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Dissertation
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Assessing energy efficiency potential in the building stock

Method for estimating the potential for improvements and their economic effects

Pekka Tuominen

VTT SCIENCE 117

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Pekka Tuominen

VTT Technical Research Centre of Finland Ltd

Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Lecture Hall M1 at Otakaari 1, Espoo, at Aalto University, on the 18th of December 2015 at 12 noon.

ISBN 978-951-38-8372-0 (Soft back ed.)
ISBN 978-951-38-8373-7 (URL: http://www.vttresearch.com/impact/publications)

VTT Science 117

ISSN-L 2242-119X
ISSN 2242-119X (Print)
ISSN 2242-1203 (Online)
http://urn.fi/URN:ISBN:978-951-38-8373-7

JULKAISIJA – UTGIVARE – PUBLISHER

Teknologian tutkimuskeskus VTT Oy
PL 1000 (Tekniikantie 4 A, Espoo)
02044 VTT
Puh. 020 722 111, faksi 020 722 7001

Teknologiska forskningscentralen VTT Ab
PB 1000 (Teknikvägen 4 A, Esbo)
FI-02044 VTT
Tfn +358 20 722 111, telefax +358 20 722 7001

VTT Technical Research Centre of Finland Ltd
P.O. Box 1000 (Tekniikantie 4 A, Espoo)
FI-02044 VTT, Finland
Tel. +358 20 722 111, fax +358 20 722 7001

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Juvenes Print, Tampere 2015

Preface

Among the great challenges facing our generation is climate change, one of the truly global threats to humanity. To counter the perilous rise in temperatures, we must reduce our greenhouse gas emissions to the atmosphere. This means fundamentally shifting our energy use towards less polluting alternatives. Buildings are recognized as the largest energy consuming sector in the world economy. Thus they can be seen as being the greatest culprit behind or having the greatest potential in solving our climate crisis, depending on how pessimist or optimist one chooses to be. To me it signifies that energy efficiency in buildings represents the greatest battle on the largest front in the crucial fight against climate change.

Being able to offer my own contribution to the body of research on energy efficiency in buildings has been a rewarding and worthwhile enterprise, not least because of the support I have received from so many people. I feel that no list can be exhaustive, but especially I would like to express my gratitude to Professor Risto Lahdelma, my supervisor, and Doctor Mari Tuomaala, my advisor, who gave me invaluable guidance throughout the work. I am also grateful to the coauthors of the publications, whose contributions made the research possible. I thank my team leader Jari Shemeikka for giving his full support for the research.

Parts of the research have been conducted in the IDEAL EPBD and NorthPass projects supported by the Intelligent Energy Europe program of the European Commission. One of the publications was enabled by action C24 of COST, a European framework enabling international cooperation between scientists conducting nationally funded research. I have also been supported in various ways by my employer, VTT, and my university, Aalto, for which I am very grateful. Such support towards a better scientific understanding of the problems of energy use is much needed in our time.

Finally, I would like to thank my parents, Helvi Tuominen and Eero Tuominen, for giving me an early interest in science as well as other members of my family for their support and encouragement. And of course, I am grateful to my dear Senni who has made the past years the best ones of my life so far.

Helsinki, 18 November 2015
Pekka Tuominen

Academic dissertation

Supervising professor	Professor Risto Lahdelma Aalto University School of Engineering Department of Energy Technology P.O. Box 11000 00076 Aalto Finland
Thesis advisor	Doctor Mari Tuomaala Technology Manager Gasum Ltd. P.O. Box 21 02150 Espoo Finland
Preliminary examiners	Professor Luís Bragança Civil Engineering Department University of Minho, 4800-058 Guimarães Portugal
	Associate Professor Karl Sperling Department of Development and Planning Aalborg University 9000 Aalborg Denmark
Opponent	Professor Targo Kalamees Faculty of Civil Engineering Tallinn University of Technology Ehitajate tee 5 19086 Tallinn Estonia

List of publications

This dissertation is based on the following original publications which are referred to in the text as I–V. The publications are reproduced with kind permission from the publishers.

I **Pekka Tuominen**, Riikka Holopainen, Lari Eskola, Juha Jokisalo, Miimu Airaksinen, 2014: Calculation method and tool for assessing energy consumption in the building stock. Building and Environment 75, pp. 153–160.

II **Pekka Tuominen**, Juha Forsström, Juha Honkatukia, 2013: Economic effects of energy efficiency improvements in the Finnish building stock. Energy Policy 52, pp. 181–189.

III **Pekka Tuominen**, Krzysztof Klobut, Anne Tolman, Afi Adjei, Marjolein de Best-Waldhober, 2012: Energy savings potential in buildings and overcoming market barriers in member states of the European Union. Energy and Buildings 51, pp. 48–55.

IV Andreas Müller, Lukas Kranzl, **Pekka Tuominen**, Elisa Boelman, Marco Molinari, A.G. Entrop, 2011: Estimating exergy prices for energy carriers in heating systems: Country analyses of exergy substitution with capital expenditures. Energy and Buildings 43, pp. 3609–3617.

V **Pekka Tuominen**, Riikka Holopainen, Paula Ala-Kotila, Guanyu Cao, 2011: Low energy building market trends in Northern Europe. Proceedings of the International Heating, Ventilation and Air-Conditioning Conference, pp. 39–44, Tongji University, Shanghai, China; 6–9 November 2011.

Author’s contributions

The author is the principal author of four publications (I–III, V). In (I) the author is the principal developer of the building stock model and conducted the calculations with it. In (II) the author carried out the building stock, investment cost and externality calculations while the energy system and economic modelling were conducted by the co-authors. In (III) the author conducted the energy and cost calculations for the building stocks and participated in the compilation and interpretation of the results of the interviews. In IV the author carried out the Finnish case study and participated in the development of the methodology. In (V) the author participated in planning the study and interpreted the results while the interviews were conducted by the co-authors.

Contents

Publications I–V

Abstract

Tiivistelmä

List of abbreviations

AGE	Applied general equilibrium
BAU	Business as usual
CES	Constant elasticity of substitution
CO_2	Carbon dioxide
DD	Delayed development (scenario)
DOE	Department of Energy
EU	European Union
GDP	Gross domestic product
GIS	Geographical information system
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
OECD	Organisation for Economic Co-operation and Development
RD	Rapid development (scenario)
US	United States
VTT	VTT Technical Research Centre of Finland Ltd

1 Introduction

1.1 Background

Energy consumption in the world can be attributed to a few major categories of consumers – among them buildings. One quarter of the global energy production is consumed in residential buildings, one tenth in commercial buildings. Commercial and residential buildings represent one of the largest energy use segments in the global economy (IEA 2008). In fact, energy consumption in buildings has been estimated by Farrell et al. (2007) to be the single largest end use for energy in the world.

Thus it makes sense that ever since the energy crisis of the 1970's the buildings sector has been central to the efforts to increase energy efficiency through policy measures. This emphasis given to buildings in energy policy is justifiable if the greatest efforts are to be exerted where the greatest effects can be expected. Studies by IEA (2014), IPCC (2007), European Commission (2006) found the greatest energy efficiency potentials in buildings compared to other sectors of the economy. Their results were corroborated by the industry's own findings published by the World Business Council for Sustainable Development (WBSCD 2009).

The significance of energy efficiency in securing the supply of energy is major. The European Commission (2006) has reported that the improvement of energy efficiency in the EU countries from 1971 to 2005 meant that they now save a total of 33% in their annual primary energy consumption – more than is provided by any single source of primary energy, including oil.

While buildings hold great potential in terms of energy efficiency, typically the time needed to reach that potential can be rather long. This is due to the inertia in the renewal of the building stock. Buildings can have lifespans in the range of 50 to 100 years and each building part is typically renovated only a few times in that time period. The overall renewal rate of the building stock is typically around 1% annually for European countries (Meeus et al. 2012). It is clear, therefore, that major effects from energy efficiency improvements can take decades to be fully realized. Thus, forecasting the development of energy use in the building stock over long periods of time is a necessary undertaking if one is to make informed policy decisions.

Buildings represent also an important, if not the most important, category of tangible investments in industrialized economies. In the United States construction investments represented 53.2% of all fixed capital investments in 2011, in Japan 52.8%, in Germany 54.1% and in Finland 52.6% (European Commission 2014). This underscores the economic importance of buildings not only as major energy consumers but also as investments and property.

Recent international examples of studies estimating the effects of various policies on the energy use of building stock include the following. Sartori et al. (2009) use different categories of buildings to forecast energy use in the Norwegian building stock until 2035. Schimschar et al. (2011) provide forecasts until 2020 for the effects of tightening building regulations in Germany using the energy consumption levels defined in the regulations. McKenna et al. (2013) divide the German building stock into representative buildings and assign these, within the model, into federal states based on statistical information to reach estimates concerning energy-political targets until 2050. This approach has also been used to study even larger building stocks, including by Uihlein, and Eder (2010), who provide forecasts of the effects of different energy efficiency measures in the building stock of the EU-27 countries until 2060. A more exhaustive review of studies extending to the 1990’s is given by Kavgic et al. (2010).

There are fewer studies aimed at assessing the economic effects of energy efficiency improvements in the building stock but some examples can be found, all fairly recent. In Estonia Pikas et al. (2015) have calculated the employment and investment effects of energy efficiency renovations to help develop a national renovation roadmap. Their approach included direct effects only, leaving outside their scope indirect effects in other sectors of the economy. Choi et al. (2014) have studied the community-level economic impacts of energy efficiency improvements in buildings in terms of economic output and employment. However, they limited their study to the level of one city. Liu et al. (2009) conducted economic modelling of building energy regulation on GDP in China. Their approach was a pure top-down economic model that did not include technological details of the improvements in the building stock. In addition to these, the construction industry has lately shown interest in showcasing positive economic impacts from energy efficiency renovations in the United Kingdom (Washan et al. 2014) and the European Union (Naess-Schmidt et al. 2012) with commissioned studies.

While there are numerous studies about the effects of energy efficiency improvements on energy consumption in the buildings stock, fewer studies include economic effects such as changes in GDP, employment and external costs. On the level of national economies, in fact, such studies of economic effects are missing from the scientific literature reviewed. This is a major consideration that merits more attention considering the significant share of buildings in energy consumption as well as the importance of investments in buildings.

1.2 Objectives

The main objective of this thesis is to develop a method for assessing the energy efficiency potential of the building stock and to assess the economic effects of the realization of the potential in terms of changes in GDP, employment and external costs. Energy efficiency potential was estimated by calculating the effects of scenarios based on different energy efficiency measures in representative building types comprising the building stock. The assessment of economic effects concentrates on GDP, employment and externalities. GDP was selected as it is the most commonly used measure of the economic performance of a country. Employment, on the other hand, tends to be a high-interest topic for policymakers, an important potential user of the results. Finally, external costs were included due to the fact that energy consumption tends to entail rather high externalities.

The developed method is useful for the calculation of energy efficiency potentials under different sets of measures. This is needed, for example, for the assessment of the effects of different technologies and policy measures that can be applied to the building stock. Moreover, the presented method allows studying the economic effects of energy efficiency improvements. The economic effects of the changes in energy use will radiate, through the building and energy sectors, throughout the whole economy. Thus, the question of economic effects of energy use is an important one.

1.3 Research approach

To achieve the objective of calculating the energy efficiency potential of the building stock and assessing the economic effects of the realization of that potential the approach presented in Figure 1 was taken. Scenarios entailing different energy efficiency measures applied to the building stock were studied using a building stock energy model to assess the ensuing changes in energy use. Then the various economic effects were studied using economic modelling, externality calculations and an analysis of exergoeconomic effects. Finally, the likelihood of the scenarios was assessed based on an assessment of market demand based on surveying experts in the construction industry and prospective builders. These survey results are offered in support of the interpretation of the results and are not directly related to the chain of argumentation presented in Figure 1.

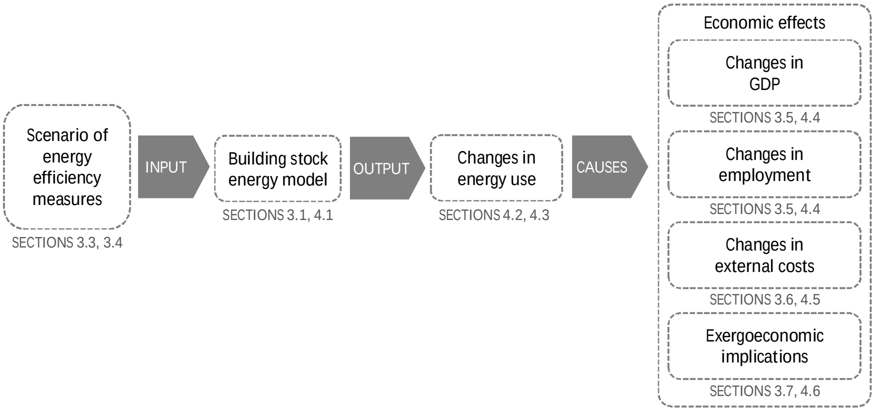


Figure 1. Main topics included in the different sections of the thesis.

Building stock energy modelling is based on an archetypal engineering model of the bottom-up type. This approach was selected because the effects of building-level technological improvements to their energy efficiency are the focus of the study. Such improvements are in the purview of regulation and other policy measures, the impacts of which on the national level are the main interest for conducting the modelling.

During the course of the study, a calculation tool called REMA was developed based on the methods used. The purpose of REMA is to allow conducting similar analyses in the future with relative ease in a systematized way. In this study the complete REMA model was used to study the final case concerning Finland called BAU*, all the other cases presented in this thesis have been calculated using similar methods that are described in detail in Section 2 while not using the finalized REMA model.

Even though the method is meant to be applicable to different building stocks, the Finnish building stock was mostly studied as the method was developed over time. Therefore many of the scenarios studied concern the Finnish case. Similar but more limited analysis was also conducted for a number of EU member states to show the applicability of the approach to different building stocks.

The Finnish case was studied further in terms of economic effects, including employment and GDP, external effects and carbon dioxide emissions. This is necessary to provide context and better understanding of the effects of energy efficiency improvements in the building stock, considering the major role of buildings as energy consumers and the importance of energy to the economy and as a major source of external costs in the form of harmful emissions.

Economic modelling was conducted to find out GDP and employment effects for selected scenarios concerning Finland. Two separate models were used to obtain the presented results. First the POLA model provided the effects on the energy sector. Then the VATTAGE model was used to calculate economy-wide effects of the scenarios using the results of the POLA model as input. The VATTAGE and POLA models have been developed for the purposes of economic evaluation of policy decisions and were thus deemed suitable for the needs of the study.

Changes in external costs were estimated based on the results from the POLA model using estimates concerning the external costs of various energy carriers derived in the ExternE project of the European Commission. Exergoeconomic effects of energy efficiency improvements were analysed to find out whether a correlation can be found between costs and changes in exergy content of the energy use in buildings.

1.4 Outline of the thesis

The thesis begins with Chapter 1 Introduction, where background including the presentation of the context and the gaps in current research are examined. Also presented are the objectives of the thesis and the limitations in the approach selected. Then, in Chapter 2 Theoretical background, literature concerning relevant theories is reviewed. Chapter 3 Methods presents the methods that are used in this thesis to develop the results presented in Chapter 4 Results, the implications of which are discussed in Chapter 5 Discussion and conclusions.

In more detail, following the chain of reasoning presented in Figure 1, the scenarios studied are presented in Sections 3.3 and 3.4, the building stock energy model is presented in 3.1 and 4.1, changes in energy use in the scenarios studied are presented in 4.2 and 4.3, changes in GDP and employment are presented in 3.5 and 4.4, changes in external costs are presented in 3.6 and 4.5 and, finally, exergoeconomic implications are examined in 3.7 and 4.6.

In the publications, Publication I deals mainly with the building stock energy model, Publication II economic effects, III energy efficiency potentials, IV exergoeconomics and V provides a description of the market environment relevant to scenario development. Energy scenarios are presented in Publications I, II and III.

1.5 Limitations

While building stock models are a valuable tool for assessing various policy options, there are also limitations to what can be learned from modelled data. This has to be kept in mind when interpreting the data. Booth et al. (2012) list three types of sources of uncertainty in building stock models. The first issue is model realism, meaning how well the model represents the true underlying process. To address this issue, it is important to provide a transparent description of the model to those who interpret the results.

The second issue is that of heterogeneity, meaning the variation of the characteristics of the buildings within the stock. Any groupings of buildings will inevitably contain some heterogeneity; thus one has to choose a level of satisfactory aggregation balancing accuracy with complexity within the model.

Finally, even within a relatively homogeneous set of buildings there is uncertainty due to two factors: random variation, called first-order uncertainty, and insufficient knowledge about the defining parameters, called second-order uncertainty or epistemic uncertainty. Therefore the well-informed interpretation of modelling results requires comparing them with other sources of information and past experience.

In principle geography does not place limitations for the use of the method presented in this thesis. The method does, however, require that representative building types consuming different forms of energy can reasonably be defined. This can limit areas in the developing world outside the scope of application of this method.

The scenarios in Finland are limited to the energy consumption of space heating in residential, commercial and public buildings. Excluded from the estimate are industrial buildings, storages, buildings in agriculture, forestry and fishery. This was done mainly because in the available records, most importantly those of Statistics Finland (2012), the energy use in these types of buildings is generally included in the energy consumption of the production process. Industries particularly often use surplus heat from production for space heating.

Despite this exclusion, as residential, commercial and public buildings consume the bulk of energy in buildings (excluding industrial processes) in Finland, around 75–80%, the presented estimates are indicative of the total energy efficiency potential (Viinikainen et al. 2007, Environmental administration 2001). The decision to do this limitation in the Finnish scenarios presented in this thesis does not, however, mean that these or other building types could not be included in later studies. The method allows the inclusion of any building types necessary for the scenario being studied.

2 Theoretical background

2.1 Energy modelling of the building stock

The first efforts to study the energy use in the different sectors of the economy using modelling date back to the 1970's. Two distinct classes of energy models soon started to emerge: some used the so-called bottom-up and others the top-down approach. The various bottom-up methods that are in use focus on the effects of individual technologies or consumer-level changes in consumption. Top-down methods, on the other hand, employ a more general approach where the effects of system-wide key factors on energy consumption are investigated. (Swan and Ugursal 2009, Lanza and Bosello 2004.)

Environmental considerations in particular were an early driver for the development of both modelling approaches. The international process to limit greenhouse gas emissions has had a major impact ever since the 1988 Toronto Conference on Climate (Lanza and Bosello 2004). Efforts to limit emissions highlighted the need to understand the consequently needed changes in energy consumption. Buildings quickly became one of the focal points in the efforts to save energy as one of the major energy consumers in the economy. In fact the residential sector in particular has had more energy-related policies put in place than any other sector in the IEA countries (Haas 1997).

In the context of the building stock, top-down methods estimate energy use in buildings based on variables that pertain to the whole buildings sector. Bottom-up methods, on the other hand, attempt to calculate the sum total of energy consumption in the building stock based on limited distinct categories of buildings and their respective sizes and energetic properties, sometimes called archetypes. A more detailed taxonomy of model types is given in Figure 2. (Swan and Ugursal 2009.)

Energy models of the building stock use different types of inputs depending on the type of the model. Different strengths, weaknesses and capabilities result from the choice of modelling approach. For instance, the level of detail in the model can vary greatly depending on the selected methodology, which is also true for the inputs required. Typically input data includes information such as physical properties of the buildings, number of occupants, appliances and equipment in use, historical energy consumption, climate conditions and economic variables. This information can be very detailed or rely on aggregated values such as averages.

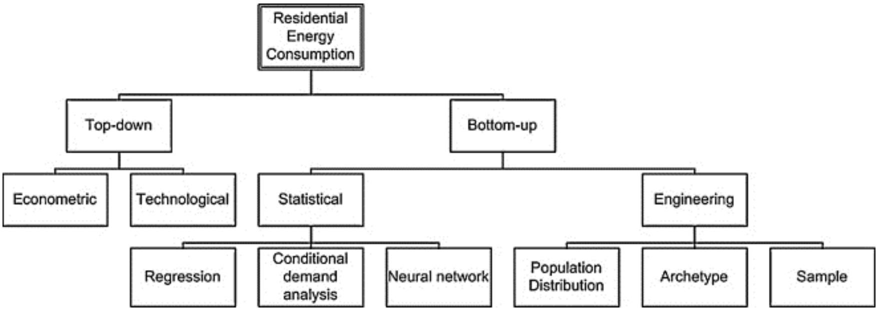


Figure 2. Taxonomy of energy consumption models for the building stock according to Swan and Ugursal (2009).

2.1.1 Top-down approaches

Top-down modelling typically begins with the acquisition of a historical time series of energy consumption in the building stock. Then, based on the historical development, future changes are forecasted based on trend-like changes in the underlying factors. Top-down models usually examine the relationship of the energy sector with the other sectors of the economy. In fact, buildings often are but one of many energy consumers in such a model. As is shown by Figure 2, they can be further divided to econometric and technological models. (Kavgic et al. 2010.)

Econometric models most commonly function using prices (e.g. energy prices and investments) and income data to produce a likely trend line for the future development of energy consumption. They usually utilize variables such as the gross domestic product (GDP), employment and price indices. Technological models, on the other hand, are often based on the market penetration of various appliances, devices and other technologies in the building stock. These can also be combined into hybrid models that incorporate features from both approaches. Common inputs include climatic conditions, construction and demolition rates and appliance ownership data.

In top-down models buildings are generally treated simply as an energy sink and there is no distribution of energy consumption for different end uses. This can be seen as a weakness and strength: some detail is lost in the results but, on the other hand, the amount of knowledge needed about the underlying technologies or consumption processes is also limited. Moreover, top-down models can usually be operated with highly aggregated data that is often easily available from statistics or similar sources. (Swan and Ugursal 2009.)

Top-down models have the greatest strength in forecasting relatively small changes in past developments in the short term. Given the slow renewal rate of the building stock – typically around 1% annually for European countries (Meeus et al. 2012) – and the rarity of sudden changes in construction and energy consumption practices, the assumption that past developments can be used to produce reasonable estimates of the future is usually sound.

On the other hand, large and sudden changes can be a major source of uncertainty for top-down models. Thus the reliance on historical data is also a drawback. Top-down models are incapable as such to model discontinuous changes in technology. Moreover, lack of detail concerning individual end uses of energy greatly diminishes the possibility of recognizing key areas for improving energy efficiency. (Kavgic et al. 2010.)

2.1.2 Bottom-up approaches

Perhaps the most inclusive definition of bottom-up models is that they are all models that “use input data from a hierarchal level less than that of the sector as a whole” (Swan and Ugursal 2009). For models of building stock energy use, it can be summarized that they utilize disaggregated data concerning energy use within buildings to produce sum totals concerning the energy use in the whole building stock (Kavgic et al. 2010).

Bottom-up models contain varying amount of detail concerning the composition of the energy consumption totals. They can be based on the energy consumption in different end uses, individual buildings or groups of buildings. These data are summed using the representative weight of each category of energy consumption in the sample.

Bottom-up models are divided broadly into two categories, as is shown in Figure 2. Statistical models, on the one hand, operate based on historical data and regression analysis to find out how total energy consumption is divided to different end uses. Engineering models, on the other hand, present the division to different end uses based on the technological characteristics of each type of end use. This can be for example the power consumption of devices or the thermodynamic properties of building parts. Such level of detail is a strength of the bottom-up approach, allowing the models to be used for examining various alternative technologies. It also signifies that the model has the capacity to calculate energy consumption totals without relying on historical or trend data. Another strength of the approach is the capability to study occupant behaviour and passive energy gains such as solar radiation.

Resulting models have a tendency to develop to high levels of complexity. This means that the input data can also be rather detailed, which is can be considered to be the major drawback of the bottom-up approach. (Swan and Ugursal 2009.)

2.2 Scenario analysis

In economic research a scenario is broadly defined as “a set of assumptions on policy choices and the values of exogenous variables that will be used to determine the future developments” (Black et al. 2009). Scenario analysis can be used for example to study the effects of different policy alternatives or to assess how conclusions are affected by changes in selected exogenous variables.

The most common use of sectoral energy models is to compare the effects of different scenarios to each other. This applies also to building stock energy models. In a study, scenarios can either be made highly different from each other or only having relatively small individual changes in them akin to a sensitivity analysis. A common use for the results is for informing government officials, who are interested in finding out the effects of different policy alternatives. (Sathaye and Sanstad 2004.)

A baseline scenario is produced for the purpose of comparing the other scenarios to it. It reflects the world without the proposed policy measures or other changes to be studied in the alternative scenarios. It also serves as the starting point for the development of the other scenarios. As the analysis of the results will be done by comparing with the baseline, it is important that its specifications are sound. Usually a lot of background research is needed to produce a baseline scenario that agrees with existing statistics, forecasts, projections and plans to a reasonable extent. (EPA 2014.)

The other scenarios assume conditions that are exogenous, meaning activities or effects that are based on external estimates or projections rather than being produced by the model. These conditions typically represent technological, policy or price changes. Projections start from the base year values of the various variables and then divert from the baseline according to the scenario definitions. The main use for the results is to examine the ramifications of alternative paths for future. (Sathaye and Sanstad 2004.)

