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Exploring the effects of 'Green Energy Economy' policies for transforming the Swedish building stock

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Abstract

Following the 2008–2009 global financial crisis, 'green energy economy' packages have been implemented to stimulate sustainable economic growth in several Organisation for Economic Co-operation and Development (OECD) countries. Clearly focused on the energy sector, these packages typically include energy-efficiency policy measures and aim to encourage the transition towards a low-carbon economy. We take the Swedish single- and two-household residential sector as a case study for an ex-ante assessment of 'green energy' policies that target energy efficiency improvements. We use the EEB_Sweden v1.0 modelling tool to quantitatively evaluate various green energy policy scenarios. We simulate two baselines and three policy scenarios in order to predict the extent to which green policy measures (e.g. 'Net Zero Energy Building' regulations) can change energy use patterns. The model implemented financial and non-financial determinants of technology choice. Our results suggest that technology-specific policies (e.g. subsidies for energy-efficient windows or solar photovoltaics) are insufficient to stimulate homeowners to make radical changes. In fact, we find that microeconomic decision-makers respond much better to systemic policy instruments, in particular maximum energy thresholds for whole buildings.

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1. Introduction

There is growing consensus that our traditional economic growth model has created considerable loss of natural capital, encouraged unsustainable patterns of energy production and consumption, produced climate instability, triggered social inequalities, and even proven to be economically unstable (e.g. Jackson 2009; Johansson et al. 2012; Stern 2007). Lately, 'Green Growth' and a 'New Green Economy' (NGE) have received increasing policy attention. Following the 2008–2009 global financial crisis, many countries, mostly in the Organisation for Economic Co-operation and Development (OECD) have implemented 'green' economic recovery packages. These packages aim to reform economies in ways that are far less damaging to our climate, society and the economic system itself (OECD 2010; E. Barbier 2010a). The NGE literature, albeit not a new field of research, has grown rapidly in recent years, and numerous conceptual approaches and policy support mechanisms have been proposed (e.g. E. Barbier & A. Markandya 2012; UNEP 2011; Huberty et al. 2011; UN ESCAP et al. 2012).

At its most simple, and with a focus on energy, a NGE can be conceptualised as a system that pursues growth by simultaneously achieving economic, environmental, and social goals through the rapid expansion of low-carbon technologies. Our interest in the energy sector originates in discussions about green stimulus economic packages. Such schemes have been portrayed as both a great opportunity and an entry point into a NGE (see e.g. Huberty et al. 2011; Pew Charitable Trusts 2009; IEA 2009; E. Barbier 2010b). Green stimulus packages have heavily targeted renewable energy and energy-efficient technologies (OECD 2010; E. Barbier 2010b), and improved energy efficiency has re-gained political momentum (e.g. UNEP 2011; E. Barbier 2010a). Arguments that efficiency improvements can reduce atmospheric pollution, lessen negative externalities, boost industrial competitiveness, generate employment and business opportunities, improve the housing stock, enhance productivity, increase security of supply, contribute to poverty alleviation, etc. have been around for a long time (e.g. European Commission 2005; IPCC 2007; Johansson et al. 2012; IAC 2007; E. Barbier & A. Markandya 2012). The private and commercial building sector alone is estimated to account for at least 40 % of energy use in most countries (WBCSD 2009) and worldwide offers the best potential for the mitigation of greenhouse gases (IPCC 2007). Estimates suggest that, if implemented in old and new buildings, efficient technologies and practices could save approximately 35% of primary energy use in buildings by 2020. Such a radical change could, by 2030, lead to a reduction in building energy use equal to the current total energy consumption in Europe (UN Foundation 2007).

Sweden (the geographical domain for our research) has placed heavy emphasis on energy efficiency (UN & Swedish Ministry of Foreign Affairs 2010). As part of preparations for the Rio +20 conference in June 2012, the United Nations asked governments to respond to a questionnaire on 'Green economy in the context of sustainable development and poverty eradication'. The Swedish Ministry for Foreign Affairs (in consultation with other ministries) responded on behalf of the Swedish government. Their responses showed a clear preference for energy efficiency and the use of market-based policy instruments to support or encourage a green economy (e.g. by taxing pollution) (UN & Swedish Ministry of Foreign Affairs 2010). Sweden is often recognised as a country with a good track record in energy-efficiency policies and while this assertion may hold true for certain sectors, performance in the building sector is not so clear (Nässén et al. 2008; Nässén & Holmberg 2005). In May 2006, the Swedish government adopted the 'National programme for Energy Efficiency and Energy Smart Construction', which set targets for a reduction in total energy consumption of 20% by 2020 and 50% by 2050 based on a 1995 baseline.

With this as background, this paper makes a quantitative assessment of the potential impacts of green energy policies aimed at the Swedish construction sector. Specifically, the analysis focuses on the single- and two-household residential sector. We evaluate whether existing and/or new energy-efficiency policies have the potential to trigger radical change, which would transform the

construction sector and support the transition to a green energy economy.[1] We developed a model (the EEB_Sweden v1.0), which provides a data-rich, bottom-up representation of the Swedish residential sector and can be used to carry out quantitative simulations. The model can be used to reflect a more decentralised microeconomic decision framework for low-carbon technologies. Important factors include: (*i*) equal weight given to financial/technological and non-financial decision criteria; (*ii*) use and inclusion of non-financial criteria (e.g. reliability, predictability and appearance); and (*iii*) the development and introduction of property owner-tenant relationships (to capture the 'principal-agent' problem). Our experiments simulated two baselines and three policy scenarios in order to understand, ex-ante how, and to what extent, future energy use may be driven by specific policy measures. Policy scenarios were based on potential policy mechanisms (e.g. taxes, regulations, market-based instruments) to encourage a NGE (see e.g. E. Barbier & A. Markandya 2012; Pearce et al. 1989; OECD 2010).

We must stress that the modelling exercise described here is simply a departure point for further research. The EEB_Sweden v1.0 model is still at an early stage of its development and the energy use model continues to be improved. In this context, our results should be used with caution and (as with any modelling study) for policy insights rather than the forecasting of specific numbers.

2. Model and method

It is important to note that there is no 'best' method for policy evaluation, and our research focuses on data collection, model development and implementation. The overall methodological process was resource-intensive and the main elements are described below.

2.1. EEB_Sweden Model v 1.0

The generic Energy Efficiency in Buildings (EEB) modelling process formed the basis for the development of the EEB_Sweden model (v 1.0). This model was used to run simulations and perform the analysis. The generic EEB modelling process (see Figure 1) was developed by Robust Systems and Strategy LLC under the World Business Council for Sustainable Development's (WBCSD) Energy Efficiency in Buildings Project. It combines *simulation* and *accounting* methodological approaches.[2] The approach aims to represent observed and expected microeconomic decision-making behaviour that is not necessarily limited to the optimal pattern suggested by financial parameters. The EEB model uses spreadsheets to show efficiency improvements. These are presented in prescriptive form – for example the impacts of highly-efficient technology adoption by end-users, or descriptive form – for example the portfolio of technologies resulting from one or more policy instruments (Otto, Taylor, et al. 2010; Otto, Kornevall, et al. 2010).

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[1] There have been very few evaluations of energy-efficiency policies in the Swedish construction sector and those that do exist are based on outdated statistical data (collected between 1983 and 1993). This problem led the government to carry out a study of the actual technical status of the building stock. The National Board of Housing Building and Planning (Boverket) was mandated to collect up-to-date and relevant statistics (the BETSI project).

