska värden för att kunna användas mer strategiskt. Införandet av solkartor har också visat sig medföra att insatser krävs för att höja kunskapen hos bygglovsavdelningar då de får fler förfrågningar kring solenergiinstallationer än tidigare.

I framtiden behövs det även utredas hur svensk lagstiftning förhåller sig till solrättigheter. Idag beaktas skuggning av omkringliggande fastigheter utifrån ett dagsljusperspektiv, framförallt på uteplatser.

När fler ytor på byggnader blir energiproducerande kommer nya konflikter uppstå. Frågor uppstår om lagstiftning kan skydda energiproducerande byggnader som aktivt bidrar till att uppnå Sveriges nationella miljömål. I andra länder, framförallt USA och Australien har detta utretts i högre grad och regler har utformats för att skydda och eventuellt kompensera en fastighet som skuggas.

Länder som t.ex. Tyskland, Österrike, Japan och USA ligger långt före Sverige när det gäller solenergiimplementering men flera trender och politiska målsättningar pekar mot att solenergilösningar kommer att bli mer attraktiva även i Sverige och har potential att bidra väsentligt till att minska CO2-utsläppen och uppnå våra nationella miljömål. Solenergi har som teknik även potential att möta energibehovet lokalt och kommer att bidra till att energiproduktionen i högre grad decentraliseras. Detta medför att nya avväganden kommer behöva göras i stadsplaneringen. Strategier, riktlinjer och kunskap behövs från den stora skalan ned till enskilda kvarter och byggnader för att säkerställa att det vi bygger idag möjliggör för framtidens energisystem. Planerare kan redan idag lyfta frågan och använda de hjälpmedel som finns för att i framtiden få en mer intuitiv förståelse för hur deras beslut och avväganden påverkar möjligheten att implementera solenergi.

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Vidare läsning

www.solarplanning.org Kunskapsplattform med allmän information om solenergi och hur stadsplanerare kan arbeta. Slutrapporten till Sunscape Index och Årstafältet finns även här.

task51.iea-shc.org Länk till forskningsprojektet IEA SHC Task 51 – Solar Energy in Urban Planning

www.polis-solar.eu Avslutat EU-projekt om hur städer kan arbeta strategiskt med solenergi.

Arkitektur och Solenergi: Nyhetsbrev om det senaste inom solenergi riktat mot arkitekter och planerare. För gratis prenumeration, kontakta johan.dahlberg@white.se



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