2.3 Building stock energy modelling in Finland

Early use of building stock energy modelling in Finland include a bottom-up model for the North Karelia region developed and used primarily in the 1990’s by Snäkin (2000), and work done at VTT and Tampere University of Technology on building stock models and energy consumption models leading to the development of first ISREM and later EKOREM and POLIREM models also of the bottom-up type (Heljo et al. 2005). Moreover, Statistics Finland has used a bottom-up energy model to calculate annual energy statistics for buildings since 1995 (Aalto 2009). Among these, EKOREM has been used most for published studies and is presented here in more detail. ISREM is an earlier development no longer used in published research, while POLIREM is mentioned to be still under development.

Presently in use for scenario analyses, in addition to the method presented in this thesis, is the EKOREM model. It was developed at the Tampere University of Technology in cooperation with VTT Technical Research Centre of Finland in 2003–2005 (Heljo et al. 2005). According to Heljo et al. (2005) the EKOREM was developed based mainly on the following past research and sources: Statistics Finland, which for its part uses the building registry of the Population Register

Centre, the national statistics for new construction, VTT's KORVO and REMO studies from 1982, 1990 and 2000 concerning renovations and VTT's periodical surveys concerning new construction. After EKOREM, the researchers have been working on a new model called POLIREM (mentioned e.g. in Vihola and Heljo 2012), the results of which remain unpublished as of early 2015.

The EKOREM model has been used for estimating the current energy use and the ensuing CO_2 emissions in the existing Finnish building stock (Heljo et al. 2005) and to produce scenarios of future development (Vehviläinen et al. 2010). Other results from the EKOREM model include an assessment of the effects of electric heating and heat pumps on energy consumption and emissions (Heljo and Laine 2005), the energy efficiency potential of energy renovations in Finland (Heljo and Vihola 2012) and more specifically in the housing stock of Tampere (Heljo and Vihola 2011). Moreover, EKOREM has served as a source of data for a study of geographical information system (GIS) based visualization of energy use and emissions (Mattinen et al. 2014).

3 Methods

The approach used in the research presented in this thesis is an archetypal engineering model of the bottom-up type, as presented in Section 2.1 and in Figure 2. This approach was selected because the effects of building-level technological improvements to energy efficiency are the focus of the study. Such improvements are in the purview of regulation and other policy measures, the impacts of which on the national level are the main interest for conducting the modelling.

In archetypal methods, such as the one developed in this study, building types are defined that can be satisfactorily used to represent the building stock. This process is presented in Section 3.1 and in more detail in Publications I, II and III.

Next, scenarios need to be defined that contain different energy efficiency measures in the building stock. This is presented in Sections 3.3 and 3.4 and again in more detail in Publications I, II and III.

3.1 Rationale for selecting building types

In this thesis bottom-up scenario modelling is used to calculate energy use in the building stock. The selected approach entails using representative building types, archetypes in the IEA nomenclature (Hobday 2005), for estimating the energy consumption in different segments of the building stock. Future developments are estimated using annual rates of new construction, renovations and removals from the building stock. This approach is described in more detail in Publications I, II and III.

A limited number of representative building types are selected and their energetic properties are used to calculate the energy consumption of that particular building type in the building stock. In the model data on the building stock is divided into four categories: detached houses, apartment buildings, commercial buildings and holiday homes. Detached houses are understood as one-family residences. Apartment buildings are defined as having more than one apartment, meaning multi-storey buildings and row houses. Commercial buildings are defined as being in commercial use (offices, stores etc.) or public buildings (schools, hospitals etc.). Holiday homes represent a relatively small portion of the building stock, but their importance as energy consumers is growing in Finland as more and more are equipped with electricity and heating, therefore they were included as a fourth category.

Moreover, each category is divided into age groups: buildings constructed before 1959, during 1960–1979 and during 1980–2009. These age groups were chosen because of the availability of compatible data (Heljo et al. 2005) and they represent distinct periods in the history of the Finnish building stock: 1960–1979 saw mass urbanization and an accelerated pace of construction using new methods such as prefabrication. Buildings older than that typically used more traditional methods and were often built of wood. After the energy crises in the 1970's more attention was paid to insulation, airtightness and mechanical ventilation became more commonplace, meaning again a change in the makeup of the building stock. For the international comparison presented in Section 3.4, a similar logic was used but the age groups were different for each country depending on classifications used in the statistics available.

Similarly, new buildings are assumed to have different properties depending on the time period when they will be constructed. The model also allows the user to define parallel building types to be built at the same time with varying energetic properties, dubbed A, B and C. This only applies to future buildings. The division into building types and nomenclature used in the model is presented in Figure 3. In the international scenario of Section 3.4, new buildings were omitted altogether and only renovations were considered.

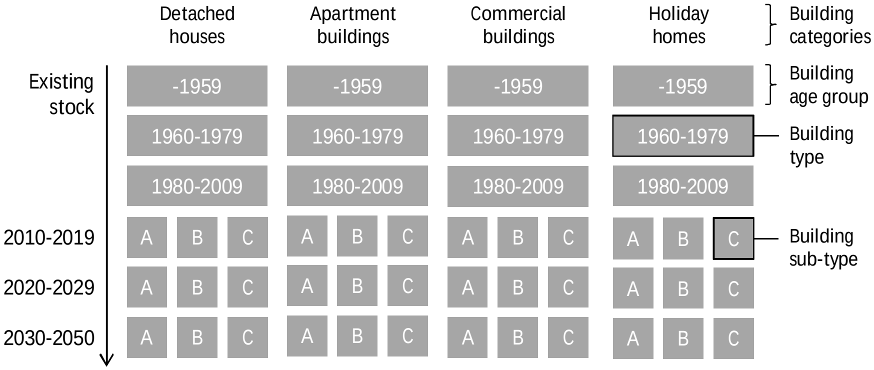


Figure 3. The division of the existing and future building stock into building categories, age groups, types and sub-types called here A, B and C. Building age group refers to all building types of same age, whereas building type only refers to a certain category of building of a certain age.

The data concerning the building stock was obtained from the EKOREM model (Heljo et al. 2005). The forecast used as a basis in the REMA model, presented in Table 1, was made in 14.10.2007 by Harri Nuutila at VTT and was included in Publications I and II. For holiday homes the development of the stock follows the forecast published by Rytkönen and Kirkkari (2010): 490 000 holiday homes with an average area of 44 m^2 in 2007 and 550 000 in 2020, with the growth proceeding in a fairly linear fashion. For longer periods, extrapolation is used.

The reduction of old building stock, shown in Table 1, was assumed to consist mostly of the oldest buildings in the stock. Thus the share of buildings built before 1960 would fall at a faster rate than the share of those built during the 1960’s and 1970’s, which in turn would outpace those built after 1980’s.

Table 1. The forecast development of the Finnish building stock.

	Building stock (1000 m^2)			Reduction (1000 m^2)		Construction (1000 m^2)	
	2007	2020	2050	2007–2020	2020–2050	2007–2020	2020–2050
Detached houses	142 000	163 800	180 200	8 100	44 800	29 900	61 200
Apartment buildings	116 200	128 700	131 000	3 800	29 300	16 300	31 600
Commercial buildings	101 800	112 100	119 400	17 700	46 400	28 000	53 700
Total	360 000	404 600	430 600	29 600	120 500	74 200	146 500

3.2 Assessing the demand for energy efficiency in buildings

The increase of energy efficient buildings is not only dependent on the availability of the necessary technologies but also on the demand in the market. In Publication V the market situation was studied in Finland and three other Northern European countries to assess the likely development of energy efficient construction in the near future. The surveys are described in greater detail in Ahvenniemi et al. (2011). Results for Finland are used in this thesis as one approach to assess the likelihood of the various scenarios studied.

Two surveys in a questionnaire form were carried out in the participating countries and were similar in each country apart from questions which needed some country specific modification. The research teams in each country decided on the execution of the surveys. The results of the questionnaires were sent to VTT where the data was entered into a database run with Digium software for analysis and reporting.

The builder survey was targeted at individuals, who were building a single family house. The main purpose of this survey was to find out the interest to build low-energy house and what options builders considered and into which result did they arrive. This market sentiment can be used to assess the likelihood of the different scenarios: if high interest is observed, then more optimistic scenarios appear likely. The target group was land owners who had no building permit or who had a permit but had not started building yet. For finding the respondents the help of local authorities, architects, product suppliers, organizations and fairs was used. In total 102 persons were surveyed in Finland.

The aim of the expert survey, on the other hand, was to find out the amount of low-energy houses, level of costs, stage of development of the business, experiences of the industry and market situation in general. The target group for expert survey was different stakeholders, such as representatives of the industry, authorities, researchers and officials of organizations. The questionnaires were distributed through workshops, symposiums, conferences and emails, depending on the country. Altogether 40 experts were thus surveyed in Finland. As was the case with the builder survey, the observations concerning the construction industry gained from the expert survey are used to assess the likelihood of various scenarios.

3.3 Scenarios for the Finnish building stock

The development of the building stock was studied with a scenario based approach. The future heating energy consumption in buildings was estimated based on the forecast development of the Finnish building stock in the coming decades, estimates of typical energy consumption for different kinds of buildings and the expected rate of renovations. Using this method, four scenarios for future development in Finland were created. These are listed in Table 2. BAU, DD and RD were studied before the completion of the REMA model while BAU* was calculated using the complete REMA model.

Table 2. Scenarios concerning the Finnish building stock.

Short name	Full name	Short description
BAU	Business as usual	Continuation of construction practices of 2008 with no change.
DD	Delayed development	Slow increase in energy efficient construction and renovation.
RD	Rapid development	Fast increase in energy efficient construction and renovation.
BAU*	Updated business as usual	Update of BAU after the 2010 EPBD directive (European Commission 2010)

The baseline scenario for Finland is called Business as usual (BAU); it was made based on the assumption that buildings continue to be built according to the practices prevalent in 2008. Delayed development (DD) and Rapid development (RD) scenarios are compared to BAU to quantify the energy efficiency potentials and the economic consequences of their realization. The BAU scenario is not meant to be in any way prognostic. Rather, it offers the possibility to compare the present level of efficiency to more likely future scenarios. DD and RD scenarios are based on BAU, but they assume that future developments will take a different path in a number of ways. Both heating energy and electricity consumption in buildings are considered. All three scenarios are presented in detail in Publication II.

Delayed development (DD) assumes that the share of low-energy buildings will gradually increase so that by 2030 most new detached houses are low-energy houses whereas among the rest of new construction low-energy buildings will achieve similar market penetration ten years later. Passive buildings will become the norm much later, in the 2070’s and 2080’s. Furthermore, it is assumed that modest energy efficiency improvements will be completed in buildings that would undergo renovation in any case for other reasons.

Rapid development (RD) assumes that the share of low-energy buildings will increase rather quickly so that by 2015 most new detached houses are low-energy houses. Other construction will follow the development rather quickly, so that low-energy buildings will become the norm by 2020. Passive buildings will follow suit and be the norm in new buildings by the 2030’s. Moreover, it is assumed that thorough energy efficiency retrofits will be completed in buildings that would undergo renovation in any case for other reasons.

For construction and reduction rates the scenarios follow the development presented in Table 1. Concerning renovations, in both DD and RD scenarios the annual amount of energy efficiency improvements completed during renovations is assumed to be the same, namely 3.5% of the building stock built before 2008. This rate was chosen because it agrees with the observed number of renovations in relevant building parts (Vainio et al. 2002) and because at that rate all of the building stock will be renovated once by 2040–2050. Given that the building envelope should usually be renovated every 25 to 35 years (Virtanen et al. 2005), the assumed rate of renovations seems very reasonable, even conservative.

While the study was underway, more changes were introduced in the building code based on the recast of the EPBD directive of the European Union (European Commission 2010). In accordance with these changes, an update of the Business as usual scenario, BAU*, was produced for Publication I. While DD and RD were speculative in nature, BAU* is based on actual policy changes enabling a comparison with BAU and representing a new baseline for future research. At the same time BAU* is the only scenario that has been calculated with the finalized REMA tool, whereas the others represent results from a calculation method still under development. Namely, for new buildings in BAU, DD and RD a Gaussian S-curve representing gradual increase in the rate of adoption for new technology was used. In the REMA model and for BAU* scenario this approach was substituted with immediate changes in construction practices at particular years. Even though the gradual change approach is likely to be a more realistic depiction of the actual development of the building stock, it complicates the model while having relatively modest effects on the results. The renewal rate of the building stock being at around 1–1.5% a year, effects on energy consumption accumulate slowly in any case. Using the midpoint of the Gaussian S-curve as the timing of an immediate change will produce similar results when the interest is in medium to long-term effects.

3.4 Scenarios for selected EU countries

An international comparison of energy efficiency potentials was done concerning selected EU member states in Publication III. Only one scenario was calculated in addition to the baseline. This calculation spanning nine different countries serves to demonstrate the applicability of the methodology developed in the course of this research to various different building stocks. A similar logic to that presented in Section 3.1 was used for dividing the building stock to building types and age groups. However, here the age groups were different for each country depending on classifications used in the statistics available.

As this part of the study took place before the completion of the REMA model, the approach used was more limited in scope than in the Finnish scenarios presented in Section 3.3. This approach differs from the scenario assessment done for Finland in Publications I and II. The main methodological difference in that in the Finnish scenarios renovation rates were based on historic renovation rates, whereas here the economicality of renovations was used as the criterion. Only economically viable energy renovations in the residential building stock by the year 2020 and 2030 were included. Moreover, here only heating energy is considered. The countries included were Bulgaria, the Czech Republic, Denmark, Finland, Germany, Latvia, the Netherlands, Portugal and the United Kingdom. These were selected based on the availability of data from partner organizations participating in the study.

The inventory of housing stock was compiled from data collected by the research teams from each country participating in the European research project IDEAL EPBD. The method chosen here is similar to Nemry et al. (2010) in the criteria for defining building typologies. Research partners in each country provided their respective stock data including the following information:

- Size of housing stock categorized by two general types of buildings: single-family houses and apartment buildings. Dwellings were also grouped by age.
- Past and expected rates of renovations aimed at improving energy efficiency of homes.
- Types and costs of different energy efficiency measures, etc.

The data on the housing stock collected from each country provided a baseline for the energy efficiency potential for existing dwellings. Age groups varied between the countries depending on the categories used in the data provided, as is seen in Table 3. The calculations were carried out for each country separately. The necessary data was collected by the project partners in the various countries and supplemented with expert estimates where figures were not available. The primary sources are listed in Publication III.

To start estimating the energy efficiency potential, first the data on the size of each age group of buildings and their respective heating energy consumption was used to calculate the present energy consumption to be used as a baseline. Then, for each type of energy efficiency improvement, an effect on the energy consumption and a price for the improvement was acquired from the various countries. The costs of each improvement were annualized for ten years with a discounting rate of 10%.

Table 3. Age groups in each country.

Country	Age groups
Bulgaria	–1960, 1960–1969, 1970–1979, 1980–1989, 1990–
Czech Republic	–1970, 1970–1980, 1981–
Denmark	–1931, 1931–1950, 1951–1960, 1961–1972, 1973–1978, 1979–1998, 1999–
Finland	–1960, 1960–1969, 1970–1979, 1980–
Germany	–1919, 1919–1948, 1949–1957, 1958–1968, 1969–1978, 1979–1983, 1984–1994, 1995–2001, 2002–
Latvia	–1960, 1960–1969, 1970–1979, 1980–
Netherlands	–1960, 1960–1969, 1970–1979, 1980–
Portugal	–1990, 1990–2001, 2001–
United Kingdom	–1960, 1960–1975, 1976–1982, 1982–

Selecting a discounting rate is particularly challenging in the residential sector, as the circumstances of each household can vary significantly. Short et al. (1995) have reported empirical observations of implicit discount rates as high as 25% and 39% for energy efficiency investments in the residential sector. Generally, the discount rates appear to be much higher than the cost of capital. Possible explanations include uncertainties in the investments, shortness of residency periods compared to investment periods, limits in income and availability of capital and noneconomic factors. The recommendation of US DOE is followed here of using the 10% rate for the residential sector when investment-specific data is not available. (Short et al. 1995.)

To get a price for the energy saved, the annualized costs were divided by the annual energy savings of the improvement in question. For each country, the prices of energy saved were compared with local electricity prices (Zwanenburg 2009). When the cost of energy saved was lower than the price of electricity, an improvement was deemed cost-effective.

For each age group of buildings it was calculated how much energy consumption would fall, if the cost-effective improvements were implemented at the expected autonomous renovation rate. Since these renovations would occur in any case, the price for efficiency improvements is substantially lower than if implemented independent of other renovations. For each age group the new energy savings achievable each year will be the product of the autonomous renovation rate, the total area of that age group and specific energy savings of the improvements deemed cost-effective for that age group. Then summing for all age groups in the country, the total new annual energy savings are obtained. Cumulating these annually achieved new savings for a given year, an estimate of energy efficiency potential for that year in the country was calculated.

3.5 Assessment of economic effects for the Finnish scenarios

The economic effects of energy efficiency improvements in BAU, DD and RD scenarios, concerning the Finnish building stock, were studied in Publication II. To estimate the investments required for energy savings, two separate methods were employed: one for new buildings, another for renovations. In accordance with Viinikainen et al. (2007), for low energy buildings a construction cost 4% higher was chosen, for passive buildings 10%.

The investment costs in BAU were estimated based on the present level of investment, as reported in the official national statistics (Statistics Finland 2007). The costs were scaled by the anticipated changes in construction. The investment estimate of BAU formed the basis for similar calculations in DD and RD scenarios. Using the shares of each building type and the said estimates of cost increases, the annual investment in low energy and passive buildings were calculated.

For energy efficiency retrofits, a cost estimate based on the applied measures is used. As both DD and RD scenarios assume improvements only in buildings that would be renovated regardless of energy efficiency considerations, the cost estimates include only the supplementary cost caused by the actual efficiency improvements and not the total renovation cost. This is far less than what a dedicated energy efficiency retrofit of similar scope would cost.

The cost of renovation is rather different for small houses and large buildings. Therefore two different estimates were used for each. For detached houses the estimate was based on Holopainen et al. (2007), for buildings of all other types, an IEA survey (Waide 2004). These cost estimates were for mature technologies at the time. As new technologies mature, wider adoption of them and economics of scale can bring costs down. Since the studies are about ten years old, that could mean that somewhat higher efficiency improvements would be available nowadays for the same level of investment.

For both houses and other buildings in the RD scenario, similar exercises were conducted. As each additional efficiency investment tends to be less cost-effective than the preceding ones, the cost per energy savings is higher in the more thorough renovations assumed in RD.

Finally, having reached cost estimates for each level of improvement for both types of buildings, the estimates were used with the assumed amount of renovation to calculate the annual investment cost.

Economic modelling was conducted to find out the effects on GDP and employment of the DD and RD scenarios. Two separate models were used to obtain the presented results. First the POLA model provided the effects on the energy sector. Then the VATTAGE model was used to calculate economy-wide effects of the scenarios using the results of the POLA model as input. This modelling sequence is presented in Figure 4.

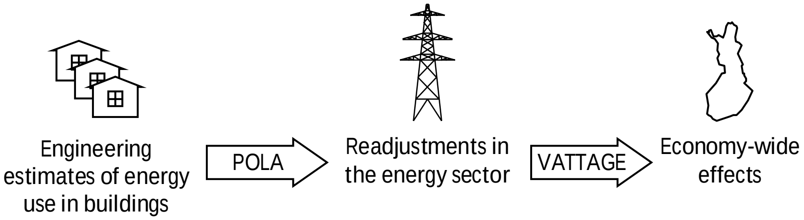


Figure 4. The modelling sequence used to estimate the economic effects. Engineering estimates of energy use in buildings were used as inputs for the POLA model that was used to analyse readjustments in the energy sector. POLA model calculated the investments in energy infrastructure as well as changes in energy consumption. These were then used as inputs for the VATTAGE model to calculate economic effects.

The VATTAGE and POLA models have been developed for the purposes of economic evaluation of policy decisions and have been gradually improved based on their past performance. POLA was developed at VTT and it is based on the commercially available What's Best modelling environment. A detailed description of the model is available at request from VTT (Forsström 2004). VATTAGE is a dynamic applied general equilibrium (AGE) model based on the Australian MONASH model (Dixon and Rimmer 2002). It is a traditional comparative-static AGE that uses Leontieff and CES aggregators. A detailed description of the model has been published by Honkatukia (2009).

The POLA model is a partial equilibrium model of the Finnish energy sector. It uses linear programming to calculate partial equilibriums of energy production and consumption. In other words, the model calculates a clearance on the market for energy independently from prices and quantities demanded and supplied in other markets (Forsström 2004). Thus the energy sector adjusts dynamically each year to changes in the market. It uses as inputs the annual energy consumption numbers from the scenarios presented here.

In the VATTAGE model the economy has macroeconomic constraints for employment, capacity and external balance. Price signals are the drivers in the adjustment of the economy. Currently the model aggregates the economy into 51 sectors of industry and 43 commodities. Yearly input-output tables of the Finnish national economy are used to update the model. For the energy sector, these are acquired from the results of the POLA modelling.

Three inter-temporal links connect consecutive periods in the model: accumulation of fixed capital, accumulation of financial claims and lagged adjustment mechanisms, such as the labour markets and the public sector budget. Together, these mechanisms result in gradual adjustment to any policy shocks to the economy. (Honkatukia 2007.)

This combination of models suits well to the problem at hand, given their development history that has aimed for the estimation of the economic effects of policy decisions. Nevertheless, the results of any economic modelling should not be taken as a final analysis of the problem, rather they offer helpful insight into the potential effects of given scenarios under certain assumptions and are, therefore, contingent on those assumptions.

3.6 Assessment of external costs for the Finnish scenarios

External costs, also called external effects or externalities, occur whenever the decisions of economic agents cause incidental costs or benefits borne by others that are not reflected in market prices. Energy use as an economic activity tends to entail especially severe negative environmental externalities, therefore they merit particular attention and were included in the analysis of BAU, DD and RD scenarios in Publication II.

Table 4. External costs in electricity production in Europe in c/kWh as reported by the European Commission (2003).

Country	Coal	Peat	Oil	Gas	Nuclear	Biomass	Hydro	Solar	Wind
Austria				1-3		2-3	0.1		
Belgium	4-15			1-2	0.5				
Germany	3-6		5-8	1-2	0.2	3		0.6	0.05
Denmark	4-7			2-3		1			0.1
Spain	5-8			1-2		3-5*			0.2
Finland	2-4	2-5				1			
France	7-10		8-11	2-4	0.3	1	1		
Greece	5-8		3-5	1		0-0.8	1		0.25
Ireland	6-8	3-4							
Italy			3-6	2-3			0.3		
Netherlands	3-4			1-2	0.7	0.5			
Norway				1-2		0.2	0.2		0-0.25
Portugal	4-7			1-2		1-2	0.03		
Sweden	2-4					0.3	0-0.7		
Britain	4-7		3-5	1-2	0.25	1			0.15
Average	5.71	3.50	5.70	1.79	0.39	1.13	0.43	0.60	0.15

*Cofired with lignite

The externalities of energy consumption are especially significant compared to market prices. Hall (2004) has estimated that for many energy sources negative externalities amount to well over 100% of the market price. Table 4 shows the external costs in a set of European countries with current levels of technology as they were estimated by the ExternE research network (European Commission 2003). Included in the figures are all major types of externalities that are quantifiable, such as global warming, public health, occupational health and material damage.

The results reported by the ExternE research show that in some countries some energy sources can cause externalities as high as 15 c/kWh, while others as low as less than 1 c/kWh. This can be compared to the price of electricity from the Helsinki city electric utility, 7.44 c/kWh or 13.36 c/kWh including transmission (Helsingin Energia 2011).

The highest costs come from direct health damage, damage to ecosystems and, above all, global warming. These effects are all caused by harmful emissions. Hence, it is no surprise that the energy sources that entail no polluting emissions are the ones with external costs of less than 1 c/kWh, namely nuclear, solar, wind and hydro energy. (European Commission 2003.)

ExternE has published typical external costs per energy unit produced for each energy source in different European countries. The figures for Finland were multiplied with the energy production data obtained from the POLA model. Where figures for Finland were not available, European averages were used. It should be noted that some forms of external costs are difficult to evaluate, especially the value of climate change mitigation.

3.7 Exergoeconomic analysis of different energy carriers

When studying energy efficiency potentials, it makes sense to differentiate between different energy carriers such as electricity, various fuels and district heat. This is ultimately due to the different physical properties of these energy forms, most important of which is the ability to do work, also called exergy content. This issue has also economic importance. To demonstrate that exergy value indeed correlates with economic value in common energy carriers for heating, the issue was studied with an analysis of cost and technology data for different heating systems in Finland and three other countries in Publication IV.

The hypothesis presented here is that a correlation should be possible to find between the exergetic value and monetary value of an energy carrier, as the ability to do work has economic value in real terms. Concentrating on heating, it is further postulated that energy prices reflect the exergy content of the energy carrier and that capital expenditures can substitute for exergy to some degree.

The forms of energy at the disposal of the economy can be classified according to their exergy content, that is, their ability to perform potentially useful work. For energy carriers of highest quality such as electricity, the exergy factor is 100%, chemical energy carriers such as oil, gas and biomass count as superior and do have a exergy factor in the vicinity of 95% (Hepbasli 2008, Wall 1977). The exergy content of heat depends on the temperature of the energy carrier and the temperature level of applicable ambient (dead state).

A maximum exergy of 85% is derived in Publication IV for a fully oxidized combustion. In contrast, the exergy content indicate that chemical energy could in principle be converted into other forms of energy by up to ~95%. The difference defines the exergy destruction that is unavoidable for thermodynamic causes and the highest achievable combustion temperatures with current technologies. The equation yields the exergy contents presented in Table 5 for the different energy carriers.