[2] The WBCSD-EEB project developed a building stock energy use simulation model to understand how to encourage building stakeholders to reduce carbon emissions by 2050 (WBCSD 2009). The project focused on six geographical building markets, namely: the United States, Japan, Brazil, China, France and India. These markets were used to analyse different energy-efficiency policy scenarios. The project focused on energy use during the operational life of buildings. However, researchers acknowledged that the operational phase is only one aspect of the life of buildings (other examples are construction and demolition). Although the project acknowledged the importance of energy supply, the analysis was limited to the demand side. For further information about the project and its outcomes see WBCSD (2009).
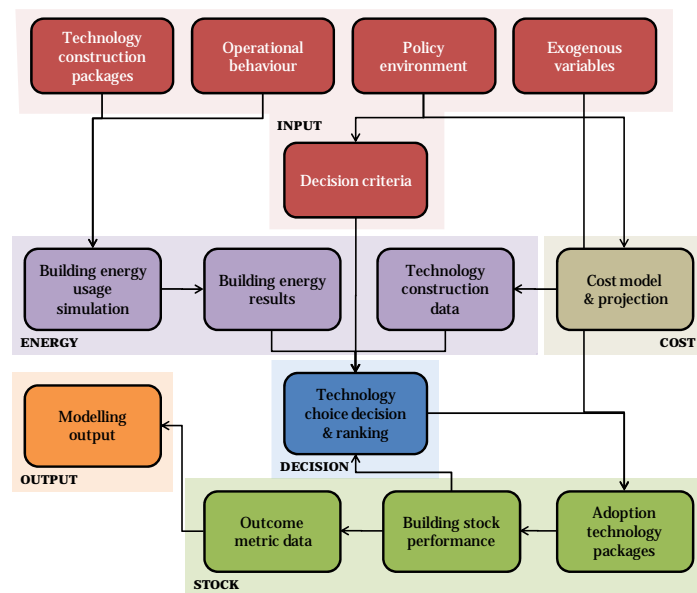
Figure 1: The generic EEB modelling process
Source: Adapted from Otto et al. (2010).

We fine-tuned the original EEB model and populated it with data related to the Swedish residential sector. The final model consists of separate but interlinked sub-modules. It is able to analyse a sector or a sub-sector (e.g. multi-household dwellings) of the Swedish construction market. The model provides a data-rich, bottom-up simulation and can represent a very wide portfolio of residential technologies. These include more than 20 energy-related subsystems and more than 10 categories of material technologies (e.g. insulation, fenestration, ventilation).

Figure 1 shows that the generic EEB model is structured into six types of module (Otto, Kornevall, et al. 2010). First is the *input* module. This consists of five sub-modules, which handle data and assumptions. These include qualitative aspects relating to: (i) technology construction packages (i.e. the portfolio of residential technologies), (ii) operational behaviour (e.g. use levels, maintenance efficiency), (iii) the policy environment (e.g. subsidies, tax credits, carbon taxes), (iv) exogenous variables (e.g. energy prices), and (v) financial and non-financial decision criteria (e.g. minimum net present value, minimum value for indoor environmental quality).

The *cost* module consists of a technology construction sub-module (e.g. initial costs, maintenance costs and qualitative aspects) and a projection sub-module (to calculate costs for building alternatives).

Third, the *energy* module simulates energy usage. This is external to the EEB model (we used eQuest) and shows the energy usage for different technologies at the construction sector level. eQuest makes it possible to model buildings characterised by different construction technologies. Disaggregated data is available for: space heating and cooling equipment; ventilation equipment; distribution, lighting and cooking equipment; water heating systems; and large and small electrical appliances. In the EEB_Sweden model these elements provided the input (and values) for establishing baselines and policy scenarios.

The fourth module is the *technology choice decision* module (also called the 'rank scores of technologies'). This framework determines the adoption of construction technologies. It is composed

of the following elements: (i) decision variables, (ii) user-defined constraints, (iii) the policy environment, and (iv) exogenous variables (e.g. energy prices). We briefly describe these elements below.[3]

- *Decision variables*: The EEB framework is based on two sets of decision criteria. *Financial factors*: The EEB model simulates alternative building technology configurations using various financial criteria, which include purchase/investment and installation costs. Annual operating expenses, such as energy, operating and maintenance costs are also included. *Non-financial factors*: The EEB model includes non-financial determinants of technology choice, such as appearance, indoor environmental quality, reliability, etc.[4] Values applied to each criterion can be combined into qualitative scores for any configuration of technologies.

- *User-defined constraints*: Financial and non-financial criteria are used both separately and in combination on a weighted sum basis to determine the technologies that are finally adopted. They work as a 'technology choice filter' in the model. Financial constraints are represented by criteria such as net present value (NPV), internal rate of return (IRR), and break-even time (BET). Non-financial constraints are scored. Each construction technology package can be assessed and compared based on both financial and non-financial decision factors. The set of technology alternatives can be filtered according to financial criteria (e.g. all alternatives with a NPV less than zero are eliminated) and non-financial constraints (e.g. all alternatives with a score of less than three for 'easy installation' are excluded).

- *Policy environment*: The policy environment is user-defined and can simulate (or replicate) current and future policies targeted at the residential sector. Policy conditions can also operate as a technology choice filter. Once a construction technology package has been comparatively assessed (based on the entire set of decision factors), it can be filtered by policy. In this way, the adoption of a technology package is subject to the policy environment set by the modeller, i.e. whether single technologies or technology packages meet building codes, are subject to subsidies or bans, etc.

- *Exogenous variables*: These also affect the adoption of construction technology packages. Energy prices, carbon emission factors, etc. act as technology choice filters. They affect financial performance and thus the ranking of the construction technology package.

Fifth, the *stock* module is composed of: (i) a building stock sub-module that establishes the energy performance of different building stock levels (initialised by reference cases); (ii) a technology adoption sub-module that estimates the market share of construction technology packages; and (iii) outcome metric data that computes financial metrics (e.g. NPV). Every year a percentage of the model's building stock is refurbished and new technologies are introduced as old technologies become obsolete. In addition, a part of the building stock is destroyed and removed from the stock model, and new construction brings new technologies and building alternatives into the stock. In the EEB model, these three modes of changes to building stock define a year-on-year differential equation of building stock.

Finally, the *output module* provides the following results: (i) total and net energy consumption (primary and on-site) and CO_2 emissions (per-building and total for the submarket), including on-site

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[3] Personal communication with Kevin Otto (April 2010).

[4] The EEB model also includes other, so-called 'value enhancement' decision factors. These include building value, rent, productivity, health, sales margins (retail), and inventory (retail). However, we do not use them in our simulations as they are based on empirical data we do not have yet.

generation; (ii) investments and operating costs (per-household and submarket total); (iii) loans, subsidies and taxes linked to policy scenarios; and (iv) the total cost of policies.

The EEB model makes the following assumptions about markets and stakeholders[5]:

- Housing sector sub-markets (i.e. single- and two-household dwellings; multi-household dwellings) behave independently and are guided mostly – but not entirely – by financial decision criteria. This assumption was necessary to simplify the model of the construction market and household behaviour. While each housing sector contains a homogenous mix of construction types, all have access to energy-efficient technologies.

- The unit of analysis is a building (dwelling). The model is not able to analyse a set of buildings at district level. However, it can take into account on-site energy generation and emission factors on the supply side. Technology choices are under the control of building stakeholders.

- Although the energy and carbon performance of housing sectors is based on statistics, there is an assumption of uniform levels of energy services. This assumption was necessary to reduce the complexity of energy use patterns. Moreover, data at the energy service level is not always available.

- Efficient technology packages are price-dependent, which is treated as an independent variable in the model. This simplification was necessary because the model does not simulate the entire energy market/system.

- Building stakeholders tend to base their choices on financial criteria. However, as we aimed to develop a broader framework of technology choices, the model includes a set of non-financial determinants. This set of non-economic factors is based on qualitative factors and attempts to simulate the bounded rationality of decision-makers.

- The model assumes that resources (e.g. construction materials, fuel) are unlimited until the end of 2050. Demand for materials is infinite; however, exogenous restrictions can be set that mimic constraints on energy resources, for instance.

2.2. Key input data

The model was populated with data collected from journal articles, reports and statistics published by the Swedish Energy Agency (Energimyndigheten), Statistics Sweden (Statistiska Centralbyrån), the Swedish National Board of Housing, Building and Planning (Boverket)[6], the Swedish Environmental Protection Agency (Naturvårdsverket) and other databases at the European Union level (Mure-Odyssee). Other academic papers, dissertations and technical reports filled in any remaining gaps (see Table 1 – Table 7).

In general, there are three types of building stock in Sweden: i) single- and two-household residential buildings; ii) multi-household residential buildings; and iii) non-residential buildings. As previously mentioned, here we focus on single- and two-household residential buildings. Input data related to: facts (e.g. the number of buildings and their location); architectural features (e.g. number of floors

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[5] Personal communication with Kevin Otto and Anis Dupuis (April 2010).