In order to conduct research on the exergy content of energy carriers, the system boundaries are drawn around the final consumer, namely a representative reference building. The energy, exergy and financial streams passing through the system boundaries will be analysed. The system boundary has important implications on the following analysis. Firstly, upstream energy losses (e.g. in the electricity grid or during electricity production) are not considered. Secondly, all financial streams and the underlying prices and costs are based on consumer prices. Finally, upstream infrastructure (e.g. electricity or heating grids) and its related cost structure are not analysed. This is done as it is assumed that the costs of the infrastructure are incorporated in the consumer prices. For grid connected energy carriers a considerable part of the energy price consists of a base price, which is independent of the actual energy consumption. This base price can actually be understood as an element to take into account the up-front investments into the infrastructure.

Table 5. Exergy content of selected energy carriers.

Energy carrier	Temperature	Reference temperature	Exergy content
Oil, coal, gas	1500ºC	0ºC (-20ºC/+20ºC)	85% (86%/83%)
Biomass	800ºC	0ºC (-20ºC/+20ºC)	75% (76%/63%)
Electricity	-	-	100%
District heat inlet flow	100ºC	0ºC (-20ºC/+20ºC)	27% (32%/21%)

Total fixed costs consist of levelled investment cost of the heating system and annual operating and maintenance cost. For calculation of the levelled investment costs a depreciation time of 20 years was used. Annual operating and maintenance costs include the annual fixed amounts paid to the energy supply company regardless of the actual energy consumption.

Regression analysis was performed to plot the heat generation costs against the exergy factor of different energy carriers. The aim was to find price levels for variable costs and total costs of heating at different exergy levels and see if a correlation between costs and exergy could be found.

4 Results

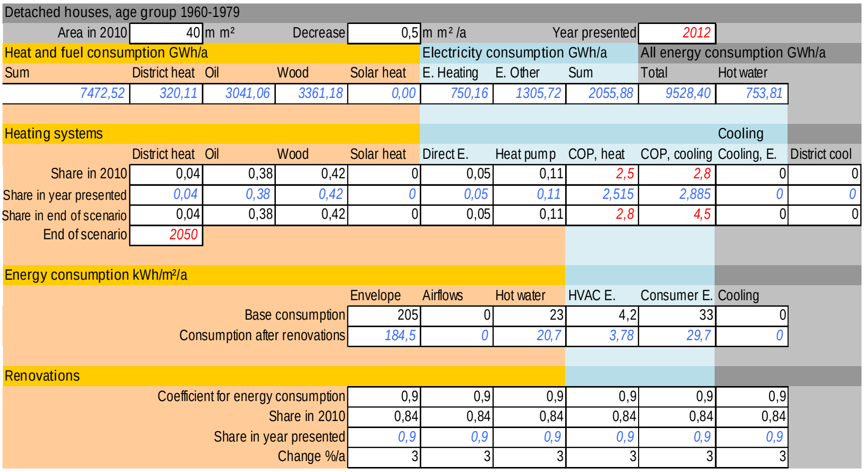
4.1 Building stock energy model

The estimation method used for assessing the energy use in the building stock was developed into a calculation tool called REMA in the course of the study. It is presented in detail in Publication I. REMA is a bottom-up engineering model of energy use in the building stock. Future developments are estimated using annual rates of new construction, renovations and removals from the building stock. The selected approach entails selecting representative building types, also called archetypes, for estimating the energy consumption in different segments of the building stock. The division used for building types and sub-types is presented in Section 3.1 and in Figure 3.

The energetic properties of each building type and sub-type are collected into tables such as the one presented in Figure 5. For existing buildings, the combined living area of the type is included and a linear annual decrease in that area over time due to demolitions or abandonment. For new buildings, a linear increase in the amount of each particular building type is assumed over time until it is replaced a newer building type as presented in Figure 3.

The annual energy consumption is calculated as a sum for all the buildings of that particular type and divided into heat and fuel consumption on the one hand and electricity consumption on the other hand. The consumption of these is derived from their component constituents, meaning heat outflows through the envelope, airflows and hot water in the case of heat, and HVAC and other technical systems of the building and consumer electricity consumption in the case of electricity. Over time, these outflows can be affected by renovations, which are assumed to affect a certain percentage of the buildings each year and accumulate annually.

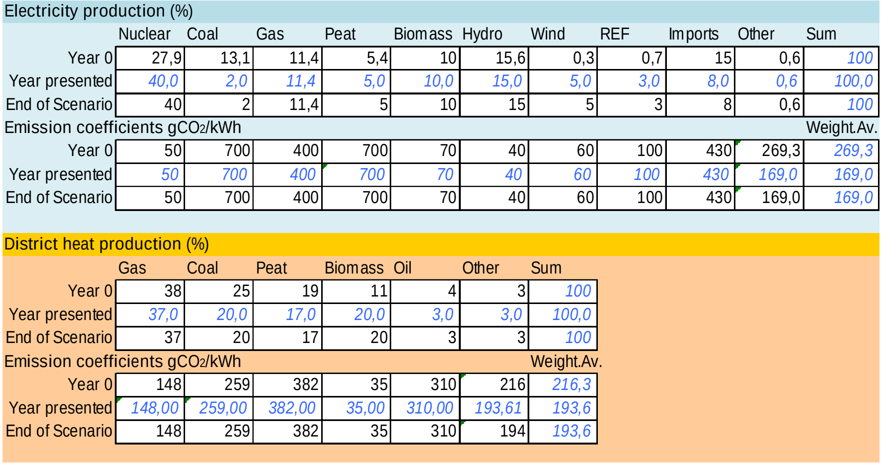
The model does not include the physical properties of particular building parts or systems, rather energetic properties are used as inputs. These properties can be derived from empirical data, estimation or simulated buildings. When calculating the input data, system efficiencies and distribution losses should be taken into account meaning that the inputs are inclusive of such efficiencies and losses. The use of dynamic simulation results of type buildings in REMA is presented in Publication I.



Detached houses, age group 1960-1979										
Area in 2010	40	m m²	Decrease	0,5	m m² /a		Year presented	2012		
Heat and fuel consumption GWh/a					Electricity consumption GWh/a			All energy consumption GWh/a		
Sum	District heat	Oil	Wood	Solar heat	E. Heating	E. Other	Sum	Total	Hot water	
7472,52	320,11	3041,06	3361,18	0,00	750,16	1305,72	2055,88	9528,40	753,81	
Heating systems									Cooling	
	District heat	Oil	Wood	Solar heat	Direct E.	Heat pump	COP, heat	COP, cooling	Cooling, E.	District cool
Share in 2010	0,04	0,38	0,42	0	0,05	0,11	2,5	2,8	0	0
Share in year presented	0,04	0,38	0,42	0	0,05	0,11	2,515	2,885	0	0
Share in end of scenario	0,04	0,38	0,42	0	0,05	0,11	2,8	4,5	0	0
End of scenario	2050									
Energy consumption kWh/m²/a										
				Envelope	Airflows	Hot water	HVAC E.	Consumer E.	Cooling	
Base consumption				205	0	23	4,2	33	0	
Consumption after renovations				184,5	0	20,7	3,78	29,7	0	
Renovations										
Coefficient for energy consumption				0,9	0,9	0,9	0,9	0,9	0,9	
Share in 2010				0,84	0,84	0,84	0,84	0,84	0,84	
Share in year presented				0,9	0,9	0,9	0,9	0,9	0,9	
Change %/a				3	3	3	3	3	3	

Figure 5. An example of the table containing the data concerning a particular building type (archetype) and its share in the building stock.

As the energy consumption of each fuel, district heat and electricity is thus calculated for each building type, they are then summed for the whole building stock. To achieve an estimate of CO_2 emissions, the model includes a highly simplified model of the energy sector, shown in Figure 6. This model contains the share of each electricity and district heat generation method, their emission coefficients, and allows the modeller to prescribe a linear development path for each.



Electricity production (%)											
	Nuclear	Coal	Gas	Peat	Biomass	Hydro	Wind	REF	Imports	Other	Sum
Year 0	27,9	13,1	11,4	5,4	10	15,6	0,3	0,7	15	0,6	100
Year presented	40,0	2,0	11,4	5,0	10,0	15,0	5,0	3,0	8,0	0,6	100,0
End of Scenario	40	2	11,4	5	10	15	5	3	8	0,6	100
Emission coefficients gCO_2/kWh											Weight.Av.
Year 0	50	700	400	700	70	40	60	100	430	269,3	269,3
Year presented	50	700	400	700	70	40	60	100	430	169,0	169,0
End of Scenario	50	700	400	700	70	40	60	100	430	169,0	169,0

District heat production (%)							
	Gas	Coal	Peat	Biomass	Oil	Other	Sum
Year 0	38	25	19	11	4	3	100
Year presented	37,0	20,0	17,0	20,0	3,0	3,0	100,0
End of Scenario	37	20	17	20	3	3	100
Emission coefficients gCO_2/kWh							Weight.Av.
Year 0	148	259	382	35	310	216	216,3
Year presented	148,00	259,00	382,00	35,00	310,00	193,61	193,6
End of Scenario	148	259	382	35	310	194	193,6

Figure 6. The simplified linear development model of the energy sector used for CO_2 emission calculations.

Based on the inputs presented here, the model then calculates three main results: (1) totals of energy consumed for each building type, (2) totals of energy consumed for each fuel, electricity and district heat and (3) CO_2 emissions caused by energy consumption in each building type. The model produces time series of energy consumption and CO_2 emissions for the whole time period modelled. Additionally, a more detailed tabular presentation of the results is possible for any given year from the modelled time period.

4.2 Energy efficiency potential estimates for Finland

In Publication II the energy efficiency potential in Finland was estimated with a scenario approach that included three scenarios: BAU as a baseline, DD to represent delayed development and RD rapid development. An update of BAU, called BAU*, was later produced in Publication I as a demonstrator case for the complete REMA model and also to provide an estimate of the effects of the recast of the EPBD directive on the development of the baseline.

Figure 7 shows the anticipated development of heating energy consumption in the three scenarios based on the conditions explained before. By 2020 the measures implemented in the delayed development scenario will allow annual energy savings of 7 TWh, which represents more than a 10% drop compared to BAU. By 2050 savings of about 40% are projected. With rapid development the pace of progress nearly doubles: about 25% by 2020 and over 50% by 2050.

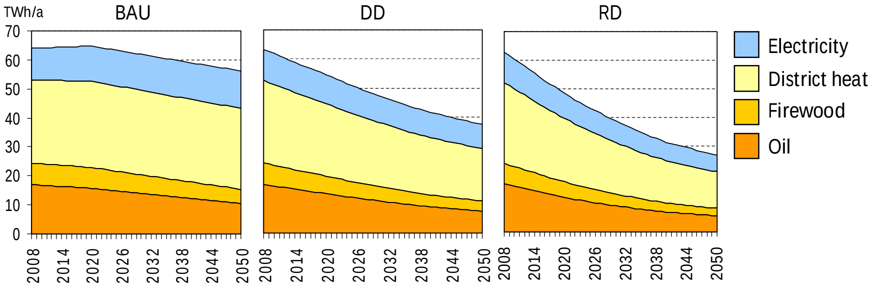


Figure 7. Heating energy consumption in the different sources of heat in the three scenarios.

The figure demonstrates that the modernisation of the building stock, as evident in the BAU scenario, is in itself enough to turn the consumption of heat downwards in the long run, even without any particular conservation measures. In the short run energy consumption can be expected to continue to rise if no changes are made in the current practices. DD and RD scenarios show that even relatively conservative additional measures can greatly affect energy consumption in the building stock over time.

For BAU*, the update of BAU scenario based on regulatory changes after the recast of the EPBD directive, for the year 2020 single-family houses will consume 31.7 TWh of heating energy (including electricity for heating) and 5.5 TWh of electricity (excluding heating), apartment buildings consume 17.0 TWh in heating and 5.8 TWh of electricity, commercial and public buildings 19.0 TWh in heating and 8.0 TWh of electricity and, finally, holiday homes 2.3 TWh in heating 0.4 TWh of electricity, totalling in 70.0 TWh of heating energy and in 19.7 TWh of electricity for the whole building stock. This development is presented in Figure 8. It can be seen, that BAU* entails an energy efficiency potential of similar magnitude as DD. Moreover, according to the results from the POLA model, in terms of total primary energy consumption a reduction of 3.8% to 1661 PJ by 2020 and 4.7% to 1853 PJ by 2050 compared to BAU can be expected in the DD scenario. For the RD scenario similar numbers are a reduction of 5.3% to 1635 PJ by 2020 and 6.8% to 1811.4 PJ by 2050.

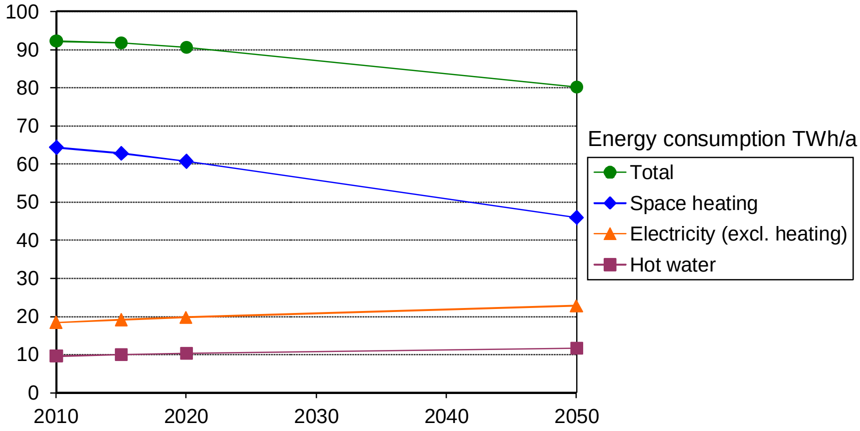


Figure 8. Modelled energy consumption in the whole building stock in the BAU* scenario.

To assess how ready the market is to allow the technical energy efficiency potential to be realized, the market situation was studied with two surveys aimed at building experts and builders, as was described in Section 3.2 and in Publication V. Among the positive signals evident in the results for Finland were that there was an expectation of growth for energy efficient buildings among the different market actors and that prospective builders were already familiar and interested in low-energy and passive buildings. Also, companies were planning to include energy efficiency expertise in the criteria they apply in recruiting. On the other hand there was not yet an indication of major product development among the construction companies. Overall, the results indicated an expectation of growth and awareness of energy efficiency issues both among the experts and builders.

These mixed results concerning the attitudes in the market support the likelihood of improvement in average energy efficiency in the building stock present in all scenarios including BAU and BAU*, but also seem to indicate that faster development present in the RD scenario would require further market interventions in the form of regulation or incentives on the government's part.

4.3 Energy efficiency potential estimates for selected EU countries

In addition to the scenarios concerning Finland, an international comparison of energy efficiency potentials in the existing residential building stock was conducted for nine EU member states in Publication III. The scope of the comparison was limited to heating energy in the existing building stock, which means that only renovation measures were included. Moreover, only economically viable measures were studied which in practice meant limiting the assessment to energy efficiency improvements included in renovations that would be conducted in any case.

The data indicated that average heating energy consumption varied between 96 kWh/m²/a in apartment buildings in Bulgaria and 273 kWh/m²/a in houses in Latvia. Furthermore, the results show that the existing stock of single-family houses in the nine countries consume 877 TWh of energy for space heating annually. For apartment buildings, the consumption is 474 TWh annually.

As can be expected, the countries have very different energy efficiency potentials. Figure 9 shows how countries with a large inventory of buildings probably hold the largest energy efficiency potentials in absolute terms, namely Germany and the United Kingdom. On the other hand, based on average consumption numbers, some countries are likely to have large potentials for energy efficiency improvements on national level, but their relative contribution to the European total will remain small nevertheless. Such is the case of Latvia, for instance. In this comparison, Finland seems to have a middle-range energy efficiency potential for single-family houses and a relatively low potential in apartments. The effects of annually applicable cost-effective energy efficiency retrofits will accumulate to produce the annual savings shown in Figure 9 by 2020 and 2030. These figures should be understood in comparison to a baseline of no energy efficiency measures included in renovations.

Summing up the results for all nine countries, 88 TWh/a could be saved in single family houses by the year 2020 and 58 TWh/a in apartment buildings, totalling 146 TWh/a. Respective figures by 2030 are 169 TWh/a for houses and 110 TWh/a for apartments, totalling 279 TWh/a for all dwellings. In relative terms these savings represent approximately 10% by 2020 and 20% by 2030 of present heating energy consumption.

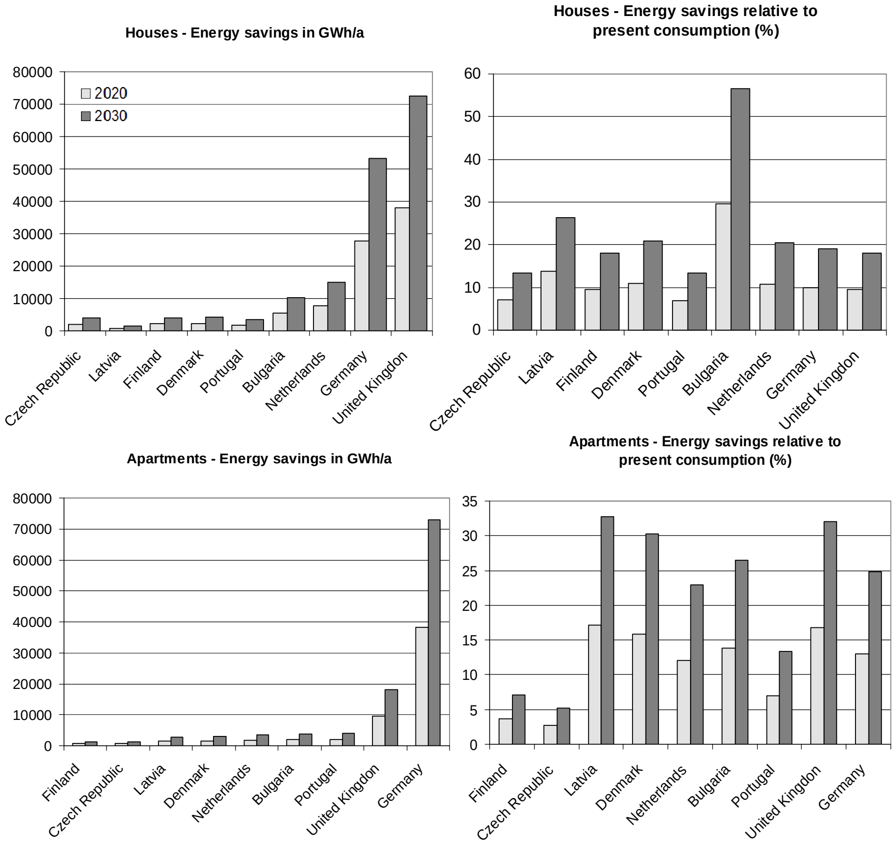


Figure 9. Cost effective energy efficiency potentials in energy efficiency renovations in the various countries compared to a baseline of no energy efficiency measures included in renovations.

4.4 Assessment of economic effects for Finland

Publication II presents an assessment of economic effects, both direct and indirect, of energy efficiency improvements in the building stock. These results were acquired for BAU, DD and RD scenarios. The direct economic effects can be measured in the investments that they entail. For new buildings, the annual direct investment in new buildings in each scenario, based on cost estimates for 2020 and 2050, are shown in Table 6. The figures indicate that the shift to low energy buildings would require increases of only a few percent to the level of investments that is to be expected anyway.

Table 6. Annual construction investment (M€) to new buildings in Finland.

	2020	2050
BAU	7500	9700
DD	7600	10100
RD	7800	10500

Direct investments in energy efficiency retrofits are shown in Table 7. The results suggest that the measures assumed in these scenarios would require a rather inconsequential increase of a few percent in the current annual investment of about 8 billion in renovations (Rakennusteollisuus 2010).

Table 7. Investment in energy efficiency retrofits (M€) in Finland.

	2020	2050
BAU	0	0
DD	200	100
RD	300	200

The wider economic implications of the measures applied in the two scenarios were assessed with the economic modelling as was described before. The estimates of the investments and the POLA modelling results described above were used as input for the VATTAGE model of the Finnish economy. Interpreting the results, one should bear in mind that some of the uncertainties and sources of error in the model are cumulative and, therefore, towards the end of the time series the figures should be considered mostly as indicators of the broad direction of economic development.

Figure 10 shows the effects of the two scenarios, according to the VATTAGE model, on the GDP per capita in Finland. The figure shows that initially the investments required by the energy efficiency improvements will cause limitations on economic development. The GDP can be expected to be lower than in the BAU scenario for 8 years with the investment level of DD and for 17 years with the investment level of RD. However, subsequently the GDP will reach higher levels than without the investments.

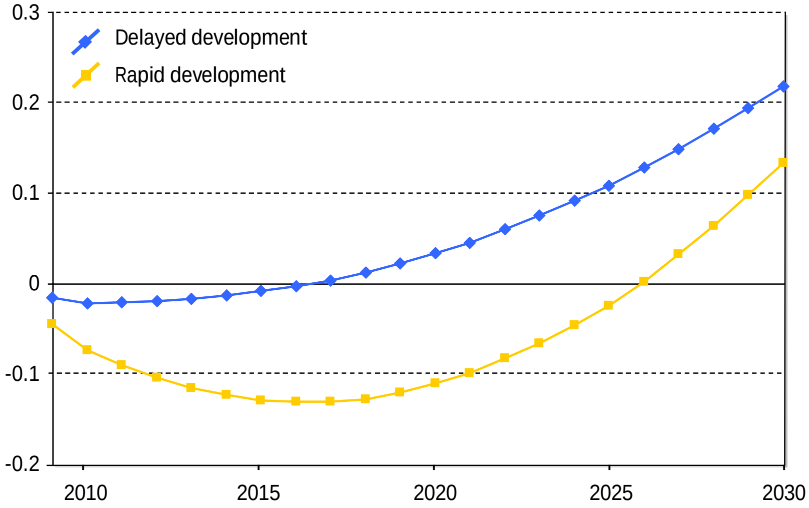


Figure 10. GDP per capita in DD and RD scenarios relative to BAU (%).

Figure 11 shows how the two scenarios would affect employment relative to BAU. A slight decrease in employment could be expected at the beginning according to the modelling results. It would seem that the small expected increase in employment in the construction sector will be too small to completely offset the effects of a generally slightly smaller economy.

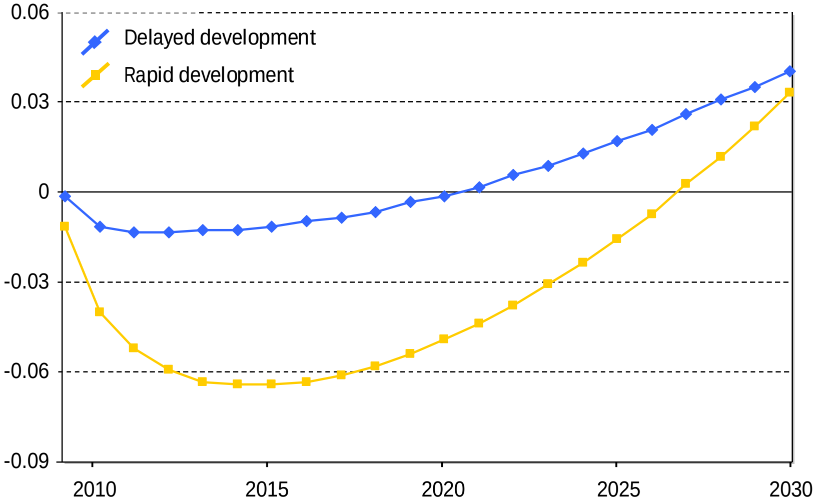


Figure 11. Employment in DD and RD scenarios relative to BAU (%).

Later on, however, employment would rise to higher levels than in BAU. This can be expected as a result of the general effects on the economy reflected by the changes in the GDP. It should be noted, however, that the effects on employment, both negative and positive, are very small, less than 0.1%. The timeframe at which the modelling suggests that the positive effects offset the negative effects is around ten to fifteen years. However, the relative changes are very small relative to the inherent uncertainties of the modelling approach so that this is at best a cursory estimate of the timespan.

4.5 Assessment of external costs for Finland

A GDP only approach to estimating the economic effects would underestimate the utility of energy efficiency investments as it excludes the external costs caused by energy production. Especially important is the externality of global warming caused by greenhouse gas emissions. The modelling results from the VATTAGE model, presented in Publication II, show that both DD and RD scenarios can have a substantial effect on carbon dioxide emissions even on the national level, as is demonstrated by Figure 12.

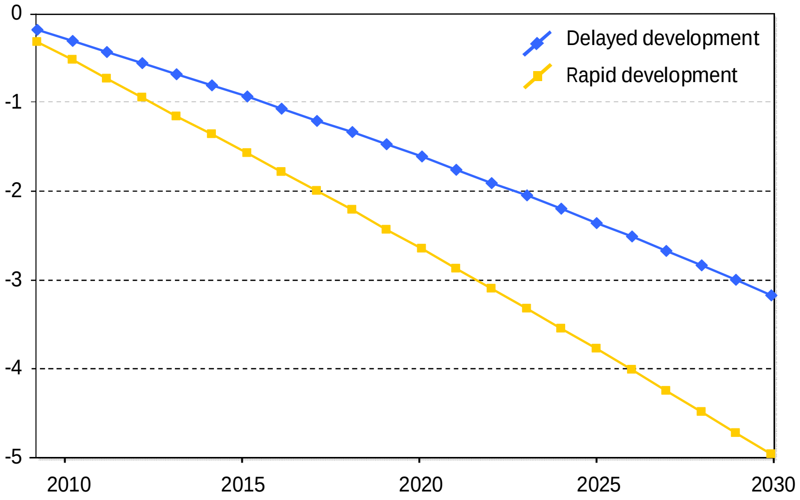


Figure 12. Total domestic CO_2 emissions in DD and RD scenarios relative to BAU (%).