[6] In December 2006, the Swedish government commissioned Boverket to conduct the BETSI survey of Swedish building stock. BETSI focused on the technical design of buildings. One of the main reasons for the survey was that building stock statistics were outdated and inadequate.For further information see http://www.boverket.se/Bygga--forvalta/sa-mar-vara-hus/Tre-forskarseminarier-om-BETSI/ At the time of writing, it is not clear when researchers will have full access to the technical database developed by the project. For more information see http://www.boverket.se/Om-Boverket/Webbokhandel/Publikationer/2010/Statistiska-urval-och-metoder-i-Boverkets-projekt-BETSI/

per building, construction technique and materials, surface area); mechanical parameters (e.g. heating and cooling systems); electrical features (lighting equipment); internal loads (peak occupancy, lighting and equipment, water usage); commercial prices (e.g. energy, material and technology); and CO_2 emissions.

Table 1: Residential building stock

Single- and two-household dwellings	Value (2005)	Source
Total stock	2,007,097	
Newly built in 2005	10,076	
New building growth rate	2.2% Source: based on SCB, 2010 projected dwelling stock	
	6.0% Source: MURE (2010)	SCB (2007)
Demolition rate	0.07% (assumed to be equal to multi-dwelling)	
Total area	255.5 million m^2	
Average area	124.2 m^2	

As with any building stock energy accounting model, differentiated data about the age of the building stock is needed to define its physical features. Similarly, its technological characteristics are needed to identify and assess the energy efficiency of its current and future state. In other words, the age band of the building stock is critical in order to characterise it in technological terms. Banding was based on official statistics, and given an abbreviation (Ref 1 to Ref 8) that represented the following time spans: Ref 1: before 1920; Ref 2: 1921–1940, Ref 3: 1941–1960, Ref 4: 1961–1970, Ref 5: 1971–1980, Ref 6: 1981–1990, Ref 7: 1991–2000, and Ref 8: 2001–2005 (see Table 3).

Table 2: Value of single- and two-household residential stock according to year of construction

Year of construction		Number of residential units	Source
Ref 1:	- 1920	316,000	
Ref 2:	1921 – 1940	247,000	
Ref 3:	1941 – 1960	302,000	
Ref 4:	1961 – 1970	286,000	
Ref 5:	1971- 1980	435,000	SCB (2007)
Ref 6:	1981 – 1990	222,000	
Ref 7:	1991 – 2000	88,346	
Ref 8:	2001 – 2005	44,518	
n/a		66,233	

The model looked at four categories of technology, namely windows, flooring, roof insulation and wall insulation (based on the eQuest input classes). Table 4 shows baseline energy use values for the sector. Note that energy use statistics only reflect energy losses in the building itself. Losses related to generation and distribution are accounted for on the supply side (STEM 2009b).

Table 4 shows these four types of technology and their corresponding U-values. The U-value is the heat transfer coefficient[7], and indicates how a specific building element conducts heat, hence, how well isolated it is.

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[7] The overall heat transfer coefficient (U) measures the ability of conductive and convective materials to transfer heat over a given area at 24°C, 50% humidity and with no wind. The smaller the U-value, the better the isolation. It is measured in W/m2K.

Table 3: Four categories of technology and corresponding U-values for single- and two-household dwellings according to construction year

	Ref 1	Ref 2	Ref 3	Ref 4	Ref 5	Ref 6	Ref 7	Ref 8
	- 1920	1921 - 1940	1941 - 1960	1961 - 1970	1971 - 1980	1981 - 1990	1991 - 2000	2001 - 2005
Windows	3.0 *	3.0 *	2.4 [a]	2.3 [a]	2.0 [a]	2.0 [a]	1.8 [a]	1.3 [b]
Floor	0.22 [c]	0.22 [c]	0.22 [c]	0.20 [d]	0.19 [d]	0.19 [d]	0.19 [d]	0.19 [d]
Roof	0.30 *	0.22 *	0.22 *	0.20 [d]	0.18 [d]	0.18 [d]	0.18 [d]	0.13 [e]
Walls	0.50 *	0.50 *	0.48 [a]	0.30 [a]	0.22 [a]	0.18 [a]	0.18 [a]	0.18 [a]

Notes

* Assumed value

[a] Values are based on figures given by Boverket (2010) for a given construction year

[b] Source: Bülow-Hübe (2001)

[c] Approximation based on values given by Schaefer (2000) for the case of Sweden

[d] Approximation based on values given by Lechtenböhmer & Schüring (2011) for cold climate zones

[e] Source: EURIMA (2012)

Table 4 shows baseline energy use values for the sector. Note that energy use statistics only reflect energy losses in the building itself. Losses related to generation and distribution are accounted for on the supply side (STEM 2009b).

Table 4: Residential energy use (2005)

Single- and two-household dwellings	Total energy use	Source
Electricity	26 TWh	
Natural gas	n/a	
Fuel/diesel oil	5.3 TWh	SCB/STEM (2006)
Coal	n/a	
District heating	3.5 TWh	
Biomass (wood chips + pellets + firewood)	11.2 TWh	

Table 5 shows energy use statistics for 2005. This table shows that the combined energy use (i.e. electricity and heating) per unit is within 180-190 kWh/m^2. Note that heating and hot water in particular, the energy intensity of different building types varied significantly depending on the year of construction.

Table 5: Average energy use (2005) in Single- and two-household dwellings

Energy form	Energy use per unit area	Source
Electricity	42 kWh/m^2	STEM (2009b)
Heating and hot water (upper and lower bounds)	148 kWh/m^2	
	138 kWh/m^2	SCB & STEM (2008)

Figure 2 shows that single and two-household dwellings built before the 1940s have both the largest heated floor area and the highest energy consumption (kWh/m^2), although the trend is less consistent in later years. A particularly interesting observation is that that Ref 6 (1981–1990) has a higher energy use than Ref 5 (1971–1980). Despite the increase in the number of dwellings, we argue that total overall energy use in the residential sector has remained relatively constant in the past 30–40 years (STEM 2009a). Electricity is the main fuel in this sector, delivering 43% of total heating energy, compared to 6% in multi-household dwelling and 16% in non-residential buildings (SCB & STEM 2006). In single- and two-household dwellings heated solely by electricity, average energy use is about 150 kWh/m^2. The next most popular option is a combination of electricity and biofuels, followed by heating with biofuels alone. Only 13% of buildings are heated either in whole or in part by oil (SCB & STEM 2006).
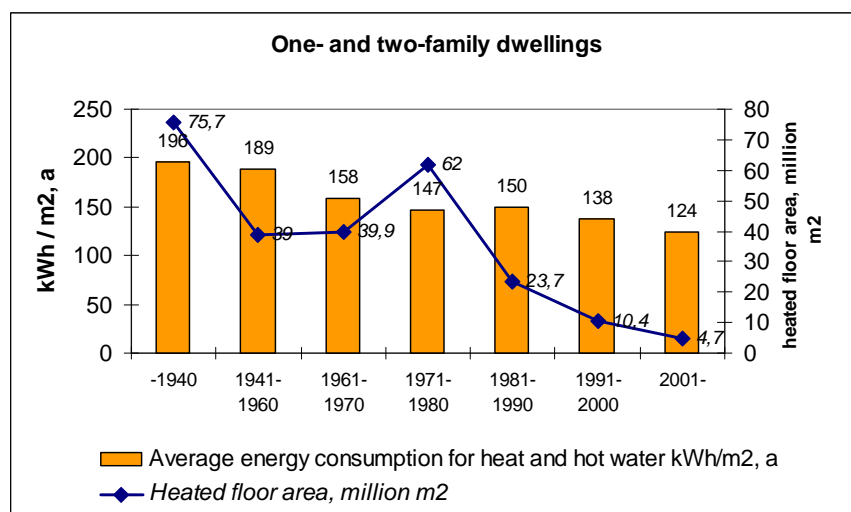
One- and two-family dwellings

Figure 2: Energy use for heating and hot water in single- and two-household dwellings according to year of construction
Data source: SCB and STEM (2006)

Economic and environmental data relate to the price of fuel, taxes and value-added tax (see Table 6). The final price of energy includes operating, maintenance, conversion, distribution and capital costs, taxes, and the returns required by energy utility companies. No distinction is made between imported and indigenous fuel, although imported fuels have traditionally been more heavily taxed. In contrast to the real price of electricity, which doubled between 1990-2005, the cost of district heating has not increased by the same amount. In addition to energy taxes, the introduction of value-added tax (VAT) in 1990 increased the cost of energy for domestic users. Finally, it should be noted that the electricity price also includes end-user charges linked to Swedish green electricity certificates.