Estimates of total external costs, including effects other than climate change and based on the figures published by ExternE (European Commission 2003), are shown in Figure 13 for each scenario.

The external costs in DD and RD are systematically lower than in BAU, which was to be expected due to lower levels of energy consumption. Monetarily DD has 170 M€ lower external costs in 2020, 230 M€ in 2050. For RD similar figures are 380 M€ and 440 M€ respectively. This can be compared to the Finnish GDP of 180 000 M€ in 2007. It is noteworthy that the volume of avoided external costs outweighs any losses or gains estimated in the previous sections in the GDP. Therefore from a welfare economic point of view both RD and DD are preferable to BAU.

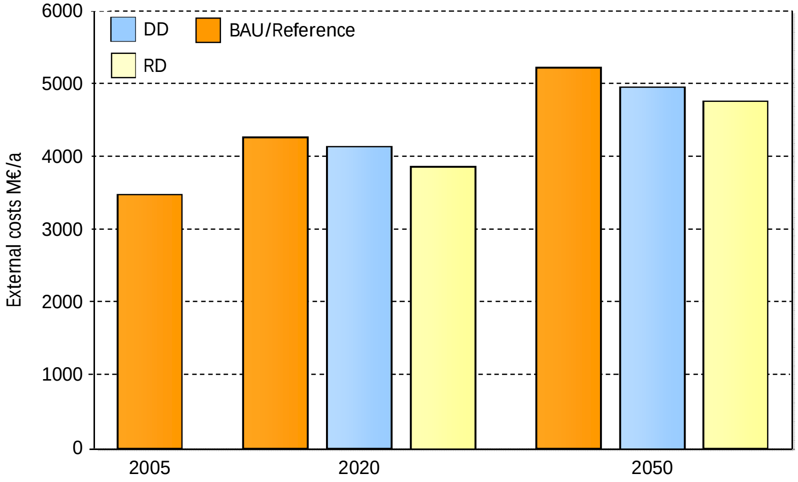


Figure 13. External costs of energy production in Finland in the three scenarios.

4.6 Results of exergoeconomic analysis

The correlation between exergy content and economic value of heating energy was studied to see whether physically differing energy carriers also hold different economic values and how value is distributed among them. The analysis was done based on technological and price data on different heating energy systems commonly in use in Finland and is presented in more detail in Publication IV.

Figure 14 shows the relation between the total cost and the variable costs of using each energy carrier relative to the exergy content of the said carriers. The results indicate that in the Finnish case the postulated correlation is visible: indeed the lower the exergy content, the lower the price of energy and thus the variable costs of its use. When fixed costs are included, the price differences are levelled off somewhat, although not entirely. However, the lower exergy alternatives are not systematically cheaper now. For example, district heating appears to be somewhat more expensive than the higher exergy alternative, heat pump. The levelling of price differences would appear to confirm the hypothesis of the exchangeability of capital and exergy, since higher capital investment seems to allow the use of lower exergy energy.

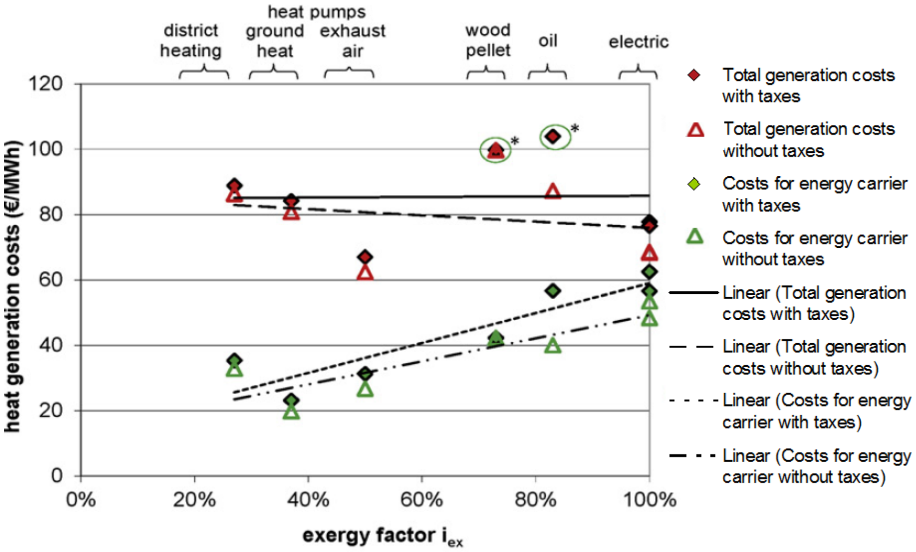


Figure 14. The energy costs and variable costs relative to the exergy content of the energy carrier in Finland.

Publication IV also includes similar analyses for Austria, Sweden and the Netherlands by other researchers. Overall, the results from other countries further support the hypothesis. The conducted regression indicated an overall capital-expenditures-to-exergy substitution rate of 64%.

5 Discussion and conclusions

5.1 Discussion of results

This thesis aimed to develop a method for calculating the energy efficiency potential in the building stock. The method, based on the use of building types and scenario analyses, was finalized in the form of a calculation tool called REMA. The model is constructed to be light, simple and flexible so as to allow testing different contingencies and the sensitivities of scenarios with relative ease. The effects of changing a particular parameter can be tested in quick succession. REMA was built for calculating the Finnish building stock but, since the energetic properties of the building types and their shares in the stock are variables, the model can be modified for use with a given building stock.

A benefit of the approach chosen here is that each type and sub-type of buildings is individually modelled and, therefore, their contribution to the total energy consumption can be traced to the modelled physical characteristics of the buildings. This allows the study of individual building modifications and their effects to energy consumption on a large scale.

During the development of REMA, three scenarios were calculated with a methodology slightly different from the final REMA model. BAU scenario was created as a baseline with no changes in the 2008 building stock and construction practices, whereas delayed development (DD) represented modest changes and rapid development (RD) fast changes in construction and renovation practices. A fourth scenario called BAU* was calculated with the completed REMA model. BAU* can be seen as an updated BAU scenario for Finland after the changes in regulation after the recast of the EPBD directive have taken effect.

The economic analysis of the scenarios indicates changes in the economy due to energy efficiency investments: slightly less is consumed and cost of capital rises minutely resulting in the small relative decrease in GDP in the short term. On the medium to long term, however, the effects on both would be positive as the benefits begin to accumulate. Furthermore, a significant drop in harmful emissions and hence external costs is anticipated. Overall, a clear net benefit is expected from improving energy efficiency.

The results of BAU*, compared with BAU, indicate that the EPBD directive is likely to succeed in affecting an overall reduction in the energy consumption in the building stock in Finland. On the other hand the effects of BAU* are quite close to the DD scenario, which would seem to indicate that there are still technological measures available, as is evident in the RD scenario, that could allow a more rapid development path for energy efficiency improvements.

Survey results concerning the attitudes in the market for low energy buildings seem to support the likelihood of improvement in average energy efficiency in new buildings as interest and knowledge in the issue was prevalent among both builders and experts in the sector. Since the BAU scenario only presumes the continuation of existing construction practices, this would seem to indicate the likelihood of energy efficiency levels at least present in the DD scenario as being higher. There was enough ambivalence, however, to indicate that faster development present in the RD scenario would require further market interventions in the form of regulation or incentives on the government's part. Particularly the lack of product development in the construction sector has the potential to become a hindrance for the fast development of energy efficiency.

Moreover, an estimate of energy efficiency potential in the existing residential stock in nine EU member states was calculated concerning heating energy and renovations. It seems that in most countries cost-effective energy savings of about 10% can be achieved by 2020 and 20% by 2030. For Finland the analysis indicated a moderate cost-effective energy renovation potential in single-family houses and a relatively small potential in apartment buildings, generally these are smaller than what was estimated in DD and RD scenarios for Finland. The main reason for this difference in that in the DD and RD scenarios renovation rates were based on historic renovation rates, whereas here the economicality of renovations was used as the criterion. This resulted in a more conservative estimate of energy efficiency improvements. Moreover, this approach led to high energy efficiency potentials for countries with low renovation costs, most visibly for Bulgaria. For all countries together, a total annual heating energy saving of approximately 150 TWh by 2020 and 280 TWh by 2030 appears possible. This can be compared to the total annual primary energy consumption of 21 000 TWh in all EU countries combined.

Finally, an exergoeconomic analysis of heating energy carriers, exergy content and capital and variable costs was conducted with the aim of finding a correlation with price and exergy content. This was done to examine whether energy prices reflect the exergy content of the underlying energy carrier and that capital expenditures can substitute for exergy to some degree. Price and energy data for Finland was presented to explore the issue. A correlation was indeed found between the exergy content and price of heating energy carriers.

Additional analysis demonstrated that the share of capital costs on total heating cost increased with lower exergy input. Based on the data used in this analysis, it is concluded that for the case of modern cost effective heating systems the substitution rate between exergy and capital is in the vicinity of 2/3. This means that by reducing the average specific exergy content of the applied energy carriers by one unit, the share of capital costs on the total costs increases by 2/3 of a unit.

The meaning of these findings on studying energy use in the building stock is twofold: first, it shows that the varying exergy content of different energy carriers has economic meaning and that, therefore, different energy carriers should be analysed separately when studying energy efficiency potentials. Proskuryakova and Kovalev (2015) have called this finding surprising, that a somewhat obscure physical measure should correlate with economic value. The separation of different fuels, heat and electricity is thus preserved in energy calculations in REMA. Second, it means that the society has a choice in selecting more valuable, high-exergy energy sources or substituting them for capital investments. These alternatives have different economic implications, the former being more often coming from an import source than the latter, for instance. Assessing the effects of alternative policy choices can be informed by these findings.

5.2 Policy implications

Finnish energy policy has developed parallel to the research presented in this thesis, some of it informed by results from REMA calculations (e.g. Airaksinen and Vainio 2012). Concerning energy efficiency of buildings, the principal guideline for policy development has been the European EPBD directive. The EU's regulation goal for 2020, namely a nearly zero-energy building level in new construction, is ambitious enough to be very close to the studied RD scenario.

To what level regulation needs to be further developed depends on how well EU's 2020 goals are reached. If energy consumption levels indicated by the RD scenario are indeed achieved, relatively steep reduction in energy consumption of the building stock can be reached. However, any changes in the energy consumption of the building stock are slowed down by the inertia of the stock, meaning the demolition, construction and renovation rates, all in the vicinity of one to two percent annually. This means that achieving reductions in emissions necessary to limit climate change necessitates wide ranging parallel actions in energy production towards low-emission energy sources.

In light of this study, measures aimed at renovation and new buildings appear both important, one cannot be shown to be significantly more effective than the other based on the results of this thesis. A key variable is the renovation rate as major energy efficiency improvements tend to only be economical when combined with other renovations. Boosting the renovation rate itself with policy measures is one policy option, but one that may not be sensible to sustain as in the long term renovation rates are dependent on the lifespan of building parts in any case. However, it is sensible to encourage or regulate the combining of energy efficiency measures to renovations that are bound to take place in any case.

5.3 Suggestions for future research

Sensitivity analyses have not been performed in this study. However, as was stated in Section 2.2, the scenario analysis approach in itself can serve some of the goals of a sensitivity analysis. Here, in the Finnish case, the combination of BAU, DD and RD scenarios do in a sense provide approximate minimum (BAU) and maximum (RD) values for plausible development paths to the future, which in itself can be seen as serving as a rough sensitivity analysis. A formal sensitivity analysis would, however, involve the systematic testing of a number of variables for the effect of changes. Considering the amount of variables and complexity of calculations this would be a somewhat laborious undertaking, although not prohibitively so. Therefore sensitivity analyses are indeed one obvious topic for future research.

Another major avenue for future work is the further development of the REMA model itself. For example, more developed interfacing with POLA and VATTAGE models could streamline the modelling process in future studies. Some cost components could conceivably be included in REMA itself for producing cost estimates. Moreover, the energy flows to and in the buildings could be modelled in more details including physical efficiencies and thermodynamic properties of the building parts. Now these are exogenous to the model.

EKOREM and REMA models share similarities as both are bottom-up type engineering models of the Finnish building stock. Calculations similar to the ones presented in this thesis could also be performed with the EKOREM model, in fact such an undertaking for validation and cross-checking purposes could be a sensible topic for future research. One summary comparison of existing published studies is provided in Publication I.

While conducting the study it became apparent that studying energy consumption in the Finnish building stock is hindered by the lack of empirical data. There is no systematically gathered data of actual energy use in actual buildings, only single case buildings have been studied which cannot be used to produce a representative sample. Gathering empirical data as Mills et al. (2004) have done in the US from Finnish energy efficiency renovations would be extremely useful for future research. Now the study had to rely largely on estimates. Also, empirical data, ideally based on random sampling, concerning the actual energy consumption of different types and ages of buildings would greatly improve our understanding of the composition of energy consumption in the building stock.

As new ways of providing energy and improving energy efficiency are studied, more should be done to study the economic effects of the new technological solutions, as here was done. This would gradually provide the policymakers with the means to compare different solutions with one another. Thus the most cost-effective technologies could be adopted first. This could help address problems like exhaustion of natural resources and the climate change more effectively.

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PUBLICATION I

Calculation method and tool for assessing energy consumption in the building stock

Building and Environment 75, pp. 153–160.

Building and Environment 75 (2014) 153–160

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Calculation method and tool for assessing energy consumption in the building stock

Pekka Tuominen [a,*], Riikka Holopainen [a], Lari Eskola [b], Juha Jokisalo [b], Miimu Airaksinen [a]

[a] VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland
[b] Aalto University, P.O. Box 14400, 00076 Aalto, Finland

ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form
24 January 2014
Accepted 2 February 2014

Keywords:
Energy efficiency
Modelling
Simulation
Building stock
Archetype
Building type

ABSTRACT

A novel calculation tool (REMA) for assessing the effects of various energy efficiency measures in buildings on the scale of the whole building stock of Finland is presented along with an estimate concerning the most recent changes in the regulation for energy use in buildings. REMA is a bottom-up model that uses representative building types (archetypes) for estimating energy consumption in different segments of the building stock. Future developments are estimated using annual rates of new construction, renovations and removals from the building stock. REMA was used to calculate the development of energy use in the building stock after the latest changes to the Finnish building code. For this purpose, the energy demands of the different standard building types were simulated using the IDA-ICE 4.2 dynamic simulation program. The results show a decrease of about 3% in heating energy consumption to 70.0 TWh and a 6% increase in electricity consumption to 19.7 TWh by the year 2020 corresponding to a reduction of 2% in total energy consumption. For CO_2 emissions, a decrease of about 4% can be expected by 2020 concerning all energy use in the building stock. Over longer periods of time, the pace of reductions is accelerated as the share of new buildings in the stock grows larger.

1. Introduction

Buildings, representing more than a third of global energy consumption [1], have long remained one of the focal points for the efforts to increase energy efficiency. The residential sector in particular has had more energy-related policies put in place than any other sector in the IEA countries [2]. Therefore, the question which policies will have the greatest effect over time is very relevant to the policymakers.

According to the IEA 38% of world's final energy was consumed and 33% of CO_2 emissions were caused by residential and commercial buildings in 2005 [1]. Finland is no exception in its energy consumption: buildings consume 31% of all primary energy production. The share of heating is even larger than usual, 70% of energy consumption in buildings or 22% of all energy. [3]

Thus it makes sense that ever since the energy crisis of the 1970's the buildings sector has been central to the efforts to increase energy efficiency through policy measures. This emphasis given to buildings in energy policy is justifiable if the greatest efforts are to be exerted where the greatest effects can be expected. The studies by IPCC [4] and the European Commission [5] are among the latest to uncover the greatest energy saving potentials in buildings compared to other sectors of the economy. Their results were lately corroborated by the industry's own findings published by the World Business Council for Sustainable Development [6].

While buildings hold great potential in terms of energy efficiency, typically the actual effects take a long time to reach their potential. This is due to the inertia in the renewal of the building stock. Buildings can have lifespans in the range of 50–100 years and each building part is typically renovated only a few times in that time period. In Finland the amount of new buildings built in a typical year is about 1.4% compared to the existing stock, whereas about 1.0% of existing buildings are demolished leading to a net increase of 0.4% [7]. It is clear, therefore, that major effects from energy efficiency improvements can take decades to be fully realized. Thus, forecasting the development of energy use in the building stock over long periods of time is a necessary undertaking if we are to make informed policy decisions.

Recent examples of studies estimating the effects of various policies on the energy use of building stock include the following. Sartori et al. [8] use different categories of buildings forecast energy use in the Norwegian building stock until 2035. Schimschar et al. [9] provide forecasts until 2020 for the effects of tightening

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[*] Corresponding author. Tel.: +358 50 5309759; fax: +358 20 7227001.
E-mail address: Pekka.Tuominen@vtt.fi (P. Tuominen).

http://dx.doi.org/10.1016/j.buildenv.2014.02.001
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building regulations in Germany using the energy consumption levels defined in the regulations. McKenna et al. [10] divide the German building stock into representative buildings and assign these, within the model, into federal states based on statistical information to reach estimates concerning energy-political targets until 2050. Tuominen et al. [7] use a similar method and time horizon to assess the development in Finland. This approach has also been used to study even larger building stocks, including by Uihlein, and Eder [11], who provide forecasts of the effects of different energy efficiency measures in the building stock of the EU-27 countries until 2060, and Tuominen et al. [12], who present similar forecasts for eight EU member states until 2030. A more exhaustive review of studies extending to the 1990's is given by Kavgic et al. [13].

While building stock models are a valuable if not essential tool for assessing various policy options, there are also limitations to what can be learned from modelled data. This has to be kept in mind when interpreting the data. Booth et al. [14] list three types of sources of uncertainty in building stock models. First there is model realism, meaning how well the model represents the true underlying process. To address this issue, it is important to provide a transparent description of the model to those who interpret the results. Second issue is that of heterogeneity, meaning the variation of the characteristics of the buildings within the stock. Any groupings of buildings will inevitably contain some heterogeneity, thus one has to choose a level of satisfactory aggregation balancing accuracy with complexity within the model. Finally, even within a relatively homogeneous set of buildings there is uncertainty due to two factors: random variation, called first-order uncertainty, and insufficient knowledge about the defining parameters, called second-order uncertainty or epistemic uncertainty. Therefore the well-informed interpretation of modelling results requires comparing them with other sources of information and past experience.

This paper presents a novel calculation tool for assessing the effects of various energy efficiency measures in buildings on the scale of the whole building stock of Finland. An estimate concerning the most recent changes in the regulation for energy use in buildings is presented. The effects of the recent policy changes concerning minimum energy efficiency levels are presented for the years 2020 and 2050. At the same time, this can be seen as an update of a previously published energy efficiency potential calculation for the Finnish building stock [7].

2. Methods

2.1. Description of the REMA model

The calculation methods used for assessing energy efficiency potentials in previous studies ([7,12]) were systematized into an MS Excel based modelling tool, called REMA, that can be used for forecasting the development of energy consumption in a building stock with given policy measures. REMA is a bottom-up model that uses representative building types, archetypes in the IEA nomenclature [15], for estimating the energy usage in different segments of the building stock. Future developments are estimated using annual rates of new construction, renovations and removals from the building stock. REMA also includes a simplified model of the energy sector allowing CO_2 emission calculations.

The model is constructed to be light, simple and flexible so as to allow testing different contingencies and the sensitivities of scenarios with relative ease. The effects of changing a particular parameter are calculated instantaneously and the results are displayed. To allow this flexibility, REMA does not include any dynamic modelling. It will only calculate linear development based on predetermined parameters and time intervals. REMA uses as input data the energetic properties of building types. These properties can be derived from empirical data, estimation or simulated buildings. In the example presented here, dynamic simulation done with IDA-ICE software was used to produce the input data.

Moreover, REMA does not account for the economicality of the modelled policies, which has to be studied separately. The model was built for the Finnish building stock but, since the energetic properties of the building types and their shares in the stock are variables, the model can be modified for use with a given building stock.

As REMA is a bottom-up model, the calculation is based on choosing a few representative building types and using their energetic properties to calculate the energy consumption of that particular building type in the building stock. In the model data on the building stock is divided into four categories: detached houses, apartment buildings, commercial buildings and holiday homes. Detached houses are understood as one-family residences. Apartment buildings include buildings that have more than one apartment, namely multi-storey buildings and row houses. Commercial buildings include buildings in commercial use (offices, stores etc.) and public buildings (schools, hospitals etc.). Holiday homes represent a relatively small portion of the building stock, but their importance as energy consumers is growing in Finland as more and more are equipped with electricity and heating, therefore they were included as a fourth category. Overall, this choice of categories was made based on the roughly similar typical heating energy use in the buildings grouped together. Some buildings, particularly in the commercial buildings category, can have unusually high (e.g. public pool, ice-rink, etc.) or unusually low (storage, carage, etc.) energy consumption levels. It has to be borne in mind that they have an effect on the average values used in the model. However, unless there is a reason to expect a major change in their relative share in the building stock, it is deemed a reasonable assumption that their typical energy consumption will change in similar fashion with the majority of buildings keeping the average figure reliable for the purposes of this modelling. As was recognized by Booth et al. [14], this problem is typically shared by all archetype-based modelling methods, as even the most detailed taxonomy of buildings will necessarily preserve some heterogeneity within the selected categories of buildings.

Moreover, each building category is divided into age groups: buildings constructed before 1959, during 1960–1979 and during 1980–2009. These age groups were chosen because of the availability of compatible data [17] and they represent distinct periods in the history of the Finnish building stock: 1960–1979 saw mass urbanization the quick construction of buildings using new methods such as prefabrication. Buildings older than that typically used more traditional methods and were often built of wood. After the energy crises in the 1970's more attention was paid to insulation, airtightness and mechanical ventilation became more commonplace, meaning again a change in the makeup of the building stock.

Similarly, new buildings are assumed to have different properties depending on the time period when they will be constructed. The default values for the future time periods are 2010–2019, 2020–2029 and 2030–2050, but these can be modified by the user. In the scenario example calculated for this paper, the main interest is in the effects of the EPBD directive recast of the European Union [16]. As the directive stipulates that buildings have to be nearly zero-energy buildings by 2020, emphasis was given to the time period from 2010 to 2020. A milestone year was selected for 2015 to allow a gradual approach to the nearly zero energy buildings. 2020–2050 was included to allow an estimate of the long term effects.

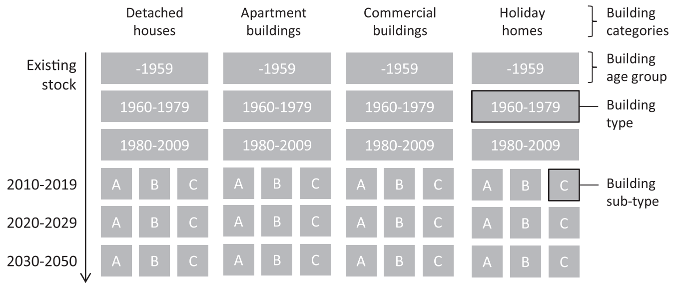


Fig. 1. The division of the existing and future building stock into building categories, age groups, types and sub-types called here A, B and C.

The division into building types and nomenclature used in the model is presented in Fig. 1.

As can be seen from Fig. 1, the model has more detail concerning the future building stock, allowing for sub-types that are given the placeholder names A, B and C. This allows the user to include building sub-types of various energetic properties in the modelling, e.g. low-energy buildings, passive buildings and energy-plus buildings. This was done for two reasons: first, compared to new buildings the properties, and therefore energy consumption, of the existing building stock has already been decided to a large extent, even though renovations can have some effect on them. As this model is intended to be used to assess the effects of policy decisions, it is reasonable to provide more detail where more effects can be achieved. While the energy consumption of existing buildings is likely to remain very large for a long period of time, the opportunities to affect it are inherently smaller than in new buildings because changing existing structures is more difficult and expensive than enacting design changes in new ones. Second, as time progresses, the proportional importance of the existing building stock diminishes as old buildings are removed from the stock and new buildings replace them. This means that in the assessment of future effects of policy decisions, their importance will similarly decline over time. This process is of course lengthy and for a very long period of time measures taken in old buildings can have a very significant effect on energy consumption in the building stock and, therefore, renovations are also included in the model.

The data concerning the building stock was obtained from the EkoREM model developed at the Tampere University of Technology and VTT Technical Research Centre of Finland in 2003–2005 [17]. According to Heljo et al. [17], the input data for EkoREM originates from multiple sources: Statistics Finland, which for its part uses the building registry of the Population Register Centre, the national statistics for new construction, VTT's KORVO and REMO studies from 1982, 1990 and 2000 concerning renovations and VTT's periodical surveys concerning new construction. The forecast used as a basis in the REMA model, presented in Table 1, was made in 14.10.2007 by Harri Nuutila at VTT and has been previously published by Tuominen et al. [7]. For holiday homes the development of the stock follows the forecast published by Rytkönen and Kirkkari [18]: 490 000 holiday homes with an average area of 44 m^2 in 2007 and 550 000 in 2020, with the growth proceeding in a fairly linear fashion. For longer periods, extrapolation is used.