Table 6: Residential energy prices, including grid charges, taxes and VAT (2005)

Fuel	Price (US$/kWh) including grid charges, taxes and VAT (2005)[a]	Source
Electricity	0.22	SCB (2010)
Natural gas	0.09	
Fuel/diesel oil	0.10	STEM (2009a)
District heating	0.08	
Biomass (wood chips)	0.02	

[a] Values in the EEB model are in US dollars. (Exchange rate: 1 US dollar = 7.94 Swedish krona December 2005).

CO_2 emission factors were included for each fuel according to the emissions coefficient reported by the Swedish Environmental Protection Agency (SEPA) (Table 7). The Nordic energy mix defined by SEPA and the European Topic Centre on Air and Climate Change was used for this purpose.

Table 7: CO$_2$ emissions

Fuel	Emissions (kg/kWh)	Source
Electricity	0.07	SEPA (2003)
Natural gas	0.38	Herold (2003)
Fuel oil/kerosene	0.21	SEPA (2003)
District heating	0.095	SEPA (2003)
Biomass (wood chips)	0.18	(Assumption)

2.3. Baselines and scenarios

The development of alternative baselines or counterfactuals is necessary because of uncertainties about policy developments. It is critical to determine the robustness and sensitivity of results to the assumptions and limitations used in the various models. Baseline scenarios need to reflect the current portfolio of policy instruments, as an existing portfolio may lead to a certain level of energy efficiency improvements regardless of other factors. Whether baselines or counterfactuals reflect (or not) the current mix of policy instruments can seriously affect the interpretation of the potential impact of the policy instrument being evaluated.

For the modelling exercise, we developed two baselines. These baselines are described below:

- *Baseline #1, 'No Policies' or 'Autonomous Market Response'*: Business-as-usual with no policy intervention. Using this baseline, there are no energy or carbon policy instruments and 2005 energy prices remain unchanged. Equipment prices and efficiencies increase marginally and linearly. Decision-makers (property owners and/or tenants) implement efficient technologies only when refurbishing (see Figure 3 and Figure 4).
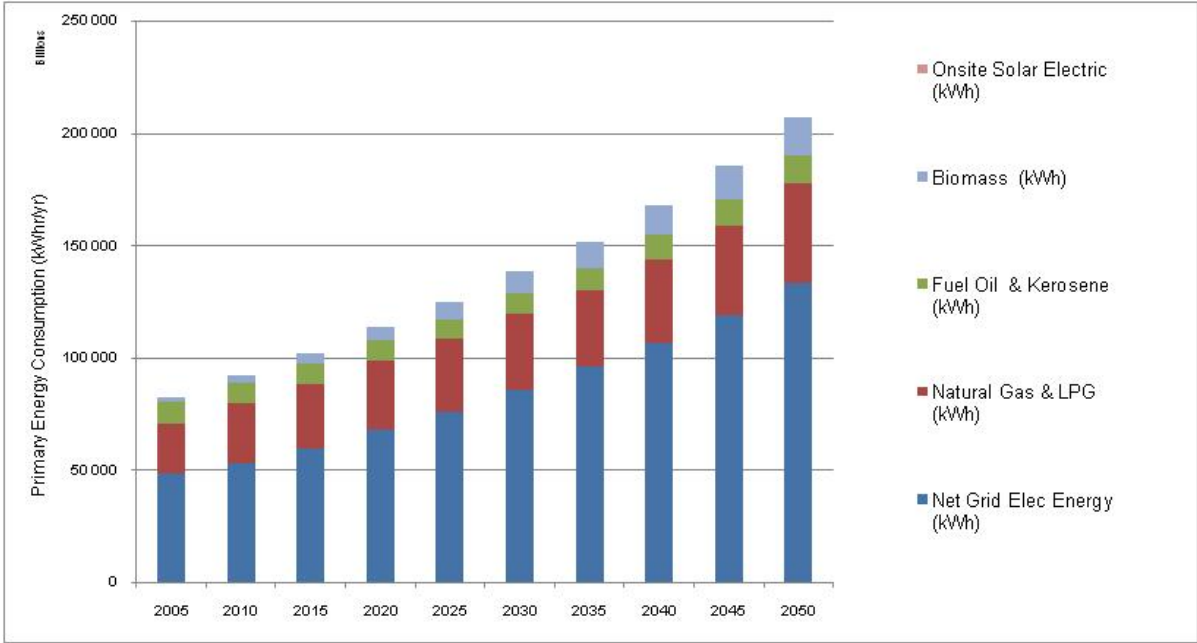

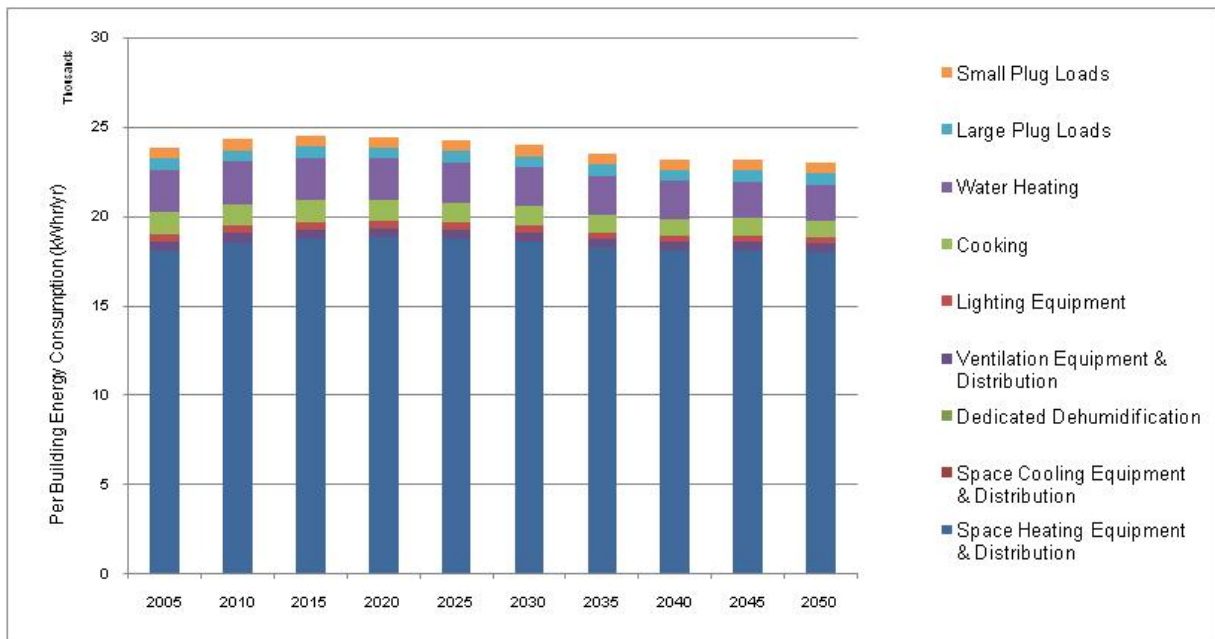**Figure 3: Baseline #1 – Primary energy consumption in the business-as-usual case**

Figure 4: Baseline #1 – Per-building energy consumption in the business-as-usual case

- *Baseline #2, 'Current' Energy Efficiency Policies*: This baseline reflects a mix of energy efficiency policies implemented by Swedish authorities in the residential sector (see Figure 5 and Figure 6). We assume that policies remain in place until 2050. Based on official information, the following instruments were simulated:

  ✓ Building regulations, including specific requirements for energy use in buildings.

  ✓ Grants for investment in solar cells: up to 65% of capital costs (assumed).

  ✓ Grants for conversion of heating systems: up to 35% of capital costs (assumed).