The buildings were further categorized according to their age. Again, the age data was acquired from the results of the EkoREM model [17] and follows the distribution presented by Tuominen et al. [7]. The reduction of old building stock, shown in Table 1, was assumed to consist mostly of the oldest buildings in the stock. Thus the share of buildings built before 1960 would fall at a faster rate than the share of those built during the 1960's and 1970's, which in turn would outpace those built after 1980's.

The data concerning each building type or sub-type is collected into a table such as the one presented in Fig. 2. For existing buildings, the combined living area of the type is included and a linear annual decrease in that area over time due to demolitions or abandonment. For new buildings, a linear increase in the amount of that building type is assumed over time until it is replaced a newer building type as presented in Fig. 1.

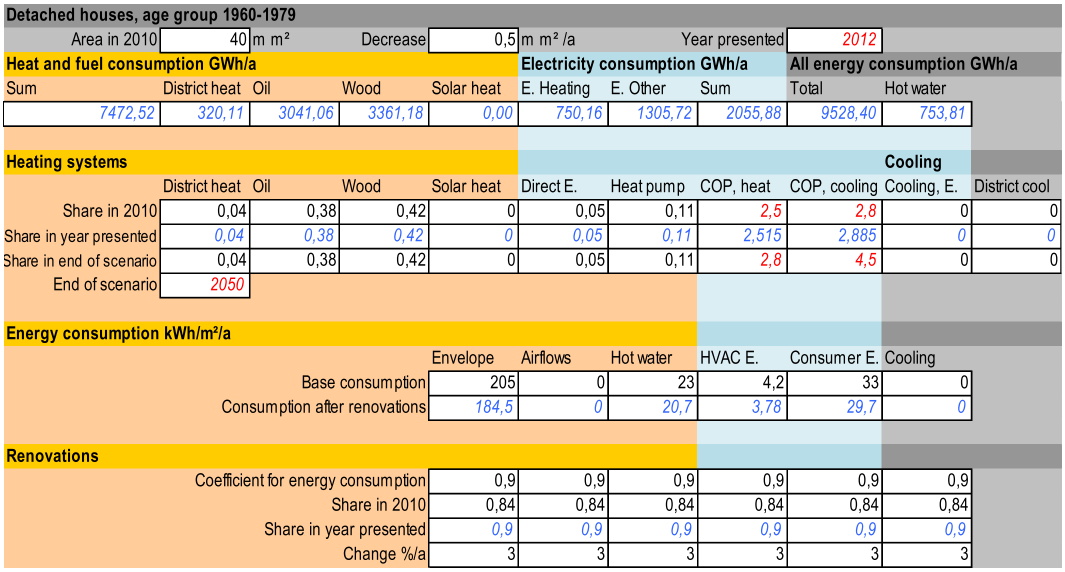
The annual energy consumption is calculated as a sum for all the buildings of that particular type and divided into heat and fuel consumption on one hand and electricity consumption on the other hand. The consumption of these is derived from their component constituents, meaning heat outflows through the envelope, airflows and hot water in the case of heat, and HVAC and other technical systems of the building and consumer electricity consumption in the case of electricity. Over time, these outflows can be affected by renovations, which are assumed to affect a certain percentage of the buildings each year and accumulate annually. The model does not include the physical properties of particular building parts or systems, rather energetic properties are used as inputs. These properties can be derived from empirical data, estimation or simulated buildings. In the example presented here, dynamic simulation done with IDA-ICE software was used to produce the input data. When calculating the input data, system efficiencies and distribution losses should be taken into account meaning that the inputs are inclusive of such efficiencies and losses.

As the energy consumption of each fuel, district heat and electricity is thus calculated for each building type, they are then summed for the whole building stock. To achieve an estimate of CO_2 emissions, the model includes a highly simplified model of the energy sector, shown in Fig. 3. This model contains the share of each electricity and district heat generation method, their emission coefficients, and allows the modeller to prescribe a linear development path for each. The shares of energy production methods, for the purposes of the scenario presented here, are expected to follow the decision of the Finnish parliament to issue three new nuclear power plant permits and the goals defined in the national energy strategy [19].

Based on the inputs presented here, the model then calculates three main results: (1) totals of energy consumed for each building type, (2) totals of energy consumed for each fuel, electricity and district heat and (3) CO_2 emissions caused by energy consumption in each building type. The model produces time series of energy consumption and CO_2 emissions for the whole time period modelled. Additionally, a more detailed tabular presentation of the results is possible for any given year from the modelled time period.

Table 1
The forecast development of the Finnish building stock in 1000 m^2 [7].

	Building stock			Reduction		Construction	
	2007	2020	2050	2007–2020	2020–2050	2007–2020	2020–2050
Detached houses	142 000	163 800	180 200	8100	44 800	29 900	61 200
Apartment buildings	116 200	128 700	131 000	3800	29 300	16 300	31 600
Commercial buildings	101 800	112 100	119 400	17 700	46 400	28 000	53 700
Total	360 000	404 600	430 600	29 600	120 500	74 200	146 500



Detached houses, age group 1960-1979										
Area in 2010	40	m m²	Decrease	0,5	m m² /a		Year presented	2012		
Heat and fuel consumption GWh/a					Electricity consumption GWh/a			All energy consumption GWh/a		
Sum	District heat	Oil	Wood	Solar heat	E. Heating	E. Other	Sum	Total	Hot water	
7472,52	320,11	3041,06	3361,18	0,00	750,16	1305,72	2055,88	9528,40	753,81	
Heating systems									Cooling	
	District heat	Oil	Wood	Solar heat	Direct E.	Heat pump	COP, heat	COP, cooling	Cooling, E.	District cool
Share in 2010	0,04	0,38	0,42	0	0,05	0,11	2,5	2,8	0	0
Share in year presented	0,04	0,38	0,42	0	0,05	0,11	2,515	2,885	0	0
Share in end of scenario	0,04	0,38	0,42	0	0,05	0,11	2,8	4,5	0	0
End of scenario	2050									
Energy consumption kWh/m²/a										
				Envelope	Airflows	Hot water	HVAC E.	Consumer E.	Cooling	
			Base consumption	205	0	23	4,2	33	0	
			Consumption after renovations	184,5	0	20,7	3,78	29,7	0	
Renovations										
			Coefficient for energy consumption	0,9	0,9	0,9	0,9	0,9	0,9	
			Share in 2010	0,84	0,84	0,84	0,84	0,84	0,84	
			Share in year presented	0,9	0,9	0,9	0,9	0,9	0,9	
			Change %/a	3	3	3	3	3	3	

Fig. 2. An example of the table containing the data concerning a particular building type (archetype) and its share in the building stock.

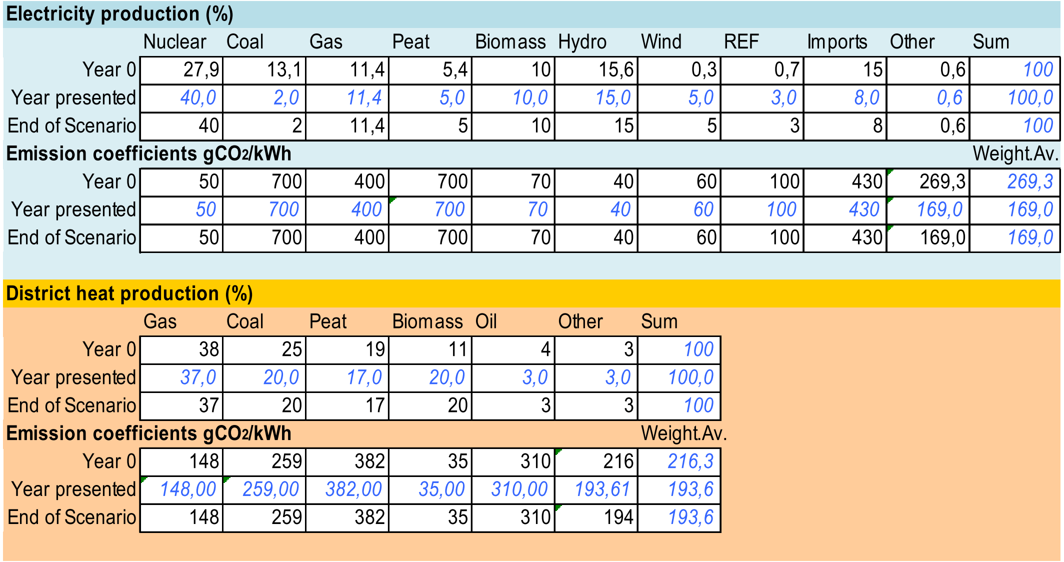
2.2. *Modelling the energy consumption of the building types*

The energy consumption of different building types in the building stock was estimated using a two-fold modelling approach. First representative buildings of various types and ages were modelled to establish their heating energy consumption using dynamic simulation tool IDA-ICE, which has been validated for example in Travesi et al. [20] and Loutzenhiser et al. [21]. The weather data used in the dynamic simulation describes the current climatic conditions of the Finnish climate zone III [22].

Then the cumulative energy consumption of these building types was calculated based on the modelled development of the building stock using the REMA model at VTT. The results were compared with the national statistics [23] and previous estimates ([17,24,25]) and four rounds of iteration were completed resulting in calibrated building types, a new estimate for the composition of energy consumption in the building stock and a forecast for expected changes in energy consumption.

Four model building types were chosen to represent the major building types that constitute the building stock in the REMA model: detached houses (about 38% of the total living area in the stock), apartment buildings (31%), commercial and public buildings, represented by an office building (26%) and holiday homes (5%). The model building types are presented in Fig. 4. The living areas of the buildings are: detached house and holiday home (134 m^2) and apartment building (814 m^2). The net area of the office building is 2695 m^2.

The buildings were further divided into four age groups and individually modelled: buildings built before 1960 (age group A), between 1960 and 1979 (age group B), between 1980 and 2000 (age group C1), and between 2001 and 2010 (age group C2). Future construction was modelled as norm buildings built according to 2010 regulation (sub-type D1), low-energy buildings (sub-type D2) and very low-energy buildings (sub-type D3). In the REMA model, all buildings after 2010 were assumed to be of sub-type D1, after 2015 sub-type D2 and after 2020 sub-type D3 assuming a linear



Electricity production (%)											
	Nuclear	Coal	Gas	Peat	Biomass	Hydro	Wind	REF	Imports	Other	Sum
Year 0	27,9	13,1	11,4	5,4	10	15,6	0,3	0,7	15	0,6	100
Year presented	40,0	2,0	11,4	5,0	10,0	15,0	5,0	3,0	8,0	0,6	100,0
End of Scenario	40	2	11,4	5	10	15	5	3	8	0,6	100
Emission coefficients gCO2/kWh											Weight.Av.
Year 0	50	700	400	700	70	40	60	100	430	269,3	269,3
Year presented	50	700	400	700	70	40	60	100	430	169,0	169,0
End of Scenario	50	700	400	700	70	40	60	100	430	169,0	169,0

District heat production (%)							
	Gas	Coal	Peat	Biomass	Oil	Other	Sum
Year 0	38	25	19	11	4	3	100
Year presented	37,0	20,0	17,0	20,0	3,0	3,0	100,0
End of Scenario	37	20	17	20	3	3	100
Emission coefficients gCO2/kWh							Weight.Av.
Year 0	148	259	382	35	310	216	216,3
Year presented	148,00	259,00	382,00	35,00	310,00	193,61	193,6
End of Scenario	148	259	382	35	310	194	193,6

Fig. 3. The simplified linear development model of the energy sector used for CO_2 emission calculations.

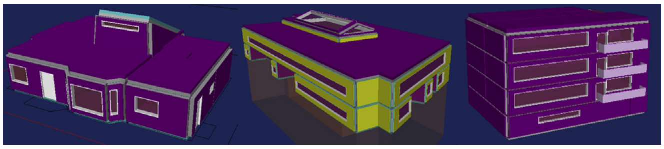


Fig. 4. Model buildings for (from left to right) detached house and holiday home, commercial building and apartment building.

approach to the nearly zero energy building level stipulated by the EPBD directive recast of the European Union [16].

Initial data used in the dynamic simulation (see Tables 2–7) are based on the numerous studies, Finnish building code, building definitions or the values are typical for the Finnish building. The air-tightness of the building envelope is presented in Table 2. For houses with natural ventilation the air-leakage through the envelope is included in the air-change rate. The level of air-tightness has improved during the years especially because attention has been paid on air-tightness in design and construction phase and air-tightness has become an important energy saving measure.

The heat loss values (U-values) of different structures are presented in Table 3. Table shows that the level of thermal insulation of the Finnish buildings has significantly improved during the studied period.

The detached house, the apartment and office buildings are heated continuously. The holiday home is heated only during the usage period, otherwise there is a base heating load. The holiday home is used annually in the model an estimated typical length. The use is estimated to span the whole of July, every weekend in June and August, and every third weekend from September to May. The heating set point temperatures of the buildings are presented in Table 4.

Mechanical cooling is continuously available in the detached houses D1, D2 and D3. The groups C1, C2, D1, D2 and D3 of the office building have a mechanical cooling system operating during weekdays between 6:00 and 20:00. A set point of cooling is 27 °C in the detached houses and 25 °C in the office building during the summer period (from the 1st of June to the 31st of August) and 24 °C in other times.

The detached house and apartment buildings are continuously ventilated. Mechanical ventilation is on in all the office buildings from B to D3 during week-days between 6:00 and 20:00. In other times only the social spaces are ventilated with the ventilation rate of 0.15 $dm^3/s,m^2$. The mechanical ventilation of holiday home is on only during the usage period. The ventilation systems of the studied building types are presented in Table 5 and the ventilation rates in Table 6. The ventilation rates of the older buildings are based on the experimental studies carried out in Finland [27,36,37] while the guideline of the Finnish building code [36,37] for the minimum ventilation rate has been used as the air change rate of the recent buildings.

Table 2
Air-tightness of the building envelope n_{50}, 1/h. For buildings marked with * the ventilation is natural and, therefore, included in the air-change rate.

Age group or sub-type	Detached house	Apartment building	Office building	Holiday home
A	*	*	*	*
B	*	2.3[a]	2.3[a]	*
C1	4.0[b]	1.0	1.5	7.9[c]
C2	3.5[b]	0.9[c]	0.9[d]	5.8[c]
D1	2.0	0.7	0.5	5.8[c]
D2	0.8	0.6	0.5	0.8
D3	0.6	0.6	0.5	0.6

[a] [26].
[b] [27].
[c] [28].
[d] [29].

Table 3
Heat loss values of the building structures: outer wall (OW), upper floor (UF), base floor (BF), window (W).

Age group or sub-type	Detached house	Apartment building	Office building	Holiday home
A	OW 0.69[a] UF 0.41[a] BF 0.48 W 2.2[a]	OW 0.83[a] UF 0.42[a] BF 0.48 W 2.2[a]	OW 0.83[a] UF 0.42[a] BF 0.48 W 2.2[a]	As a detached house in age group A
B	OW 0.42[a] UF 0.24[a] BF 0.48 W 2.2[a]	OW 0.47[a] UF 0.29[a] BF 0.48 W 2.2[a]	OW 0.47[a] UF 0.29[a] BF 0.48 W 2.2[a]	As a detached house in age group A
C1	OW 0.28[b] UF 0.22[b] BF 0.36[b] W 1.6[a]	OW 0.28[b] UF 0.22[b] BF 0.36[b] W 1.6[a]	OW 0.28[b] UF 0.22[b] BF 0.36[b] W 1.6[a]	As a detached house in age group B
C2	OW 0.25[c] UF 0.16[c] BF 0.25[c] W 1.4[c]	OW 0.25[c] UF 0.16[c] BF 0.25[c] W 1.4[c]	OW 0.25[c] UF 0.16[c] BF 0.25[c] W 1.4[c]	As a detached house in age group C1
D1	OW 0.17[d] UF 0.09[d] BF 0.16[d] W 1.0[d]	OW 0.17[d] UF 0.09[d] BF 0.16[d] W 1.0[d]	OW 0.17[d] UF 0.09[d] BF 0.16[d] W 1.0[d]	According to Finnish building code, part C3 (2010), log wall U-value 0.4
D2	OW 0.14, UF 0.08, BF 0.12, W 0.9[e]			As a detached house in sub-group D2
D3l	OW 0.08 UF 0.07 BF 0.09, W 0.7[f]			As a detached house in sub-group D3

[a] [30].
[b] [31].
[c] [32].
[d] [33].
[e] [34].
[f] [35].

The warm water usage of the studied building types is presented in Table 7. The levels of internal heat gains from the appliances, lighting and occupants used in the dynamic simulation of the detached house, apartment and office building were according to the Finnish Building Code, part D3 [41].

3. Results

3.1. Energy consumption in buildings

The results concerning the heating and cooling energy use in the various building types is presented in Table 8. Using these figures, the cumulative energy consumption of the whole building stock was calculated based on the modelled development of the building stock using the REMA model.

According to the estimate produced by the calculation for the year 2013 single-detached houses will consume, in terms of

Table 4
Heating set point temperatures.

Age group or sub-type	Detached house	Apartment building	Office building	Holiday home
A	21.0 °C[a]	22 °C[b]	21.5 °C	21.0 °C
B	21.0 °C[a]	22 °C[b]	21.5 °C	21.0 °C
C1	21.0 °C[a]	22 °C[b]	21.5 °C	21.0 °C
C2	21.0 °C[a]	21.5 °C[b]	21.5 °C	21.0 °C
D1, D2, D3	21.0 °C[a]	21.0 °C[c]	21.5 °C	21.0 °C

[a] Bathroom and sauna set temperatures 21 °C.
[b] Cellar and staircase set temperatures 19.0 °C, WC and bathroom set temperatures 23 °C.
[c] Basement and staircase set temperatures 17.0 °C, WC and bathroom set temperatures 23 °C.

Table 5
Ventilation systems: natural ventilation (NV), mechanical exhaust ventilation (ME), mechanical supply and exhaust ventilation (MSE), heat recovery (HR).

Age group or sub-type	Detached house	Apartment building	Office building	Holiday home
A	NV	NV	NV	NV
B	NV	ME	ME	NV
C1	ME	ME	MSE + HR (50%)	ME
C2	MSE + HR (60%)	MSE + HR (60%)	MSE + HR (80%)	ME
D1	MSE + HR (60%)	MSE + HR (60%)	MSE + HR (80%)	MSE + HR (60%)
D2	MSE + HR (80%)	MSE + HR (80%)	MSE + HR (80%)	MSE + HR (80%)
D3	MSE + HR (85%)	MSE + HR (85%)	MSE + HR (85%)	MSE + HR (80%)

Table 6
Air-change rate, 1/h.

Age group or sub-type	Detached house	Apartment building	Office building	Holiday home
A	0.41[b]	0.62[b]	0.62[b]	0.41[g]
B	0.41[b]	0.43[c]	0.43[c]	0.41[g]
C1	0.46[b]	0.5[d]	0.5[d]	0.46[g]
C2	0.40[a]	0.56[a]	0.5[e]	0.40[g]
D1	0.5[f]	0.5[f]	0.5[f]	0.5[g]
D2	0.5[f]	0.5[f]	0.5[f]	0.5[g]
D3	0.5[f]	0.5[f]	0.5[f]	0.5[g]

[a] [27].
[b] [36].
[c] [37].
[d] [38].
[e] [39].
[f] [40].
[g] When in use, at other times only air-leakage through the envelope.

delivered energy, 32.5 TWh of heating energy (including electricity for heating) and 5.2 TWh of electricity (excluding heating), apartment buildings consume 17.5 TWh in heating and 5.6 TWh of electricity, commercial and public buildings 20.0 TWh in heating and 7.6 TWh of electricity and, finally, holiday homes 2.4 TWh in heating and 0.3 TWh of electricity, totalling in 72.3 TWh of heating energy and in 18.8 TWh of electricity for the whole building stock.

For 2020 a similar calculation suggests that detached houses will consume 31.7 TWh of heating energy (including electricity for heating) and 5.5 TWh of electricity (excluding heating), apartment buildings consume 17.0 TWh in heating and 5.8 TWh of electricity, commercial and public buildings 19.0 TWh in heating and 8.0 TWh of electricity and, finally, holiday homes 2.3 TWh in heating 0.4 TWh of electricity, totalling in 70.0 TWh of heating energy and in 19.7 TWh of electricity for the whole building stock.

Table 7
Warm service water consumption.

Age group or sub-type	Detached house, dm^3/pers, day	Apartment building, dm^3/pers, day	Office building, dm^3/rm^2,[a]	Holiday home
A	42[a]	64[b]	100[c]	According to the usage profile
B	42[a]	62[b]	100[c]	According to the usage profile
C1	42[a]	59.2[b]	100[c]	According to the usage p rofile
C2	42[a]	57.6[b]	100[c]	According to the usage profile
D1, D2, D3	42[a]	56[b]	100[c]	According to the usage profile

[a] [42].
[b] [43].
[c] [44].

Table 8
Heating and cooling energy net demands for each building type, kWh/m^2.

Building category	Age group or sub-type	Space heating	Space cooling	Inlet air heating	Warm service water heating
Detached houses	A	242	0	0	21
	B	189	0	0	21
	C1	157	0	0	21
	C2	98	0	10	21
	D1	68	2	9	21
	D2	53	3	2	21
	D3	38	4	2	21
Apartment buildings	A	200	0	0	49
	B	125	0	0	47
	C1	51	0	0	45
	C2	22	0	17	44
	D1	11	0	15	43
	D2	8	0	4	43
	D3	4	0	3	43
Office buildings	A	232	0	0	6
	B	135	0	0	6
	C1	105	12	27	6
	C2	52	20	5	6
	D1	41	16	6	6
	D2	33	23	6	6
	D3	25	27	5	6
Holiday homes	A	94	0	0	11
	B	91	0	0	11
	C1	63	0	0	11
	C2	61	0	0	11
	D1	39	0	1	11
	D2	22	0	0	11
	D3	17	0	0	11

Fig. 5 shows the forecast development of energy consumption in the building stock, whereas Fig. 6 shows CO_2 emissions. It can be seen that over longer time periods a declining trend in total energy consumption in the building stock will be established, possibly reaching levels under 85 TWh/a after 2030. Measured in CO_2 emissions the downward trend is steeper and will go down from around 18 MT/a in 2010 to less than 16 MT/a in 2030 according to the modelling results.

The results suggest that the pace of reductions in energy consumption will accelerate over time as new buildings represent a growing share of the building stock. By 2050 the total energy consumption is forecast to reach 79.3 TWh/a and the CO_2 emissions to 13 MT/a corresponding to a reduction of 13% and 30% respectively compared to the present situation. Over such long periods of

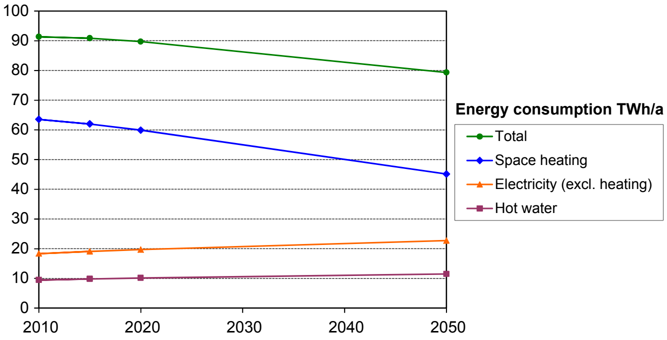


Fig. 5. Modelled energy consumption in the whole building stock.

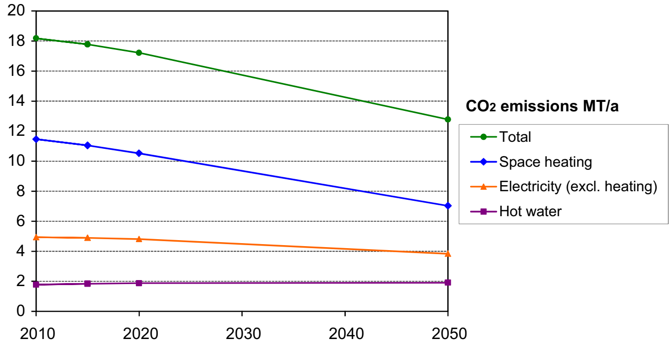


Fig. 6. Modelled CO_2 emissions in the whole building stock.

time, however, the results should be seen as only indicative of the direction of future trends.

4. Discussion

To assess the reliability of the estimate, the results were compared to other estimates concerning the most recent year, 2010, where statistics were already available. This comparison is presented in Fig. 7. The estimate fits reasonably well within the variation present in past calculations, with somewhat higher heating energy consumption in detached houses than other studies have suggested. This might be because a significant part of the stock of detached houses might be underused or in disuse and thus kept in lower than comfortable temperature. On the other hand the result is close to what Statistics Finland [24] has estimated it to be after corrections to their previous estimate [23].

There is considerable variance between the different studies with greatest agreement being in apartment buildings, where all the cited sources place the heating energy consumption between 18 and 21 TWh/a with a 21% difference between the highest and lowest estimate. In commercial buildings the differences are the greatest with the lowest estimates being 17 TWh/a and the highest 33 TWh/a, representing a difference of 97%. This is, however, due to one study which is an outlier in the set, the second highest estimate placing the value to a more modest 21 TWh/a. In any cases the differences are large and may be due to a lack of sufficient empirical data concerning the actual energy consumption in buildings, forcing the use of estimates instead.