It should be noted that these financial support mechanisms actually ended in 2011. In cases of renovation, maintenance, conversion or extension individuals now rely on tax deductions.
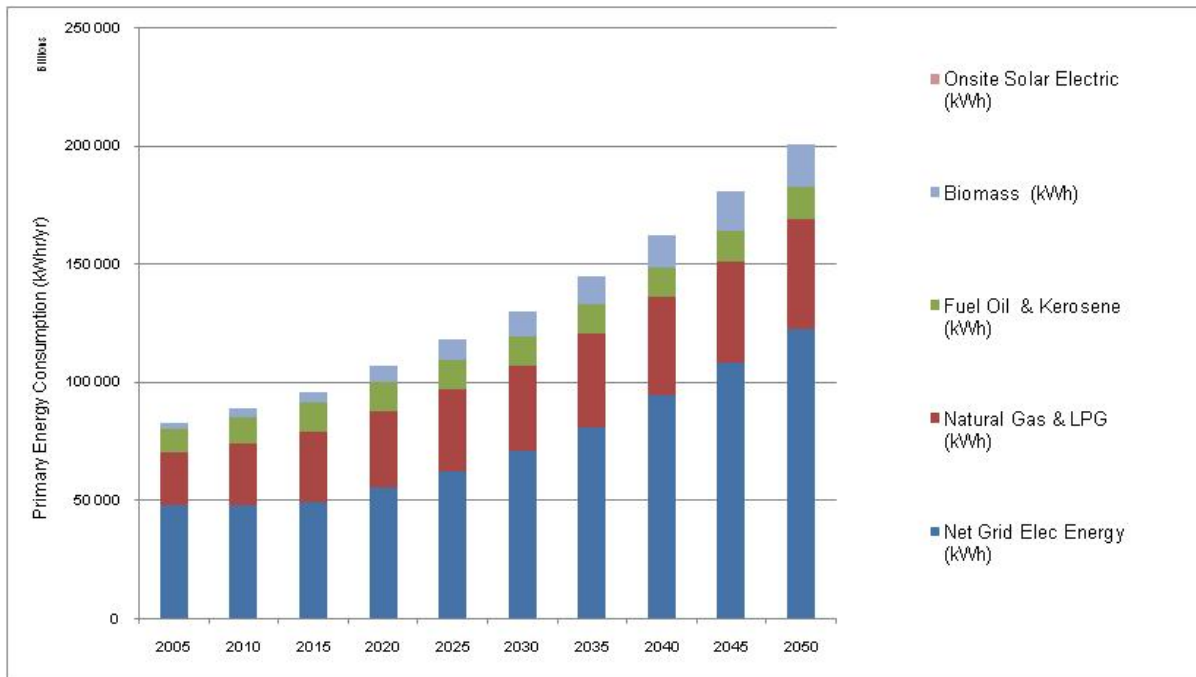

Figure 5: Baseline #2 – Primary energy consumption based on the 'current' energy-efficiency policy portfolio
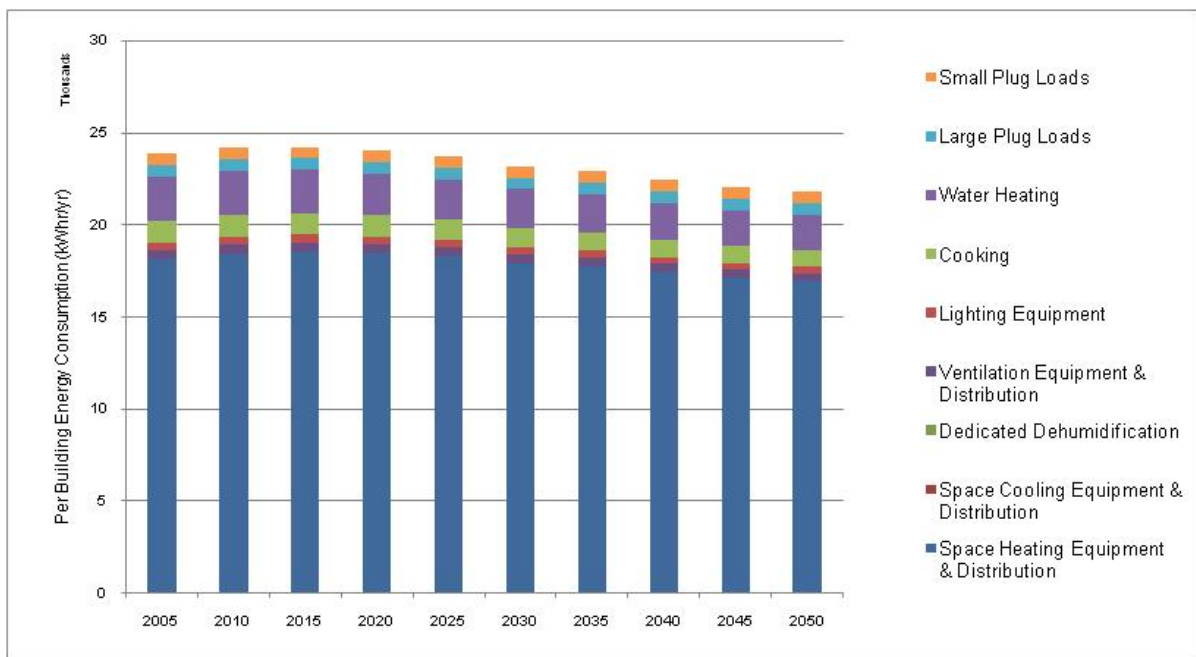

Figure 6: Baseline #2 – Per-building energy consumption based on the 'current' energy-efficiency policy portfolio

As we aimed to explore and approximate a more decentralised, less rational framework for technology choices, we implemented a number of other constraints. These constraints aimed to capture realistic microeconomic decisions related to energy-efficient technologies. Therefore, the model exercise included the following constraints for the scenarios listed below:

- *Weight of technology choice decision criteria*: 50% of the choice of technology is based on financial/technical criteria and 50% on non-financial criteria. That means that in the model financial and non-financial aspects are equally important. The first priority of tenants and/or property owners is likely to be minimizing costs. Tenants will not adopt technologies where the annual operating costs are higher than a certain level.

- *Non-financial criteria*: The following non-financial criteria were taken into account: indoor environmental quality; reliability and predictability; ease of use and installation; appearance; and energy and atmosphere. Minimum qualitative values were set at three (medium-high). Whether a technology is implemented (or not) depends on the tenant and/or owner, who will not accept any solution where the qualitative value is less than three (out of five).

- *Owner-tenant relationship*: The property owner accepts a maximum initial cost increment over the lowest cost alternative, while minimizing annual operating costs for tenants.[8] This approach addressed the complex links and relationships between stakeholders, in particular decisions concerning initial costs and potential savings. It attempted to capture information asymmetries reflected in the principal-agent problem. We assume that the tenant is only partially aware of the energy-related costs and benefits of different technologies. We also assume that they are not fully aware of the added value that efficiency improvements bring to the property.

From these constraints we created three policy scenarios in which a decentralised, non-financial technology choice framework is combined with a 'traditional' framework.

- *Scenario #1 - Energy price increase:* We introduce a sharp fuel price increase; specifically a 10-fold increase in current prices in the context of existing energy efficiency policies (i.e. baseline #2). Increases are phased in order to reach the final 10-fold rise by 2050.

- *Scenario #2 – Zero Net Energy Buildings*: This is equivalent to baseline 2, i.e. the "initial" set of policies remains in place. We introduce a constraint according to which all new construction must be zero net energy by 2020. Energy prices (2005) are kept constant. This scenario is interesting in the context of the European Union Directive on Energy Performance in Buildings (2010/31/EU), which requires all buildings constructed after 2020 to be nearly zero energy (i.e. with very high energy performance).

- *Scenario #3 – Building system incentives*: In contrast to technology-specific support policies this policy scenario sees buildings as a 'system'. It offers economic incentives for new A- and B-class buildings. A subsidy of 50% of capital and labour costs is offered for the construction of an A-class building (energy consumption of less than 50 kWh/m^2/year), and a similar 25% subsidy is provided for a B-class building (90 kWh/m^2/year). Furthermore, a ban is introduced on the refurbishment or construction of E–G-class buildings (annual energy consumption greater than 230 kWh/m^2). Current energy efficiency policies remain in place (baseline #2) and energy prices remain constant. A carbon tax of 30$US per metric ton of CO_2 emitted is included for the period 2005–2050.

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[8] For further details, see Otto et al. (2010).

3. Results

3.1. Scenario #1: Energy price increase

In the context of existing policies, this scenario does not reduce energy consumption when compared to the two baselines. Overall, our results seem to be more modest. The main reason for this may be the behavioural component that is included in our framework, rather than technical and financial aspects (see Figure 7 and Figure 8).
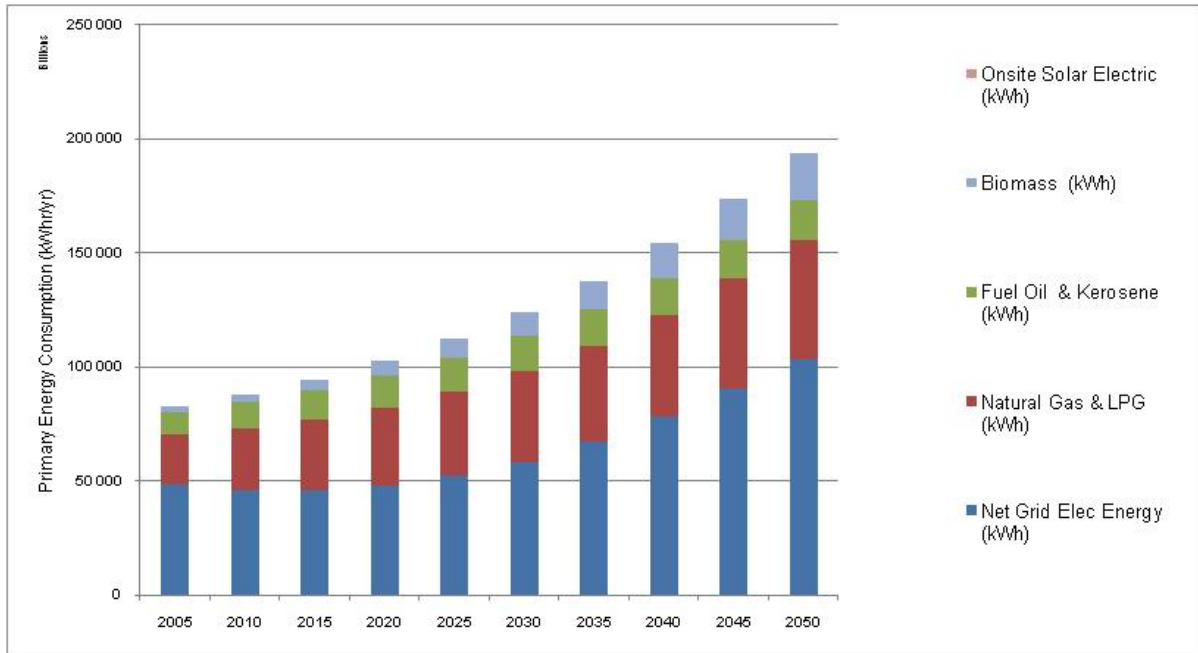

Figure 7: Primary energy consumption in the 'Energy Price Increase' scenario

Increases in building stock and the policy context mean that primary energy consumption has grown by 234% in 2050 compared to 2005. Compared to baseline #1 (a 250% increase) and baseline # 2 (a 242% increase), this scenario delivers a decreased demand in energy use (by 16% and 8% respectively). There is fuel switching; in particular, electricity replaces natural gas and LPG. The contribution of decentralised, micro-scale renewable energy technologies (e.g. solar photovoltaics and wind power) is so small that it cannot be observed.

In terms of energy consumption per building, this scenario delivers marginal efficiency improvements. Energy use per building is approximately 9% less than in 2005. Compare to baseline #1 (a 5% reduction) and baseline #2 (a 7% reduction), our 'Energy Price Increase' scenario delivers marginal efficiency improvements (around 4% and 2% respectively). These results suggest that overall, decision-makers are much less sensitive to price increases (i.e. inelastic energy use consumption) than command-and-control policy instruments (e.g. zero net energy building regulation or maximum energy use thresholds). Our results seem to be consistent with ex-post policy evaluation studies of the Swedish residential sector, which suggest there have been marginal and incremental efficiency improvements since the 1970s (Nässén & Holmberg 2005).
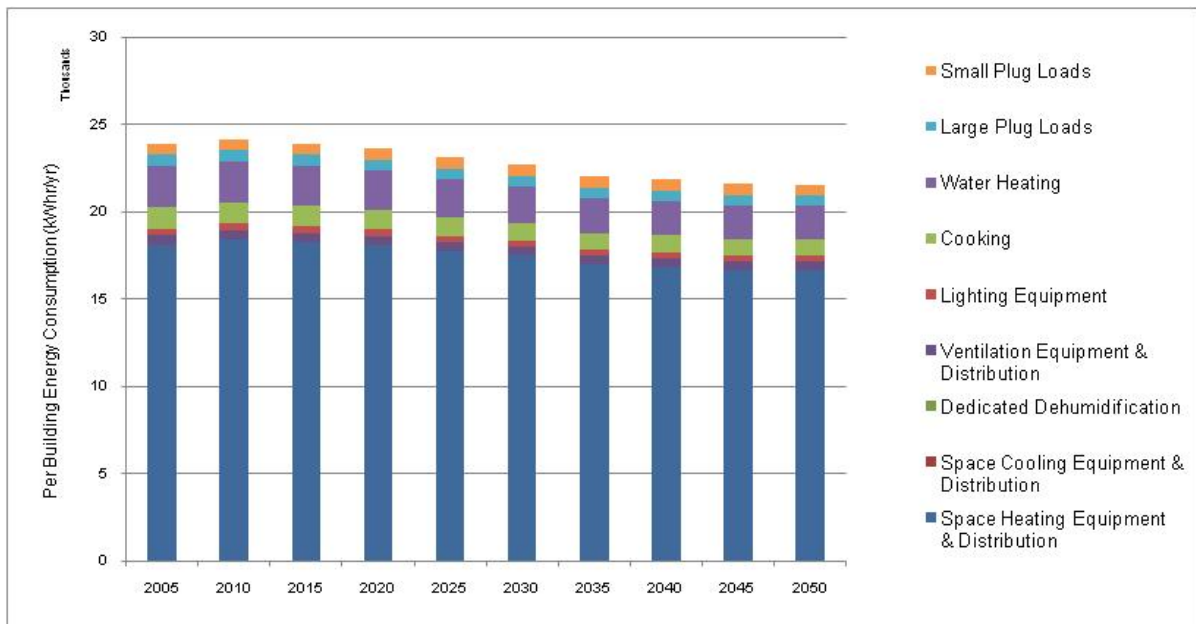
Figure 8: Per-building energy consumption under 'Energy Price Increase' scenario

Our results suggest that owners and tenants are less prone to adopt efficient technologies based on operating costs (i.e. fuel prices). They also suggest that capital-intensive efficiency improvements are not a response to increased fuel costs, as the cost of the investment is seen as comparatively excessive. Small appliances (e.g. kettles) and large appliances (e.g. dishwashing machines) do not deliver substantial energy savings. This suggests that non-financial aspects drive owners and/or tenants to adopt technologies with greater appeal based on other criteria (e.g. appearance, reliability).