The results calculated in this scenario correspond to a decrease of about 3% in heating energy consumption and a 6% increase in electricity consumption in the building stock by the year 2020. The combined effect is a 2% reduction in total energy consumption. Concerning residential buildings, this is in agreement with the rising importance of household electricity consumption that has been prevailing in the Finnish building stock over a long time already. It is noteworthy, however, that heating energy consumption will begin to decrease solely due to the better energy efficiency of new buildings and the gradual removal of old, more energy consuming buildings from the stock.

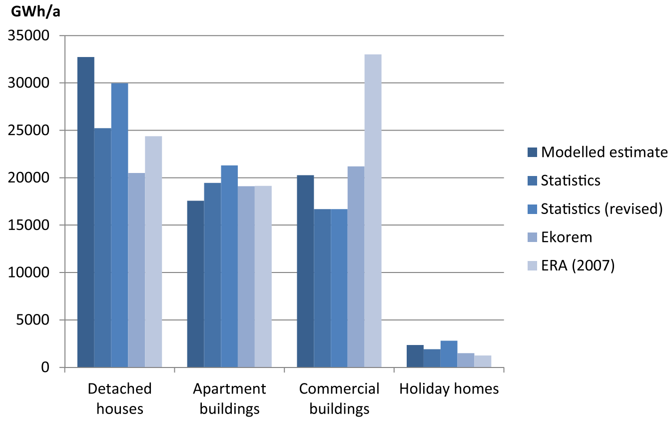


Fig. 7. Comparison of the modelled estimate for heating energy consumption in buildings in 2010 with the official statistics [23], revised statistics [24], Ekorem project [17] and ERA project [25].

The scenario presented here does not involve any renovations to improve energy efficiency in the existing building stock and all improvements are due to the regulation changes already in effect that concern new buildings. Therefore it can be called a Business as Usual or BAU type of scenario. Considering that in the future more policy measures can be expected, this scenario is more likely to underestimate the energy savings that will be achieved rather than to overestimate them. Furthermore, as the relative share of new buildings in the building stock rises over time, the pace of reductions in energy consumption will increase.

Concerning the effects of climate change on building energy consumption, Jylhä et al. [45] stated that the total delivered energy consumption of a typical new Finnish detached house and an office building will decrease by 4–7% by 2030 if the worst-case climate change scenario is realized. This means that during the period studied here, the effects of climate change are likely to be smaller than that. Moreover, it makes the estimated reductions a more conservative assessment as quickly advancing climate change would make them larger than anticipated.

Compared to the previously published estimate [7] for the development energy consumption in the Finnish building stock under BAU conditions, the results show a faster decrease over time in heating energy consumption than what was anticipated at the time when the last estimate was made. This is due to the new regulation that is in accordance with the revised EPBD directive of the European Union [16]. The level of energy efficiency stipulated by the new regulation is much higher than was anticipated in the previous assessment. Therefore, the results of the scenario presented here can be interpreted as an assessment of the effects of the EPBD directive in Finland.

For CO_2 emissions the decrease over time is sharper than for energy, as is demonstrated by Fig. 6. This is due to the changes in the energy sector towards fewer emissions at the same time as the buildings become more energy efficient. The combined effect can be significant, resulting in a 30% reduction in emissions from the building stock by 2050 in this scenario. It should be noted, however, that this modelling after 2020 is intended as only an indicator of the rough direction of future development, because this scenario assumes no further measures to be taken after 2020.

A benefit of the approach chosen here is that each type and subtype of buildings is individually modelled and, therefore, their contribution to the total energy consumption can be traced to the modelled physical characteristics of the buildings, as they are present in the IDA-ICE model used to calculate the input data. This allows the study of individual building modifications and their effects to energy consumption on a large scale. The authors are presently working on an estimate on the effect of the increase of heat pumps for heating on the energy consumption in the building stock.

5. Conclusions

The cumulative energy consumption of the whole building stock was calculated based on the modelled development of the building stock using a novel calculation tool, the REMA model. The energy demands for the building types that make up the building stock in REMA were calculated using the IDA-ICE simulation tool. These were used as inputs for the REMA model to calculate the total energy consumption of the building stock for each year, taking into consideration the estimated changes in the future development of the building stock.

In the scenario calculated, no other changes were expected to take place in the development of the building stock, except for the newest changes to the building code in accordance to the EPBD directive of the European Union [16]. Therefore the results can be treated as an updated Business as Usual scenario for Finland after the changes in regulation have taken effect. The results suggest a decrease of about 3% in heating energy consumption to 70.0 TWh and a 6% increase in electricity consumption to 19.7 TWh by the year 2020 corresponding to a reduction of 2% in total energy consumption. For CO_2 emissions, a decrease of about 4% can be expected by 2020 concerning all energy use in the building stock, partly due to improving energy efficiency and partly due to changes towards lower emissions in energy production. This dual effect explains the faster decline in emissions compared to energy.

The results indicate that the EPBD directive is likely to succeed in affecting an overall reduction in the energy consumption in the building stock in Finland. Over time the rate of reductions in energy use and CO_2 emissions will accelerate as the relative share of new buildings in the building stock grows. By 2050 reductions of 13% in terms of energy and 30% in CO_2 are estimated. This figure will, however, change as more policy measures are enacted and new technologies become available.

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PUBLICATION II

Economic effects of energy efficiency improvements in the Finnish building stock

Energy Policy 52, pp. 181–189.

Energy Policy 52 (2013) 181–189

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Economic effects of energy efficiency improvements in the Finnish building stock

Pekka Tuominen [a],*, Juha Forsström [b], Juha Honkatukia [b]

[a] *VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland*
[b] *VATT Government Institute for Economic Research, Arkadiankatu 7, P.O. Box 1279, 00101 Helsinki, Finland*

HIGHLIGHTS

- ▸ The possible cut in energy consumption: 3.8–5.3% by 2020 and 4.7–6.8% by 2050.
- ▸ Short term negative effects to GDP and long term positive effects are expected.
- ▸ A significant drop in harmful emissions and hence external costs is anticipated.

ARTICLE INFO

Article history:
Received 21 November 2011
Accepted 3 October 2012
Available online 23 October 2012

Keywords:
Energy efficiency
Economics
Buildings

ABSTRACT

This study estimates the economic effects of investing in energy efficiency in buildings on a national level. First conservation potentials in space heating for two different scenarios with different levels of investment in energy efficiency are quantified. This was done relying on statistical data and future projections of the development of the building stock. Then economic modeling was used to estimate the effects on energy sector and the economy at large. The results show that a rather modest increase resulting in a few percent rise in annual construction and renovation investments can decrease total primary energy consumption 3.8–5.3% by 2020 and 4.7–6.8% by 2050 compared to a baseline scenario. On the short term a slight decrease in the level of GDP and employment is expected. On the medium to long term, however, the effects on both would be positive. Furthermore, a significant drop in harmful emissions and hence external costs is anticipated. Overall, a clear net benefit is expected from improving energy efficiency.

1. Introduction

In this study an estimation of the economic effects of improving the energy efficiency of buildings in Finland was done in two phases: first an engineering estimate of energy conservation potentials was done for two scenarios, then economic modeling was used to assess the economic effects. The study provides insight to the potential effects of the new European Union directive on the energy efficiency of buildings that stipulates major efficiency improvements (European Parliament, 2010).

The consumption of energy can be attributed to a few major categories of consumers—among them buildings. One quarter of the global energy production is consumed in residential buildings, one tenth in commercial buildings. Commercial and residential buildings represent one of the largest energy use segments in the global economy. Major consumers of energy in buildings are lighting, electric appliances and devices and, above all, heating. As Fig. 1 illustrates, heating, together with traffic, is the most significant specific end use for energy in the world (IEA, 2008).

The average household in the US was estimated to consume 873 $ for heating each year in 2007 (Hagenbaugh, 2007). In Finland, heating is the largest component of expenses in housing companies (Marttila, 2005). The overall share of housing and energy expenses in Finnish household expenditure has increased over the past decades from 19.7% in 1985 to 28.7% in 2001 (Viinikainen et al., 2007). Thus the share of heating expenses in household expenditure is not inconsequential. It bars a considerable fraction of households' disposable incomes from other potential consumption. Furthermore, the importance of heating in the total consumption of energy means that a major portion of energy investments has been made to supply the needed heat.

Whereas most of heating needs are presently covered by the consumption of fossil fuels (Balaras et al., 1999), heating inevitably contributes to climate change. Moreover, the use of different fuels in heating, directly or indirectly, causes a variety of local and

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* Corresponding author. Tel.: +358 50 5309759.
E-mail addresses: pekka.tuominen@vtt.fi, p.tuominen@gmail.com (P. Tuominen).

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http://dx.doi.org/10.1016/j.enpol.2012.10.012

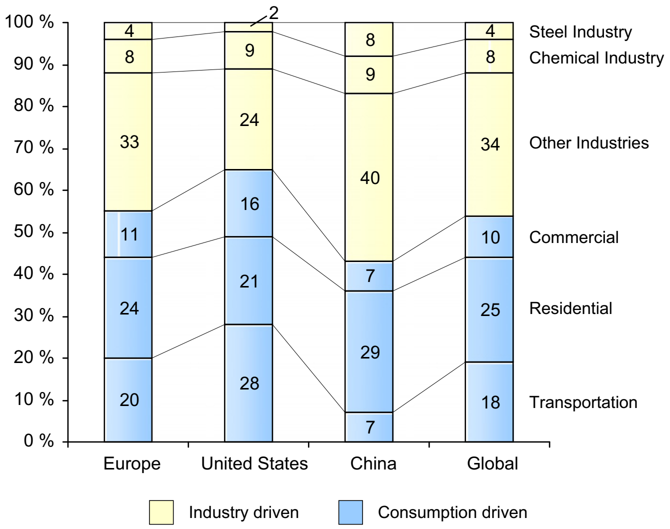

Fig. 1. Share of energy end use by sector in 2003. Adapted from Farrell et al. (2007).

regional environmental effects, such as sulphuric oxide, nitrous oxide and particulate emissions (Kara et al., 2004).

Improving energy efficiency in buildings is one possible way to limit the consumption of energy and mitigate negative environmental effects. From the policy measures under consideration, the measures that have the greatest effect with the smallest cost should be implemented first. Therefore, the economic study of the available policy measures is needed (Enkvist et al., 2007).

Energy efficiency has become a central theme in the energy policies in Finland, the European Union and around the world in the mitigation of climate change. If the recently announced legislative and regulatory programs (Ministry of the Environment, 2008; European Parliament, 2010) concerning energy efficiency in buildings are carried out, we are to expect drastic changes in energy consumption in the building sector. The effects will radiate, through the building and energy sectors, throughout the whole economy. Thus the question of economic effects of these measures is indeed an important one. This study aims to quantify those effects with economic modeling.

2. Methods

The estimation of the economic effects of improving the energy efficiency of buildings in Finland was done in two phases. First conservation potentials in space heating for two different scenarios with different levels of investment in energy efficiency were quantified. Then economic modeling was used to estimate the effects on energy sector and the economy at large.

2.1. Defining the scenarios

For estimating future levels of energy consumption, two efficiency levels for buildings had to be defined: low energy buildings and passive buildings. In Finland a *low energy building* is generally understood as a building that consumes less than half of the heating energy of a comparable ordinarily designed and constructed building, so this definition was used. At the time when this study was conducted, according to the Finnish Association of Civil Engineers (RIL, 2001), a norm residential building consumed 100 kW h/m^2 a year for heating, half of which is 50 kW h/m^2. For commercial buildings consumption was 75 kW h/m^2, half of which equals 37.5 kW h/m^2.

In a *passive building* a comfortable indoor climate is achieved with no or very little active heating and cooling. According to the classification employed by the Promotion of European Passive Houses project of the European Commission a passive house in the Nordic Countries, above 60° of latitude, has a consumption of 20 kW h/m^2 to 30 kW h/m^2 (Kaan et al., 2006). According to RIL 216–2001 a passive residential multi-storey building has a heating energy consumption of 15 kW h/m^2 and a passive commercial building 9 kW h/m^2 (RIL, 2001).

The future heating energy consumption in buildings was estimated based on the forecast development of the Finnish building stock in the coming decades, estimates of typical energy consumption for different kinds of buildings and the expected rate of renovations. Using this method, three scenarios for future development were created.

The baseline scenario is called Business as usual (BAU); it assumes that buildings continue to be built according to current practices. The results of the other two scenarios will be compared to this one to quantify the savings potential and the consequences of its realization. The BAU scenario is not meant to be in any way prognostic, in fact, considering recent developments in regulations, it is highly unlikely. Rather, it offers the possibility to compare the present level of efficiency to more likely future scenarios. The major assumptions in the two other scenarios, Delayed development (DD) and Rapid development (RD) are presented in Table 1.

Both DD and RD scenarios assume that energy efficiency improvements will be done in buildings that would undergo renovation in any case for other reasons. In DD these improvements will be relatively modest, whereas in RD major energy retrofits are assumed.

Both development scenarios, RD and DD, include the change in the construction regulation in 2010 with a 30% decrease in the maximum heating energy consumption of new buildings (Ministry of the Environment, 2008). This will be the minimum improvement compared to the BAU scenario that will affect even those new buildings that are not low energy or passive buildings. Due to a lag in the statistics available for input data, the starting point of the modeling was set at 2008.

The scenarios use the Rogers (1962) model for the diffusion of innovations for modeling the increase of low energy buildings in new construction. In the process of technology diffusion the market share of the new technology will gradually rise following the pattern of a Gaussian *S*-curve. Finally, the market will be saturated by the new product unless a new competing technology emerges.

The values used for adjusting the *S*-curves of the model are shown in Table 2. The values were chosen so that the results are in agreement with the current situation and with assumptions explained here.

2.2. Estimating heating energy consumption in buildings

The estimation of the heating energy consumption in buildings was done with MS Excel spreadsheets. It is based on the forecast

Table 1
Major assumptions concerning new buildings being built in the Delayed development (DD) and Rapid development (RD) scenarios.

Scenario	Low energy buildings, year of reaching majority in new buildings		Passive buildings, year of reaching majority in new buildings	
	Detached houses	Other buildings	Detached houses	Other buildings
DD	2030	2040	2070	2080
RD	2015	2020	2030	2040

Table 2
The values used as the parameters of the Gaussian *S*-curves of the diffusion model.

For $\Phi\mu,\sigma^2$ (x)	Delayed development scenario				Rapid development scenario			
	Low energy buildings		Passive buildings		Low energy buildings		Passive buildings	
	Houses	Other	Houses	Other	Houses	Other	Houses	Other
Standard deviation σ	17	17	33	33	5	5	9	9
Mean (year with 50% share) μ	2027	2037	2070	2070	2013	2018	2025	2030

Table 3
The forecast development of the Finnish building stock in 1000 m^2 (Nuutila 2008).

	Building stock			Reduction		Construction	
	2007	2020	2050	2007–2020	2020–2050	2007–2020	2020–2050
Detached houses	142 000	163 800	180 200	8 100	44 800	29 900	61 200
Residential buildings	116 200	128 700	131 000	3 800	29 300	16 300	31 600
Commercial buildings	101 800	112 100	119 400	17 700	46 400	28 000	53 700
Total	360 000	404 600	430 600	29 600	120 500	74 200	146 500

of the development of the Finnish building stock in the coming decades and estimates of typical energy consumption for different kinds of buildings. Using this method, different scenarios for future development were created. The data concerning the building stock was obtained from the EkoREM model developed at the Tampere University of Technology and VTT Technical Research Centre of Finland in 2003–2005 (Heljo et al., 2005). According to Heljo et al., the input data for EkoREM originates from multiple sources: Statistics Finland which for its part uses the building registry of the Population Register Center, the national statistics for new construction, VTT's KORVO and REMO studies from 1982, 1990 and 2000 concerning renovations and VTT's periodical surveys concerning new construction. These are generally considered to be reliable sources. More discussion on the matter is available from Heljo et al. (2005).

For purposes of simplification, the data on the building stock was compiled to three categories: detached houses, residential buildings and commercial buildings. Detached houses are understood as one-family residences. Residential buildings include buildings that have more than one apartment, namely multistory buildings and row houses. Commercial buildings include buildings in commercial use (offices, stores etc.) and public buildings (schools, hospitals etc.). The choice of categories was made based on the roughly similar typical heating energy use in the buildings grouped together. According to an updated forecast made in 2007, the building stock will develop as is shown in Table 3 (Nuutila, 2008).

The buildings were further categorized according to their age. Again, the age data was acquired from the results of the EkoREM model (Heljo et al., 2005). The age categories were partly based on the ones available from the source and partly on the need to have more detail in the building stock built before 1980 because most changes due to removal from the stock and renovations will take place there.

The reduction of old building stock, shown in Table 3, was assumed to consist mostly of the oldest buildings in the stock. Thus the share of buildings built before 1960 would fall at a faster rate than the share of those built during the 1960's, which in turn would outpace those built in 1970's and so on, as is shown in Fig. 2. Development along these lines seems reasonable to assume and is deemed to be a satisfactory approximation for the purposes of this study.

For each age group of buildings an average consumption of heating energy per m^2 is used to calculate the total consumption. These are necessarily based on estimates as no measurement data representative of the actual distribution of consumption levels in the building stock is available. Tuomaala (2007) has given the estimates on heating energy consumption according to the age of the building shown in Table 4. The table also shows what consumption figures were chosen for the actual calculations. The choices were made so that the resulting figures would agree with the calculated total consumption of heating energy in each category and age group of buildings as it has been reported by Heljo et al. (2005).

It can be seen that in most cases the choice had to be in and even above the upper limit of the estimate reported by Tuomaala. Also, according to consumption figures from Heljo et al. (2005), energy consumption per m^2 is much higher in commercial buildings. This was to be expected as commercial buildings usually have less insulation and more ventilation than residential buildings.

As a result, the 2008 stock of houses is estimated to consume 22 TW h of heating energy annually, residential buildings 18 TW h and commercial buildings 24 TW h. The combined estimated annual heating energy consumption is therefore 64 TW h, which is reasonably close to the 66 TW h and 69 TW h estimates given by Heljo et al. (2005) for years 2000 and 2010, respectively.

The future of heating energy use is predicted in similar fashion. The figures for energy consumption in new buildings, shown in Table 5, are used together with the data from Table 3 to form scenarios of future energy consumption. The energy consumption figures for low energy and passive buildings are based on the definitions presented earlier. For passive houses a figure of 20 kW h/m^2 is chosen as it is near the average from the available range of numbers.

The energy consumption of the norm building of 2003 is given in accordance with the classification scheme RIL 216–2001 of the Finnish Association of Civil Engineers (RIL, 2001). The norm building of 2010 is anticipated to have an energy consumption 30% lower.

2.3. Renovations

In both scenarios the annual amount of energy efficiency improvements completed during renovations is assumed to be the same, namely 3.5% of the building stock built before 2008. This rate was chosen because it agrees with the observed number

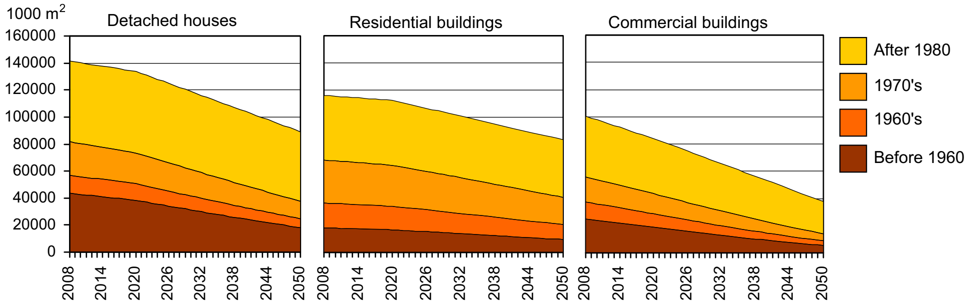

Fig. 2. The anticipated reduction in the stock of old buildings, not showing new buildings after 2008, arranged according to construction year.

Table 4
Values for annual heating energy consumption in kW h/m^2 sorted by construction year.

	1960	1960s	1970s	1980
Estimate according to Tuomaala (2007)	160–180	160–200	120–160	100–140
Estimate chosen for residential buildings	180	200	170	120
Estimate chosen for commercial buildings	260	280	250	200

Table 5
Values for annual heating energy consumption in kW h/m^2 sorted by building type.

	Norm 2003	Norm 2010	Low energy	Passive
Detached houses	100	70	50	20
Residential buildings	100	70	50	15
Commercial buildings	75	52.5	37.5	9

of renovations in relevant parts[1] of the buildings (Vainio et al., 2002) and because at that rate all of the building stock will be renovated once by 2040–2050. Given that the shell should usually be renovated every 25 to 35 years (Virtanen et al., 2005), the assumed rate of renovations seems very reasonable, even conservative.

The differences in the scenarios concerning energy efficiency retrofits come from the quality of the improvements, shown in Table 6. As systematic data is not available from renovations, the assumed improvements were based on experiences from past renovations to a number of representative old buildings (Holopainen et al., 2007).

Combining the effects of energy efficiency retrofits and efficiency improvements in new buildings for DD and RD scenarios and comparing the results with BAU gives estimates of the overall energy saving potential given two different sets of assumptions.

A final note should be made about the sources of heating energy. For old buildings actual data of the heating sources from Heljo et al. (2005) was used. For new buildings, it was assumed that the share for each source of heat will remain the same as it is buildings that have been completed in the past few years.

This is in agreement with the forecasts made in the EkoREM study, although EkoREM anticipates a possible slight rise in the share of district heat coupled with a decrease of electric heating (Heljo et al., 2005). However, low energy buildings would make large investments in heating, such as the installment of district heating, less attractive—hence the assumption made here of no change in the relative shares is well founded.

2.4. Quantifying the investment

To estimate the investments required for energy savings, two separate methods are employed: one for new buildings, another for renovations. In accordance with Viinikainen et al. (2007), for low energy buildings a construction cost 4% higher was chosen, for passive buildings 10%.

To estimate the level of investment costs in BAU, the present level of investment, as reported in the official national statistics (Statistics Finland, 2007), is scaled by the anticipated changes in construction based on data from Nuutila (2008). Finally, the numbers were adjusted for the latest developments in the costs of construction (Rakennusteollisuus, 2010) to make them more up-to-date. Naturally more changes can be expected in the future, but as any such changes are unknown, the present cost level is used throughout the scenarios.

The investment estimate of BAU formed the basis for similar calculations in DD and RD scenarios. Using the shares of each building type and the said estimates of cost increases, the annual investment in low energy and passive buildings were calculated. As the shares of both building types rise over the course of time, so do the supplementary investments required to build them.

For energy efficiency retrofits, a cost estimate based on the applied measures is used. As both DD and RD scenarios assume improvements only in buildings that would be renovated regardless of energy efficiency considerations, the cost estimates include only the supplementary cost caused by the actual efficiency improvements and not the total renovation cost. This is far less than what a dedicated energy efficiency retrofit of similar scope would cost.

The cost of renovation is rather different for small houses and large buildings. Therefore two different estimates were used for each. For detached houses the estimate was based on a VTT report (Holopainen et al., 2007), for buildings of all other types, an IEA survey (Waide, 2004).

The VTT report lists different conservation measures that may be implemented in an energy efficiency retrofit and gives both their effect on energy consumption and investment cost. To reach the level of improvement assumed in the DD scenario, a sufficient set of the most cost-effective measures needed was chosen.

The IEA survey notes that when efficiency improvements are implemented in conjunction with other major renovations, typically the cost is roughly halved. This is precisely the condition assumed in this study; therefore the investment costs were reduced by 50%.

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[1] The parts of buildings that will most effect the heating energy consumption are the shell, windows and doors, roof and floor, and heating and ventilation equipment.

For larger buildings the IEA survey gave figures for efficiency improvements implemented during major renovations for other purposes. Again, prices were available for different measures with differing costs and impacts, and again a set of the most cost-effective measures needed for reaching the savings assumed in DD was chosen.

For both houses and other buildings in the RD scenario, similar exercises were conducted. As each additional efficiency investment tends to be less cost-effective than the preceding ones, the cost per energy savings is higher in the more thorough renovations assumed in RD. Finally, having reached cost estimates for each level of improvement for both types of buildings, the estimates were used with the assumed amount of renovation to calculate the annual investment cost.

2.5. *Economic modeling*

Two models were used to obtain the results presented here, as is shown in Fig. 3. First the POLA model provided the effects on the energy sector. Then the VATTAGE model was used to calculate economy-wide effects of the scenarios using the results of the POLA model as input.

The VATTAGE and POLA models have been developed for the purposes of economic evaluation of policy decisions and have been gradually improved based on their past performance. POLA was developed at VTT and it is based on the commercially available What is Best modeling environment. A detailed description of the model is available at request from VTT (Forsström, 2004). VATTAGE is a dynamic applied general equilibrium (AGE) model based on the Australian MONASH model (Dixon and Rimmer, 2002). It is a traditional comparative-static AGE that uses Leontieff and CES aggregators. A detailed description of the model has been published by Honkatukia (2009).

Table 6
Assumed coefficients for energy consumption achieved with energy efficiency retrofits of buildings.

	No improvement	Modest improvement (DD)	Significant improvement (RD)
Shell	1	0.66	0.53
HVAC	1	0.9	0.5

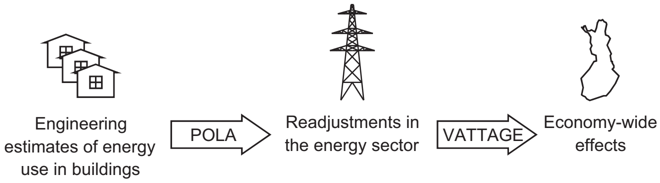

Fig. 3. The modeling sequence used to estimate the economic effects.

The POLA model is a partial equilibrium model of the Finnish energy sector. It uses linear programming to calculate partial equilibriums of energy production and consumption. In other words, the model calculates a clearance on the market for energy independently from prices and quantities demanded and supplied in other markets (Forsström, 2004).

In the VATTAGE model the economy has macroeconomic constraints for employment, capacity and external balance. Price signals are the drivers in the adjustment of the economy. Currently the model aggregates the economy into 51 sectors of industry and 43 commodities. Yearly input–output tables of the Finnish national economy are used to update the model.

Three inter-temporal links connect consecutive periods in the model: accumulation of fixed capital, accumulation of financial claims and lagged adjustment mechanisms, such as the labor markets and the public sector budget. Together, these mechanisms result in gradual adjustment to any policy shocks to the economy (Honkatukia, 2007).

This combination of models suits well to the problem at hand, given their development history that has aimed for the estimation of the economic effects of policy decisions. Nevertheless, the results of any economic modeling should not be taken as a final analysis of the problem, rather they offer helpful insight into the potential effects of given scenarios under certain assumptions and are, therefore, contingent on those assumptions.

2.6. *Externalities*

Externalities occur whenever the decisions of economic agents cause incidental costs or benefits borne by others that are not reflected in market prices. Energy use as an economic activity tends to entail especially severe negative environmental externalities, therefore they merit particular attention.

The externalities of energy consumption are especially significant compared to market prices. Hall (2004) has estimated that for

Table 7
External costs in electricity production in Europe in c/kW h as reported by the European Commission (2003).

Country	Coal	Peat	Oil	Gas	Nuclear	Biomass	Hydro	Solar	Wind
Austria				1–3		2–3	0.1		
Belgium	4–15			1–2	0.5				
Germany	3–6		5–8	1–2	0.2	3		0.6	0.05
Denmark	4–7			2–3		1			0.1
Spain	5–8			1–2		3–5[a]			0.2
Finland	2–4	2–5				1			
France	7–10		8–11	2–4	0.3	1	1		
Greece	5–8		3–5	1		0–0.8	1		0.25
Ireland	6–8	3–4							
Italy			3–6	2–3			0.3		
Netherlands	3–4			1–2	0.7	0.5			
Norway				1–2		0.2	0.2		0–0.25
Portugal	4–7			1–2		1–2	0.03		
Sweden	2–4					0.3	0–0.7		
Britain	4–7		3–5	1–2	0.25	1			0.15
Average	5.71	3.50	5.70	1.79	0.39	1.13	0.43	0.60	0.15

[a] Cofired with lignite.

many energy sources negative externalities amount to no less than well over 100% of the market price. Table 7 shows the external costs in a set of European countries with current levels of technology as they were estimated by the ExternE research network (European Commission, 2003). Included in the figures are all major types of externalities that are quantifiable, such as global warming, public health, occupational health and material damage.

The results reported by the ExternE research show that in some countries some energy sources can cause externalities as high as 15 c/kW h, while others as low as less than 1 c/kW h. This can be compared to the current price of electricity from the Helsinki city electric utility, 7.44 c/kW h or 13.36 c/kW h including transmission (Helsingin Energia, 2011).

The highest costs come from direct health damage, damage to ecosystems and, above all, global warming. These effects are all caused by harmful emissions. Hence, it is no surprise that the energy sources that entail no polluting emissions are the ones with external costs of less than 1 c/kW h, namely nuclear, solar, wind and hydro energy (European Commission, 2003).

ExternE has published typical external costs per energy unit produced for each energy source in different European countries. The figures for Finland were multiplied with the energy production data obtained in the modeling. Where figures for Finland were not available, European averages were used. It should be noted that some forms of external costs are difficult to evaluate, especially the value of climate change mitigation.

3. Results

3.1. Direct effects

Fig. 4 shows the anticipated development of heating energy consumption in the three scenarios based on the conditions explained before. By 2020 the measures implemented in the delayed development scenario will allow annual energy savings of 7 TW h, which represents more than a 10% drop compared to BAU. By 2050 savings of about 40% are projected. With rapid development the pace of progress nearly doubles: about 25% by 2020 and over 50% by 2050.

3.2. Effects in the energy sector

The energy conservation measures applied in DD and RD scenarios cause changes in the energy consumption of different heating sources as described in Fig. 4. Such major shifts in heating energy consumption are bound to cause some readjustments in the energy sector, given the heating's rather large share of 22% of the total energy consumption. Especially important to the power generation system are the effects on the consumption of district heat and electricity.

Changes in the energy sector were modelled at VTT with the POLA model. The estimates of the changes in energy consumption presented before were used as input to the model. A summary of the results can be seen in Table 8 and in Table 9.

It should be noted that the BAU scenario is formed by the POLA model when no other policy limitations are applied on the energy sources other than a limit on the number of nuclear power plants. This is, of course, unlikely to be the actual course of development in the future, but as the evaluation of policy measures other than those relating to buildings are outside the scope of this study, none were assumed. In any case the accuracy of the BAU scenario is irrelevant pertaining to the effects of the energy efficiency improvements studied here, given that the differences between the scenarios are of interest rather than the absolute values.

Table 8 shows that the electricity consumption in DD and RD scenarios is lower than in BAU, which was to be expected given the lower consumption of electricity in heating. RD has the lowest consumption, again expectedly. In DD electricity consumption is 1.5% lower in 2020 than in BAU, 2.0% in 2050. For RD similar numbers are 2.3% and 3.3%, respectively.

Table 8
Electricity production in the scenarios (TW h).

Energy source	Reference	BAU		DD		RD	
	2005	2020	2050	2020	2050	2020	2050
Hydro & wind	13.1	15.2	16.7	15.2	16.7	15.2	16.7
Nuclear	21.9	35.0	12.9	35.0	12.9	35.0	12.9
Wood & REF	9.5	13.1	20.4	11.1	18.3	10.4	17.6
Gas & oil	10.6	10.1	18.0	12.6	19.3	13.4	19.5
Coal	10.1	23.6	45.6	23.0	45.1	22.2	44.4
Peat	5.7	4.2	7.1	2.9	5.8	2.6	5.6
Other	0.4	2.1	2.1	2.2	2.3	2.2	2.1
Imports	10.0	0	0	0	0	0	0
Total	81.2	103.4	122.9	101.9	120.5	101.0	118.8

Table 9
Total primary energy consumption in the scenarios (PJ).

Energy source	Reference	BAU		DD		RD	
	2005	2020	2050	2020	2050	2020	2050
Hydro & wind	49.6	54.6	60.1	54.6	60.1	54.6	60.1
Nuclear	240.1	381.3	141.2	381.3	141.2	381.3	141.2
Biofuels & REF	325.3	488.5	679.0	454.2	640.1	445.7	617.6
Gas & oil	473.0	499.6	559.1	483.6	531.6	478.8	520.9
Coal	91.2	237.4	397.7	235.9	382.7	226.2	374.4
Peat	86.0	64.9	106.4	51.4	97.2	48.5	97.2
Electr. imports	61.2	0.0	0.0	0.0	0.0	0.0	0.0
Total	1326.4	1726.3	1943.6	1660.9	1852.8	1635.1	1811.4

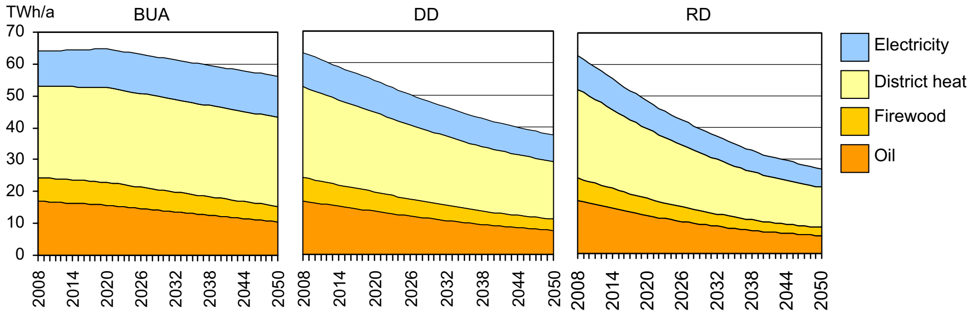

Fig. 4. Heating energy consumption in the different sources of heat in the three scenarios.

Hydro, wind and nuclear remain unchanged between the scenarios being typical base load electricity sources. Their production is largely dictated by investment decisions that the model cannot forecast. In each scenario no new nuclear power plants are expected after the one currently being built in Olkiluoto. Therefore the decommissioning of the oldest NPPs after 2020 lead to increases in other energy sources.

Among other energy sources, the diminishing demand of district heat favours large centralized power plants because large units reach higher efficiencies and without heat consumption decentralization is not necessary. Such large power plants more often burn fossil fuels than locally produced fuels. Therefore in DD and RD the relative significance of wood, REF and peat is smaller than in BAU. Nonetheless the scenarios show that smaller energy consumption leads to smaller consumption of all fuels in electricity generation.

A similar pattern can be seen in Table 9 with primary energy consumption. The rigidity of hydro, wind and nuclear is visible here as well. The relative shares of other fuels in all the scenarios are more or less similar but, again, the consumption levels are lower in DD and RD for all of them. This is explained by the fact that all of the fuel categories are employed in heating in significant amounts, as is visible in Fig. 4. In DD primary energy consumption is 3.8% lower in 2020 than in BAU, 4.7% in 2050. For RD similar numbers are 5.3% and 6.8%, respectively.

3.3. Economic effects

Annual direct investment in new buildings based on cost estimates alone for 2020 and 2050 are shown in Table 10. The table shows that the shift to low energy buildings would require increases of only a few percent to the level of investments that is to be expected anyway.

Direct investments in energy efficiency retrofits are shown in Table 11. The results suggest that the measures assumed in these scenarios would require a rather inconsequential increase of a few percent in the current annual investment of about 8 billion in renovations (Rakennusteollisuus, 2010).

The wider economic implications of the measures applied in the two scenarios were assessed with the economic modeling as was described before. The estimates of the investments and the POLA modeling results described above were used as input for the VATTAGE model of the Finnish economy. Interpreting the results, one should bear in mind that some of the uncertainties and sources of error in the model are cumulative and, therefore, towards the end of the time series the figures should be considered mostly as indicators of the broad direction of economic development.

Table 10
Construction investment (M€).

	2020	2050
BAU	7500	9 700
DD	7600	10 100
RD	7800	10 500

Table 11
Investment in efficiency retrofits (M€).

	2020	2050
BAU	0	0
DD	200	100
RD	300	200

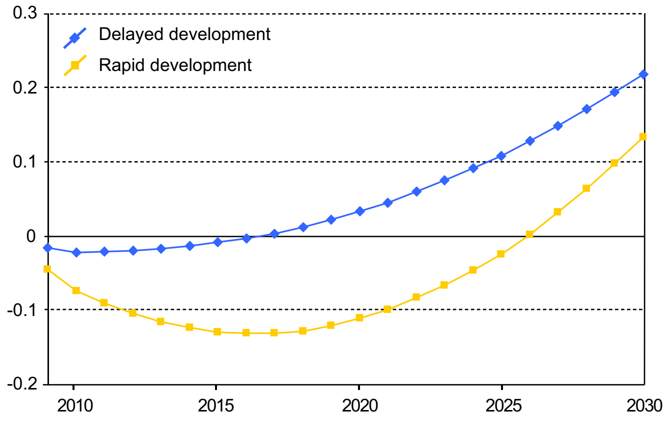

Fig. 5. GDP per capita in the two scenarios relative to BAU (%).

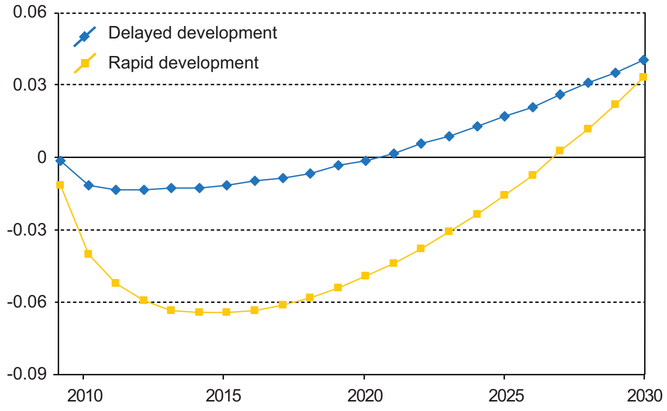

Fig. 6. Employment in the two scenarios relative to BAU (%).

Fig. 5 shows the effects of the two scenarios, according to the VATTAGE model, on the GDP per capita in Finland. The figure shows that initially the investments required by the energy efficiency improvements will cause limitations on economic development. The GDP can be expected to be lower than in the BAU scenario for 8 years with the investment level of DD and for 17 years with the investment level of RD. However, subsequently the GDP will reach higher levels than without the investments.

Fig. 6 shows how the two scenarios would affect employment relative to BAU. A slight decrease in employment could be expected at the beginning according to the modeling results. It would seem that the small expected increase in employment in the construction sector will be too small to completely offset the effects of a generally slightly smaller economy.

Later on, however, employment would rise to higher levels than in BAU. This can be expected as a result of the general effects on the economy reflected by the changes in the GDP. It should be noted, however, that the effects on employment, both negative and positive, are very small, less than one tenth of a per cent.

3.4. Externalities

A GDP only approach to estimating the economic effects would underestimate the utility of energy efficiency investments as it excludes the external costs caused by energy production. Especially important is the externality of global warming caused by greenhouse gas emissions. The modeling results show that both DD and RD scenarios can have a substantial effect on carbon dioxide emissions even on the national level, as is demonstrated by Fig. 7.

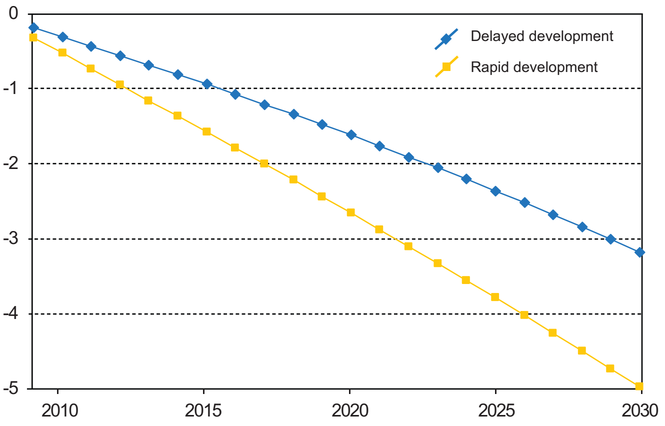

Fig. 7. Total domestic CO_2 emissions in the two scenarios relative to BAU (%).

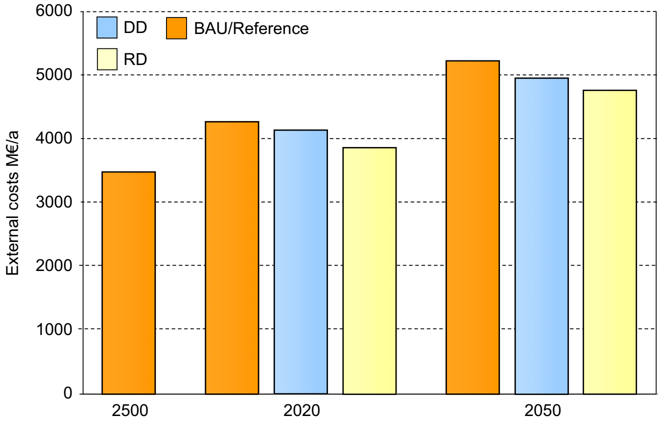

Fig. 8. External costs of energy production in Finland in the three scenarios.

Estimates of total external costs, including effects other than climate change and based on the figures published by ExternE (European Commission, 2003), are shown in Fig. 8 for each scenario.

The external costs in DD and RD are systematically lower than in BAU, which was to be expected due to lower levels of energy consumption. Monetarily DD has 170 M€ lower external costs in 2020, 230 M€ in 2050. For RD similar figures are 380 M€ and 440 M€, respectively. This can be compared to the Finnish GDP of 180 000 M€ in 2007. It is noteworthy that the volume of avoided external costs outweighs any losses or gains estimated in the previous sections in the GDP. Therefore from a welfare economic point of view both RD and DD are preferable to BAU.

4. Discussion

This study aimed at assessing the energy savings potential of measures aimed at improving individual buildings, and the economic effects thereof. It brings an economic dimension to the Finnish research of low energy buildings, which has concentrated mainly on technology thus far. Moreover, the results complement the previous work considering energy efficiency of communities, which has been studied in Finland in research projects such as METKA (Haukkasalo et al., 2008) and KulMa-Kunta (Perrels et al., 2006). The methods used here could conceivably be adapted to similar energy consuming economies.

The results show that investments in energy efficient buildings are an economically sound and effective way to save energy. The required investments carry manageable costs. A rather modest increase resulting in a few percent rise in annual construction and renovation investments can decrease total primary energy consumption 3.8–5.3% by 2020 and 4.7–6.8% by 2050 compared to BAU.

Policies aimed at increasing the amount of renovations to the level needed to realize these potentials could include mandatory energy improvements when cost-effective technology is available to any building part that is renovated for any other reason and subsidies for the adoption of emerging technologies close to maturity.

The results suggest that the energy sector can adapt quite painlessly to the changes. The improvements in energy efficiency are naturally implemented gradually due to the slow renewal rate of the building stock. Thus sudden shocks affecting the energy sector are avoided, the most significant effect being a generally lower need for new energy production capacity. It is observed, however, that the changes can adversely affect the share of renewables and other domestic energy sources.

Hydro, wind and nuclear remain unchanged between the scenarios being typical base load electricity sources. Their production is largely dictated by investment decisions that the model cannot forecast. In each scenario no new nuclear power plants were expected after the one that is currently under construction, as the study was conducted before the Finnish parliament issued to new permits for nuclear plants. Therefore the decommissioning of the oldest nuclear power plants after 2020 lead to increases in other energy sources.

Among other energy sources, the diminishing demand of district heat favours large centralized power plants because large units reach higher efficiencies and without heat consumption decentralization is not necessary. Such large power plants more often burn fossil fuels than locally produced fuels. Therefore in DD and RD the relative significance of wood, REF and peat is smaller than in BAU. Nonetheless the scenarios show that smaller energy consumption leads to smaller consumption of all fuels in electricity generation.

A similar pattern can be seen in Table 9 with primary energy consumption. The rigidity of hydro, wind and nuclear is visible here as well. The relative shares of other fuels in all the scenarios are more or less similar but, again, the consumption levels are lower in DD and RD for all of them. This is explained by the fact that all of the fuel categories are employed in heating in significant amounts, if not directly, then through district heating. In DD primary energy consumption is 3.8% lower in 2020 than in BAU, 4.7% in 2050. For RD similar numbers are 5.3% and 6.8%, respectively.

The economy would be positively affected in the long run. Both GDP and employment will reach higher levels than in BAU around 2020 in the DD scenario and around 2025 in the RD scenario. Initially, however, both the DD and RD scenario entail a decrease in GDP and employment. These effects are rather small and barely noticeable in the case of DD. In RD an initial decrease of about 0.1% in the GDP and 0.06% in employment could be expected.

It should be noted, however, that the decreases in external costs are more than enough to compensate for any temporary losses in GDP. One of the clearest effects of DD and RD would be a steady decrease in carbon dioxide emissions compared to the levels in BAU. Overall, the level of decrease in negative externalities is roughly equal to 1% of the GDP in DD and 2% in RD. Of course this particular benefit would be distributed globally, considering the nature of climate change.

All factors taken into account, both DD and RD scenario are clearly preferable compared to BAU from an economic point of view. Between the two, it is less clear which is more beneficial.

Making such a judgment requires balancing long-term and short-term benefits as DD appears more favourable in the short term and RD in the long term. In both scenarios energy efficiency appears to be a cost effective way to achieve major reductions in energy consumption without adversely affecting the economy in any significant way.

Gathering empirical data as Mills et al. (2004) have done in the US from Finnish energy efficiency renovations would be extremely useful for future research. Now the study had to rely largely on data from other countries. Also, empirical data, ideally based on random sampling, concerning the actual energy consumption of different types and ages of buildings would greatly improve our understanding of the composition of energy consumption in the building stock.

As new ways of providing energy, including improving energy efficiency, are studied, more should be done to study the economic effects of the new technological solutions, as here was done. This would gradually provide the policymakers with the means to compare different solutions with one another. Thus the most cost-effective technologies could be adopted first. This could help address problems like exhaustion of natural resources and the climate change more effectively.

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PUBLICATION III

Energy savings potential in buildings and overcoming market barriers in member states of the European Union

Energy and Buildings 51, pp. 48–55.

Energy and Buildings 51 (2012) 48–55

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy savings potential in buildings and overcoming market barriers in member states of the European Union

Pekka Tuominen[a,d,*], Krzysztof Klobut[a], Anne Tolman[a], Afi Adjei[b], Marjolein de Best-Waldhober[c]

[a] VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland
[b] BRE British Research Establishment, Bucknalls Lane, Watford WD25 9XX, UK
[c] ECN Energy Research Centre of the Netherlands, P.O. Box 1, 1755 ZG Petten, The Netherlands
[d] Aalto University, Department of Energy Technology, P.O. Box 14100, 00076 Aalto, Finland

ARTICLE INFO

Article history:
Received 14 September 2011
Received in revised form 23 February 2012
Accepted 12 April 2012

Keywords:
Energy efficiency
Savings potential
Market barriers
Policy measures

ABSTRACT

In this study the barriers to energy savings and the policy measures set up to overcome these barriers were mapped by interviewing stakeholders in ten European Union member states (MS). In addition, an estimate of energy savings potential was calculated. It seems that in most countries cost-effective energy savings of about 10% can be achieved by 2020 and 20% by 2030. A total annual energy saving of approx. 150 TWh by 2020 and approx. 280 TWh by 2030 appears possible. This can be compared to the total annual primary energy consumption of 21,000 TWh in all EU countries combined. Barriers and policies to overcome them were also studied. This was based on a literature review, stakeholder interviews and in-depth homeowner interviews in ten MS. A commonly cited problem was that people are not keen to improve energy efficiency of their homes as it does not proportionately increase the value of the property. Another widespread problem was that energy prices do not include all the negative external costs that the use of energy causes, such as pollution. The most commonly reported public policy measures in use related to information dissemination and subsidies for energy efficiency retrofits.

1. Introduction

Improving energy efficiency is regarded by the European Commission (EC) as a key element in the Community energy policy. It is described by the Commission as the most effective way to improve security of energy supply, reduce carbon emissions, increase competitiveness and stimulate the development of markets for new energy-efficient technologies. EC reports that the household sector has been estimated to represent 27% of the energy savings potential by the year 2020 [1].

Article 11 of the newest version of the Energy Performance of Buildings Directive (EPBD) stipulates that residential buildings must have an Energy Performance Certificate (EPC) when they are sold, rented out or constructed. The EPC includes a label rating of the energy efficiency of the dwelling and recommendations of cost-effective energy saving measures. The idea of the certificate is an assumption that decisions made at home are based on information available to the household about cost-effective energy saving measures (see preamble to the directive [2]).

The success of the EPC depends to a large extent on the conditions in member states. In the international cooperation project IDEAL EPBD, both technical and institutional country specific characteristics were investigated. The aim was to estimate energy savings achievable in the housing stock in selected member states (MS) in the European Union, and to identify obstacles that hinder active implementation of energy enhancement measures. The energy-savings potential was obtained by calculation. The obstacles for large-scale energy improvements were searched by studying dedicated policies in place in the MS, and by interviewing stakeholders and surveying homeowners.

The aim of this study is to analyse the effect of market barriers on energy conservation, and to compare the results from various countries and various policy measures, to learn the most effective ways to overcome market barriers and to change consumer behaviour. These insights can be used later to design country-specific policy recommendations.

2. Methods

2.1. Housing stock inventory

The retrievable statistical data on building stock is very non-uniform in different countries in the European Union and it remains very challenging to reliably assess the energy consumption on a large scale. Balaras et al. [3] used the energy consumption data collected during energy audits in 193 buildings in 5 countries as a

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* Corresponding author. Tel.: +358 407345580.
E-mail address: Pekka.Tuominen@vtt.fi (P. Tuominen).

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http://dx.doi.org/10.1016/j.enbuild.2012.04.015

base for their analysis. More recently, a typology of buildings representative for the building stock was employed by Nemry et al. [4] to study the cost of environmental impact reductions in European residential buildings.

In addition to energy consumption itself our study also had a broader context, including barriers to and policies promoting energy efficiency. Nevertheless, the starting point for our study was to estimate the size, composition and energy consumption of the housing stock in the following countries: Bulgaria, the Czech Republic, Denmark, Finland, Germany, Latvia, the Netherlands, Portugal and the United Kingdom. Moreover, Belgium was included in the study of market barriers and policy instruments.

The inventory of housing stock was compiled from data collected by the IDEAL EPBD research teams in each participating country. The method chosen here is similar to Nemry et al. in the criteria for defining building typologies [4]. Research partners in each country provided their respective stock data including, but not limited to, the following information.