3.2. Scenario #2: Net zero energy building regulation

In the context of existing policies, this scenario reduces energy use (after 2020) compared to the two baselines (see Figure 9 and Figure 10). Increases in building stock drives primary energy consumption (heavily dominated by electricity), which grows by 188% in 2050 compared to 2005. However, this figure should be compared with growth rates. Using baseline #1 (a 250% increase), efficiency improvements reduce the growth of primary energy use by 62%. Using baseline #2 (a 242% increase), efficiency improvements reduce primary energy consumption by 54% between 2005 and 2050, approximately.
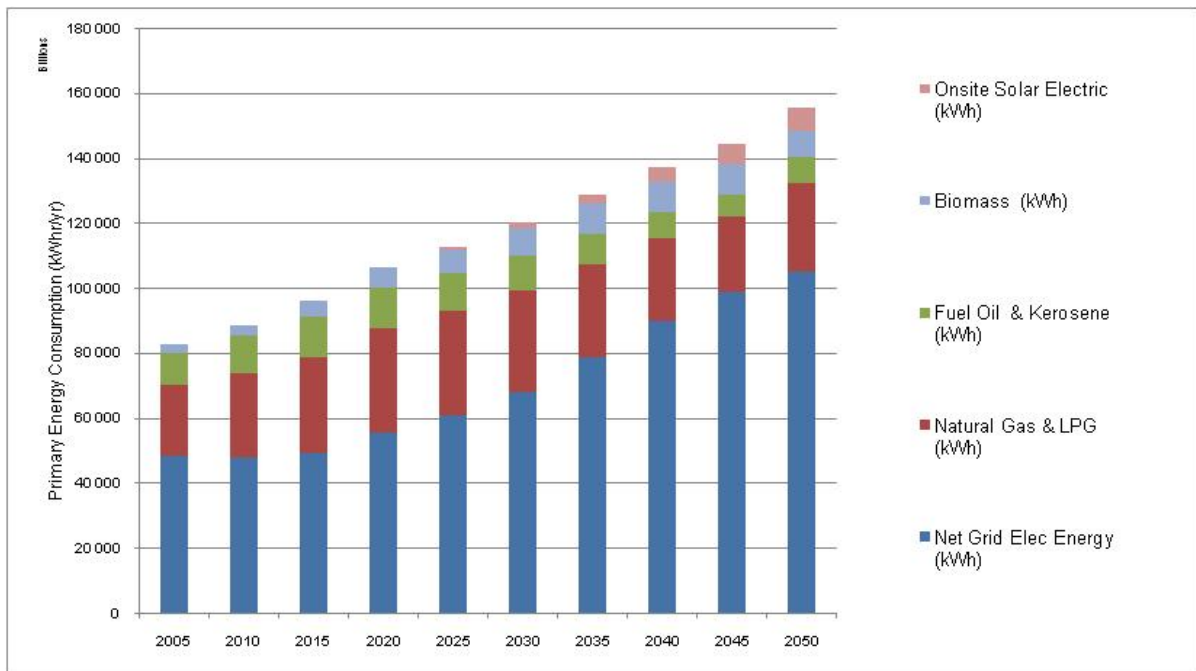
Figure 9: Primary energy consumption under 'Net Zero Energy Building' scenario

Most savings in primary energy consumption involve natural gas, LPG and electricity. Savings are particularly apparent after 2020, when zero net energy building regulations are introduced. Consequently, on-site solar electricity starts to play a significant role and it is the energy source with the highest growth rate.

In terms of energy consumption per dwelling, there is a substantial decrease from 2020 onwards. Energy use falls by 40% in 2050 compared to 2005. Compared to baselines #1 (a 5% reduction) and #2 (a 7% reduction), this scenario delivers efficiency improvements of 35% and 33% respectively. Compared to the fixed building stock (i.e. the number of buildings that do not implement any energy-efficient technology), the efficient building stock uses 70% less energy. Small appliances (e.g. kettles) and large appliances (e.g. dishwashing machines) do not deliver substantial improvements. This suggests that even if efficient technologies are attractive from the financial point of view, in the long term non-financial aspects drive owners and/or tenants to adopt technologies that have greater appeal based on other criteria (e.g. appearance, reliability). In turn, given the way that property owners and tenants use financial and non-financial criteria in their technology choices, our results suggest that technologies that are not directly regulated (e.g. small appliances) are more likely to be driven by non-financial than financial criteria.

On a per-building basis, most efficiency improvements come from space heating. On an even smaller scale, water heating delivers significant improvements. This finding is consistent with other modelling studies (e.g. Lechtenböhmer & Schüring 2011). This scenario suggests that a command-and-control policy instrument, in this case zero net energy building regulations, seems to be an effective way to encourage the construction of single- and two-household buildings that use much less energy.
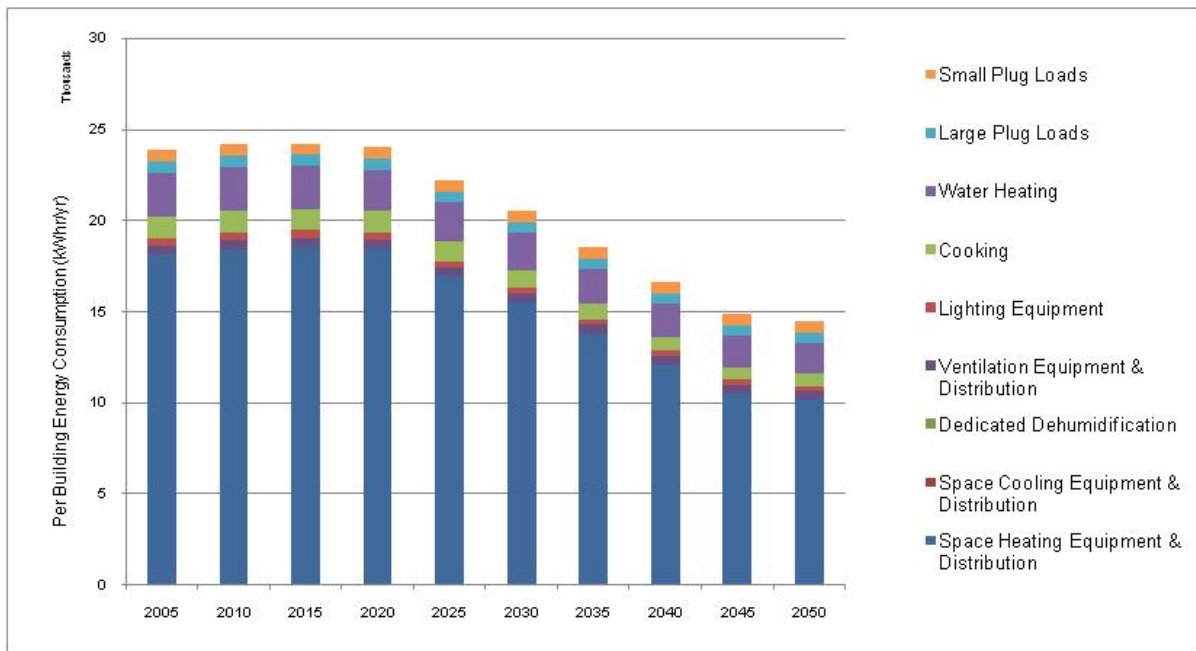
Figure 10: Per-building energy consumption in the 'Net Zero Energy Building' scenario

3.3. Scenario #3: Building system incentives

This policy scenario sees a radical transformation of the sector. Compared to the two baselines, it leads to a vast reduction in primary energy consumption (see Figure 11 and Figure 12).
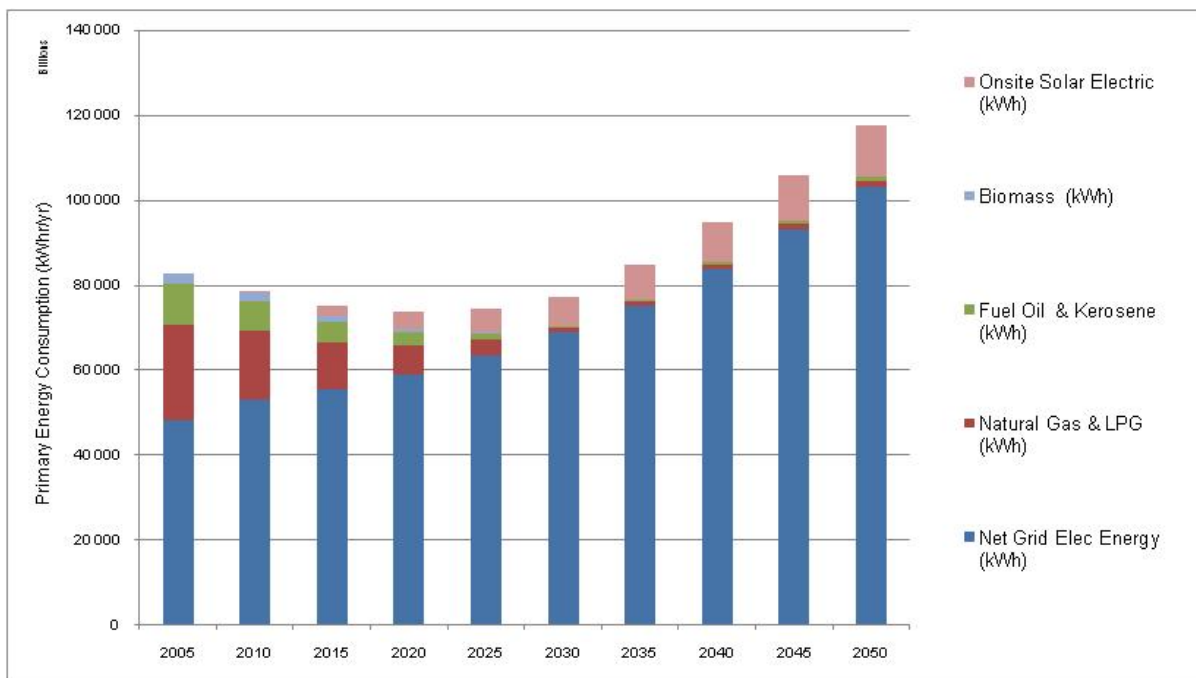

Figure 11: Primary energy consumption in the 'Building System Incentives' scenario

Primary energy consumption grows by 142% in 2050 compared to 2005. However, compared to baseline #1 (a 250% increase) and baseline # 2 (a 242% increase), this policy scenario substantially

slows growth in demand, with efficiency improvements accounting for 108% and 100% respectively. There is fuel switch, and once again, less carbon-intensive fuels (such as electricity) replace natural gas and LPG. After 2025, natural gas and LPG only make a minor contribution to the fuel mix and fuel oil and kerosene are no longer used. Space heating is now heavily "serviced" by highly efficient building envelop (i.e. wall/roof/floor insulation and triple glazing).

In this scenario, micro-scale renewable energy technologies (e.g. solar photovoltaics) contribute to a decentralised energy system. Consistent with the subsidies given to A- and B-class buildings, on-site solar electricity starts to play a role after 2015, and is the source of energy with the highest growth rate. Contrary to expectations, the contribution of biomass to primary consumption disappears after 2030. This may have two possible explanations: 1) a highly efficient building envelop reduces ostensibly the need for heating (main use of biomass), or 2) the need for further calibration rather than the policy scenario simulation as such. In any case, further research is necessary to analyse this specific issue.

In terms of energy consumption per dwelling, there is a substantial decrease from 2010 onwards. Energy use falls by 70% in 2050 compared to 2005. Compared to baselines #1 (a 5% reduction) and #2 (a 7% reduction), this scenario delivers energy efficiency improvements in the order of 65% and 63% respectively. This suggests that building system incentives that address energy use thresholds (e.g. subsidies are only given if 50 kWh/m^2/year is achieved) are more likely to stimulate decision-makers to implement efficiency measures than stand-alone policy instruments.
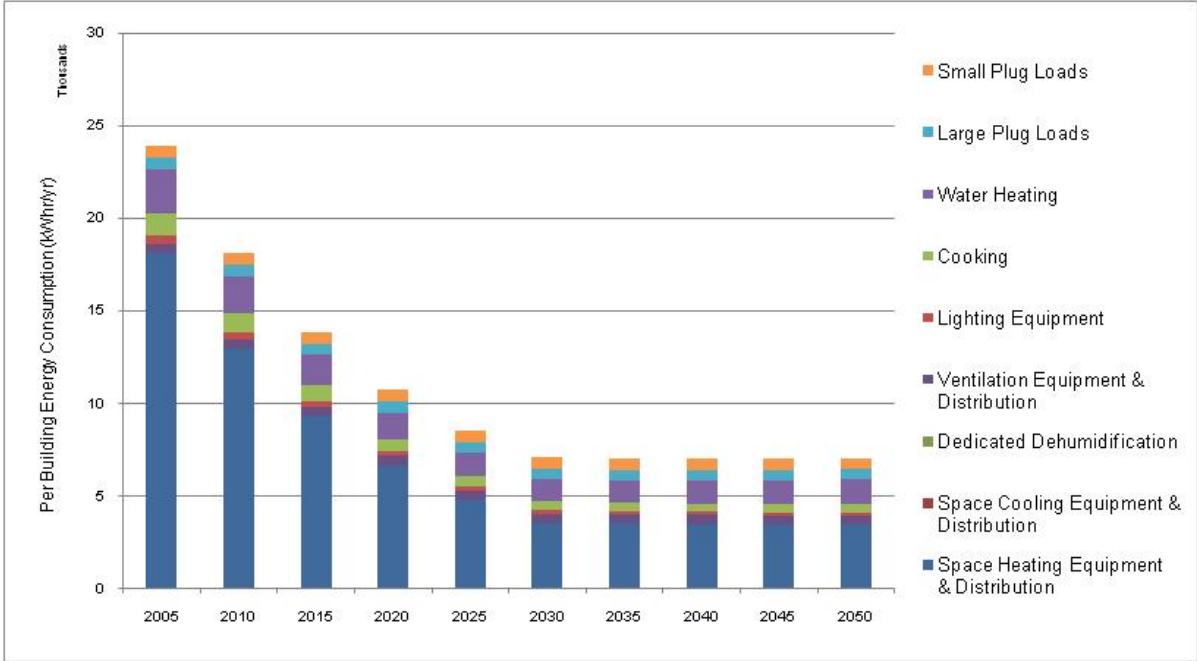

Figure 12: Per-building energy consumption in the 'Building System Incentives' scenario

The efficient building stock is 275% more efficient than the fixed building stock (i.e. buildings that do not implement energy-efficient technologies). Space heating contributes most to efficiency improvements on a per-building basis. On a smaller scale, water heating and cooking also deliver improvements. Small appliances (e.g. kettles) and large appliances (e.g. dishwashing machines) do not contribute to substantial improvements.

These results suggest that even if non-financial criteria for technology choice are included, property owners and tenants are more likely to behave "rationally" in the context of integrated policy mechanisms, i.e. those that focus on whole buildings rather than a single technology.

4. Conclusions

This paper investigated the potential impacts of green energy economic policies aimed at a radical transformation of the construction sector. We used the Swedish single- and two-household residential sector as a case study for the EEB_Sweden model v1.0. The model attempted to capture a realistic microeconomic decision framework for energy-efficient technologies. A particular feature of our modelling approach is the equal weight given to financial and non-financial decision criteria.

Our results suggest that 'Green Energy Economy' policies must be far more ambitious if the building stock is to be radically transformed. It seems that the standard approach, based on isolated or technology-targeted policy instruments, is not effective in achieving dramatic change. In fact, our results strongly suggest that microeconomic decisions (in particular capital decisions) are most affected by ambitious policies that apply to whole buildings, combined with energy (or carbon) pricing.

The results of our simulations suggest that (high) operational costs do not motivate decision-makers to adopt efficient technologies. The main reason for this seems to be the behavioural components included in the model's framework, which is consistent with ex-post assessments. In terms of the sources of efficiency improvements, space heating (via enhanced insulation technologies) contributes most to energy savings on a per-building basis.

With respect to policy instruments, we found that current policies combined with 'Zero Net Energy Building' regulations lead to reduced energy use (after 2020) compared to the two baselines. We also found that decision-makers tend to take a more rational approach to the adoption of new technologies in an integrated policy scenario where the focus is on whole buildings, rather than a single technology. In this scenario, subsidies are given once a building's energy use falls below a certain threshold (e.g. 50~75 kWh/m2/year). Scenario #2 and scenario #3 suggest that ambitious policies can be successful in significantly reducing the energy use of buildings.

The assumptions and early development phase of our model mean that our results must be viewed with caution. This modelling exercise was only a starting point. The model needs further work; in particular, to continue improving the microeconomic decision framework for energy-efficient technology choices. At all events, our findings simply support the view that it is essential for energy-modelling tools to provide a better way to represent determinants if we are to improve our understanding of policy choices and their potential impacts.

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