- Size of housing stock categorised by two general types of buildings: single-family houses and apartment buildings. Dwellings were also grouped by age, age bands varied in most countries, depending on the categories used in the data provided.
- Past and expected rates of renovations aimed at improving energy efficiency of homes.
- Types and costs of different energy efficiency measures, etc.

The inventory formed the basis for calculating the expected savings potential under the EPBD for existing dwellings, and thus provides insight into total cost-effective savings potential in dwellings of more than 1000 m^2. The results can also be used as a baseline to monitor the effectiveness of the EPBD.

2.2. Calculating the baseline and savings potential

The data on the housing stock collected from each country provided a baseline for the savings potential for existing dwellings. The calculations were carried out for each country separately, based on national statistics, in the following order. Belgium was not included in this part of the study. The data for the calculations was collected by the project partners in the various countries and supplemented with expert estimates where figures were not available. The primary sources for each country were [5,6] for Bulgaria, [7–9] for the Czech Republic, [10,11] for Denmark, [12–14] for Finland, [15–18] for Germany, [19,20] for Latvia, [21–24] for the Netherlands, [25–27] for United Kingdom and [28–30] for Portugal. The amount of input data is too large to be represented here in detail, but some average values representative of the data are shown in Table 1.

First, the data on the size of each age group of buildings and their respective heating energy consumption was used to calculate the present energy consumption to be used as a baseline. Thus, a given age group of buildings in a given country consumes the amount $Q_{heating}$ of energy for heating annually when

$$Q_{heating} = A \times Q_{specific}, \qquad (1)$$

where A is the floor area of the buildings in that age group, and $Q_{specific}$ is the average specific heating energy consumption per unit of area in the same group.

Then, for each type of energy efficiency improvement, an effect on the energy consumption and a price for the improvement was acquired from the various countries. The costs of each improvement were annualised for ten years with an interest rate of 10%, with the equation

$$R = \frac{P_{total}}{1-(1/((1+i)^m))/i} \qquad (2)$$

Table 1
Summary of key data used in the calculations.

	Area[a] (×1000 m^2)	Renovations[b] (%)	Min price[c] (€/m^2)	Max price[d] (€/m^2)	Heat before[e] (kWh/m^2)	Heat after[f] (kWh/m^2)
Bulgaria						
Houses	128,485	3.2	10	90	143	25
Apartments	154,137	3.0	10	90	96	56
Czech Republic						
Houses	155,583	1.0	13	200	190	68
Apartments	134,394	0.8	13	160	194	134
Denmark						
Houses	173,143	1.8	34	43	139	80
Apartments	101,121	2.2	31	38	135	61
Germany						
Houses	1,354,428	1.4	7	57	254	137
Apartments	2,020,743	2.0	4	57	185	74
Finland						
Houses	148,000	3.1	4	25	154	118
Apartments	120,500	3.1	7	20	154	141
Latvia						
Houses	22,237	4.9	40	130	273	202
Apartments	37,863	4.7	70	133	217	145
The Netherlands						
Houses	588,401	1.7	34	43	125	54
Apartments	150,299	2.2	31	38	103	52
Portugal						
Houses	227,480	1.1	11	36	114	45
Apartments	256,934	1.1	11	36	117	46
UK						
Houses	1,857,497	1.9	3	5	216	119
Apartments	328,111	2.2	3	7	172	53

[a] Built floor area (×1000 m^2).
[b] Weighted average of annual renovation rate (%).
[c] Lowest average cost of an energy efficiency improvement studied (€/m^2).
[d] Highest average cost of an energy efficiency improvement studied (€/m^2).
[e] Weighted average of annual heating energy consumption before improvements (kWh/m^2).
[f] Weighted average of annual heating energy consumption after all cost-effective improvements are implemented (kWh/m^2).

where R is the annualised cost of the improvement, P_{total} is the total cost of the improvement when it is done, m is the number of periods (ten years), and i is the interest rate (10%). The rate of 10% is chosen as it is commonly used in cost-effectiveness calculations as a figure higher than inflation rates and lower than consumer credit rates [31]. To get a price P for the energy saved, the annualised costs R were divided by the annual energy savings Q_{saved} of the improvement in question:

$$P = \frac{R}{Q_{saved}} \tag{3}$$

For each country, the prices P of energy saved were compared with local electricity prices [32]. When the cost of energy saved was lower than the price of electricity, an improvement was deemed cost-effective.

For each age-group of buildings it was calculated how much energy consumption would fall, if the cost-effective improvements were implemented at the expected autonomous renovation rate. Since these renovations would occur in any case, the price for efficiency improvements is substantially lower than if implemented autonomously.

For each age group j the new energy savings $Q_{saved,annual,j}$ achievable each year will be the product of the autonomous renovation rate r, the total area of that group A and specific energy savings of the improvements deemed cost-effective for that age group $Q_{saved,specific,j}$:

$$Q_{saved,annual,j} = r \times A \times Q_{saved,specific,j} \tag{4}$$

Summing all n number of age groups j in the country c we obtain the total new annual energy savings $Q_{saved,annual,c}$

$$Q_{saved,annual,c} = \sum_{j=1}^{n} Q_{saved,annual,c,j} \tag{5}$$

Cumulating savings $Q_{saved,annual,c}$ an estimate of savings potential $Q_{potential,c}$ for a given year y in the country c can be derived:

$$Q_{potential,c} = \sum_{k=1}^{y} Q_{saved,annual,c,k} \tag{6}$$

Summing for c will naturally give the total savings potential $Q_{potential,total}$ for the set of all nine countries:

$$Q_{potential,total} = \sum_{c=1}^{9} \sum_{k=1}^{y} Q_{saved,annual,c,k} \tag{7}$$

Such calculations rely heavily on average values for a large amount of buildings that are, in reality, very different. Some of the uncertainty is offset by the law of large numbers, i.e. even if some buildings are more difficult to renovate than average, others are easier, and in such a large sample both amounts are probably are of more or less similar magnitude. Nevertheless, the results should be regarded as indicative estimates of a potential development, rather than exact forecasts.

2.3. Inventory of barriers

The research concerning market barriers was limited to privately owned residential buildings in the participating member countries of the IDEAL EPBD project; namely Belgium, Bulgaria, the Czech Republic, Denmark, Finland, Germany, Latvia, the Netherlands, Portugal and the United Kingdom. The focus on privately owned dwellings was chosen because:

- consumer behaviour is especially relevant and determines what action takes place in the privately traded part of the housing stock,
- private dwelling owners comprise a target group that is hard to reach for policy makers (much more difficult than housing cooperatives or municipalities, which are often owners of rental dwellings), and
- privately owned dwellings form the bulk of the dwelling stock in Europe (74%) [33].

Energy Performance Certificates are supposed to assist consumers with recommendations for cost effective measures to improve the energy efficiency measures in their home. The inventory of barriers explores which barriers are perceived in each country. It is important to do this, in order to find effective ways to overcome both country specific and general consumer barriers.

The research teams in each country interviewed local stakeholders face-to-face or by telephone during 2008 and 2009 to find out what main barriers they perceive in their country, what their needs are and what experience they have had so far with the EPBD. The interviewees were mostly professionals such as directors of ministry departments, housing agencies, construction associations, renovators of buildings and policy makers. On average 5.75 people were interviewed per country.

For the purposes of this study the responses were categorised into four main classes: (1) regulatory barriers, (2) barriers related to organisations and decision making, (3) financial barriers and (4) barriers related to information, promotion and education.

2.4. Inventory of policy instruments

Labelling of existing dwellings smaller than 1000 m^2 is not yet mandatory in all the countries, whereas some countries have already a long history of labelling and audits of existing dwellings. Five countries included in the study had prior experiences with labelling (DK, DE, UK, FI, NL), while the rest of the countries were chosen from different regions around Europe (BE, BG, LV, CZ and PT) in order to include as much geographical variance as possible.

The partners in each country were asked to provide an inventory of the policy instruments already in place. Forms were developed and provided for delivering the results. The methods for gathering them varied and usually included literature reviews and interviews. Each policy instrument was categorised by type and linked to the barriers they were designed to address.

The categories for policy instruments were:

- EPBD
- Subsidies
- Information and tools
- Regulatory demands
- Ecological taxes
- R&D programmes
- Funding for favoured energy sources
- Action plan or strategy for energy efficiency
- Certification or classification
- Energy audits and voluntary agreements
- Training and education
- Credit facilities

Experiences on existing labelling schemes and the current status of EPBD implementation were also charted. Some ill-devised policy instruments can themselves act as barriers. The forms also included this type of barrier, and as the results will show, many countries reported such barriers.

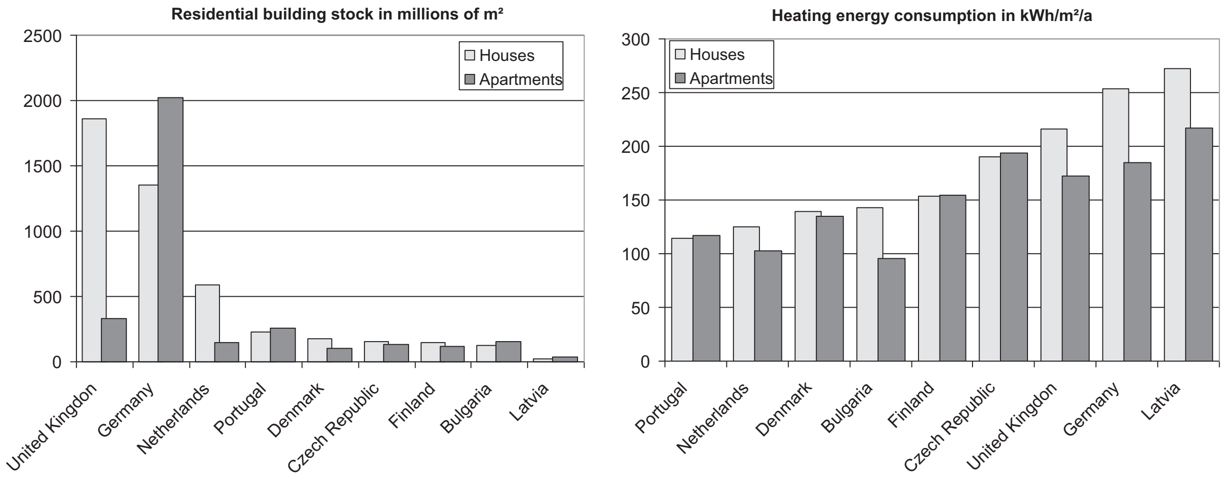

Fig. 1. Size of housing stock in each country and the weighted average of delivered combined energy for space heating and domestic hot water in each country.

3. Results

3.1. Baseline of energy efficiency

The baseline for energy efficiency in each country depends largely on two parameters: the energy consumption in the residential building types present in the housing stock, and the size of the housing stock. Based on the data reported by the partners from each country, weighted averages of combined delivered energy consumption for space heating and domestic hot water were calculated for two building types: single family houses and apartment buildings. In this context, separate houses owned and occupied by only one family belonged to the category single family houses. All the other types of dwellings (attached houses, blocks of

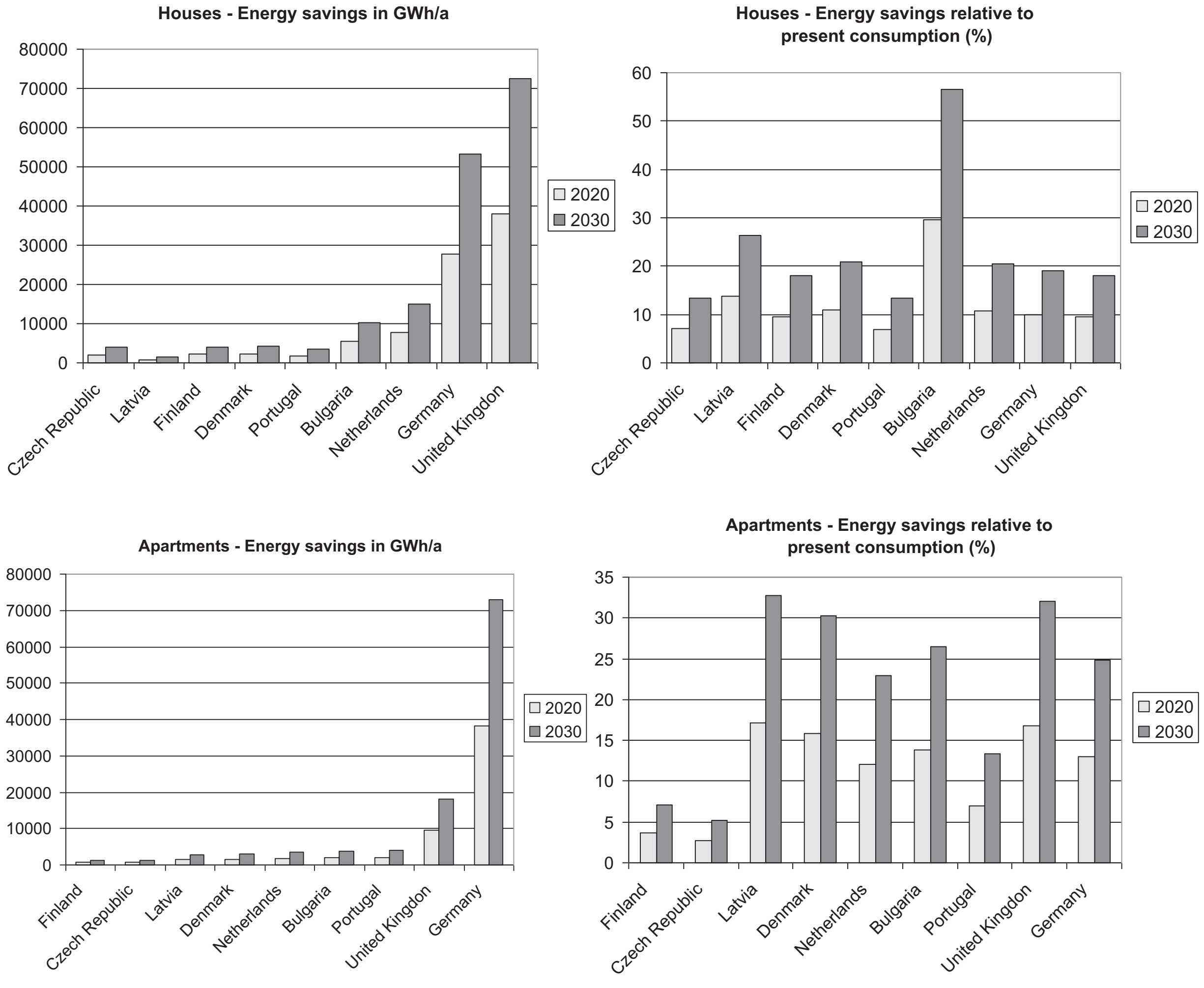

Fig. 2. Cost effective energy savings potentials in the various countries.

Table 2
Barriers related to regulation, reported by stakeholders from the member states.

	BE[a]	BG	CZ	DE	DK	FI	LV	NL	PT	UK	Sum
Insufficient or lax regulation					x		x	x	x	x	5
Incentives not working properly		x		x			x	x	x		5
Unclear regulations about labelling		x		x			x	x			4
Frequent changes in regulation	x	x		x				x			4
Insufficient subsidies						x	x	x			3
Price of labelling					x			x	x		3
Lack of supervision and enforcement	x	x			x						3
Visibility of labelling					x					x	2

[a] For Belgium data are from the Wallon Region only.

apartments, etc.) were grouped in the category apartment buildings. Average heating energy consumption varied between 96 kWh/m^2/a in apartment buildings in Bulgaria and 273 kWh/m^2/a in houses in Latvia. These results and the sizes of residential building stock are shown in Fig. 1.

The results show that the existing stock of single-family houses in the nine countries consumes 877,000 GWh of energy for space heating annually. For apartment buildings, the consumption is 474,000 GWh annually.

3.2. *Energy savings potential*

As can be expected, the countries of IDEAL EPBD have very different savings potentials. As can be seen from Fig. 1, countries with a large inventory of buildings probably hold the largest savings potentials in absolute terms, namely Germany and the United Kingdom. On the other hand, based on average consumption numbers, some countries are likely to have large potentials for savings on national level, but their relative contribution to the European total will remain small nevertheless. Such is the case of Latvia, for instance. The effects of annually applicable cost-effective energy efficiency retrofits will accumulate to produce the annual savings shown in Fig. 2 by 2020 and 2030.

Summing up the results for all nine countries, 88 TWh/a could be saved in single family houses by the year 2020 and 58 TWh/a in apartment buildings, totalling 146 TWh/a. Respective figures by 2030 are 169 TWh/a for houses and 110 TWh/a for apartments, totalling 279 TWh/a for all dwellings. In relative terms these savings represent approximately 10% by 2020 and 20% by 2030 of present heating energy consumption.

These results are rather conservative compared to other studies. The Action Plan for Energy Efficiency [1] reports an estimated savings potential in the buildings sector of 28% in 2020, of which 1000 TWh in the residential sector. Furthermore, the plan points that the Energy Performance of Buildings Directive can play a key role in realising the savings potential in the buildings sector.

The World Business Council for Sustainable Development recently published the study 'Transforming the Market: Energy Efficiency in Buildings' [34] that asserts that a 60% reduction in energy use in buildings is possible by 2050. The rate of improvement deemed possible here and in the Action Plan for Energy Efficiency would eventually lead to such levels of reductions.

3.3. *Market barriers*

This section provides a summary of the main market barriers reported by the stakeholders interviewed in countries included in this study. Some of the more uncommon barriers are omitted. One should bear in mind that the following results and statements are based on the statements from the stakeholders in the interviews, and not on empirical analyses of dwelling owners' opinions or behaviour. The responses are categorised here in into four main classes: (1) regulatory barriers, (2) barriers related to organisations and decision making, (3) financial barriers and (4) barriers related to information, promotion and education.

3.3.1. *Regulation*

Nearly all countries reported at least some barriers that were related to government regulation or its enforcement, as can be seen from Table 2. Most commonly mentioned was insufficient or too lax regulation that left some key problems unaddressed or did not set building requirements high enough. Two countries reported problems with supervision and enforcement of regulations, while three had problems with frequent regulatory changes.

Badly designed incentives distorted the development of energy efficiency in some countries, and in many cases consumers had to deal with unclear or insufficient regulations relating to EPBD labelling. The high prices and low visibility of the EPBD labelling were also highlighted.

3.3.2. *Organisations and decision making*

Some countries reported no barriers related to the decision-making process in buildings and among the actors contributing to energy efficiency, as can be seen from Table 3. Considering the ubiquity of such problems, it seems likely that they were not mentioned in the interviews, rather than that they were missing from these countries. These barriers are closely related to the informational barriers discussed below.

Many respondents stated that complications of decision making in housing companies, such as majority rule, can lead to inaction when no decision is reached. This can result in useful improvements going unimplemented. Also, the many actors of efficiency improvements – the home-owners, the government, the designers of the improvements, the renovators – reported encountering problems with communication and coordination.

Table 3
Barriers related to organizations and decision making, reported by stakeholders from the member states.

	BE[a]	BG	CZ	DE	DK	FI	LV	NL	PT	UK	Sum
Decision making process in buildings		x			x		x				3
Lack of communication and coordination		x			x					x	3
No building level coordination		x					x				2

[a] For Belgium data are from the Wallon Region only.

Table 4
Barriers related to financing, reported by stakeholders from the member states.

	BE[a]	BG	CZ	DE	DK	FI	LV	NL	PT	UK	Sum
EE has no effect on price or rent of dwelling		x	x	x	x		x		x		6
Lack of appropriate, affordable financing	x			x	x	x	x		x		6
Negative externalities not fully internalized		x	x		x				x		4
Low incomes		x					x				2
Sharing of costs among occupants		x				x					2

[a] For Belgium data are from the Wallon Region only.

3.3.3. *Financing*

Most countries reported problems with financing. It seems probable, again, that the two countries not reporting any barriers in this category, the Netherlands and the United Kingdom, had no related responses in the interviews rather than no barriers. The most commonly cited financial barriers are shown in Table 4.

Most commonly reported was the perceived barrier that energy efficiency improvements do not raise the value of the property or the rent it provides. In some countries, such as the Czech Republic, this may be due to a price ceiling in rents, but in most cases regulated pricing cannot be the reason.

Another commonly reported barrier was the lack of financing for energy efficiency improvements. Specifically, Bulgaria and Latvia reported that the low income of people prevented improvements.

The fact that negative externalities, such as the pollution caused by most forms of heating, directly or indirectly, are not included in the prices of energy, was commonly cited as a barrier. When these costs are not included in energy prices, people do not have high-enough incentives to save energy. Moreover, some countries reported that the fair sharing of renovation costs with the occupants of a building presented a problem. This is closely related to the problem of communal decision-making discussed before.

3.3.4. *Information, promotion and education*

As can be seen from Table 5, among the more prolific barriers are the ones related to information, promotion and education. All the countries reported at least some barriers in this type. It seems that in general, people are ill-informed about energy efficiency, regulations, financing and technology.

In addition, energy efficiency seems to be a low priority to people. They are perceived to be unaware of related technologies and to find it difficult to find neutral, unbiased information about it. Governments often have difficulty in finding efficient ways to communicate energy efficiency policies to the actors in the market. Therefore, it seems that there is a need for the dissemination of neutral information about energy efficiency.

Finally, there is a shortage of skilled, well trained, specialised professionals who could implement the energy efficiency improvements. It is noteworthy that many countries reported a lack of skilled labour, but very few reported educational programs aiming to overcome this shortage.

3.4. *Policy measures*

This section provides a summary of the policy measures reported by the interviewees from the countries included in this study. The most uncommon policies are omitted. The policies have been categorised into the twelve classes as shown in Table 6.

All the participating countries, except the Czech Republic, reported that the implementation of Article 7 of the EPBD directive was completed in their country. In the Czech Republic the implementation was expected to be completed during 2009 or at the

Table 5
Barriers related to information, promotion and education, reported by stakeholders from the member states.

	BE[a]	BG	CZ	DE	DK	FI	LV	NL	PT	UK	Sum
Low priority of energy efficiency		x	x		x			x		x	5
Lack of neutral information				x	x		x	x		x	5
Poor training and skills of professionals	x	x	x			x			x		5
Lack of awareness about technology		x	x						x	x	4
Lack of information about energy efficiency	x						x	x	x		4
Lack of financial understanding (payback times, etc.)	x							x		x	3
Difficulties in influencing builders			x			x					2
Lack of awareness about regulations		x			x						2
Lack of research and information on results		x					x				2

[a] For Belgium data are from the Wallon Region only.

Table 6
Policy measures reported by stakeholders from the member states.

	BE[a]	BG	CZ	DK	DE	UK	FI	LV	NL	PT	Sum
EPBD implemented		x		x	x	x	x	x	x	x	8
Subsidies	x	x	x	x	x	x	x	x	x		9
Information and tools	x		x	x	x	x	x	x	x	x	9
Regulatory demands	x			x	x	x	x	x	x	x	8
R&D programmes	x	x		x	x		x		x	x	7
Ecological taxes			x	x		x	x		x	x	6
Funding for favoured energy sources	x		x	x	x	x				x	6
Action plan or strategy for EE	x	x			x		x		x	x	6
Certification or classification	x	x			x		x				4
Energy audits and voluntary agreements	x						x	x	x		4
Training and education	x	x			x			x			4
Credit facility	x	x			x						3

[a] For Belgium data are from the Wallon Region only.

latest in 2010. Eight countries reported other regulatory demands in addition to the EPBD.

Eight out of the ten countries offered subsidies for energy efficiency and had some sort of information campaign established. In five countries one or some energy sources were favoured over others when distributing subsidies. Moreover, most countries employed some form of ecological taxation, usually in the form of energy taxes.

A distinctive Dutch policy was preferential taxation of investments in "green funds", which are publicly traded mutual funds that concentrate on ecological investments. Germany was the only country that reported that the government pays attention to energy efficiency in its own building investments such as social housing projects. This would seem to be a very direct way for governments to promote energy efficiency and should be considered for adoption in other countries.

4. Discussion and conclusion

4.1. Discussion

A multitude of barriers hinder improvements. Based on the reports of stakeholder interviews from the participating countries, the most commonly reported problem is that the improvements in energy efficiency are hindered by a lack of effect on property prices. In some countries, such as the Czech Republic, this may be due to a price ceiling in rents but in most cases regulated pricing cannot be the reason.

It is not entirely clear why potential buyers or renters would not value improvements that save them money in energy bills. The phenomenon might be related to a lack of information about the effects of energy efficiency and should be studied more. On the other hand, another important explanation could be that house owners and buyers are predominantly interested in the more visible characteristics such as the type, arrangement and age of the kitchen or the bathroom, the size of the house, the number of rooms, and – more generally – the physical condition of the house. Energy consumption and energy efficiency are commonly not placed high on the agenda of house buyers and, as a result, there is only limited correlation between efficiency level and price.

Problems with financing also appear to be common. Some countries have designated credit institutions providing financing for energy efficiency investments. This approach could merit further study by other countries. Some way of providing credit for these investments on preferential terms seems justified, based on the returns they generate in the form of savings in energy costs.

Furthermore, Bulgaria and Latvia reported that the low income of people prevented improvements. Again, this could be combated with suitably designed financing schemes, since no matter how low one's income, it always makes sense to make cost-effective investments. The cost of profitable energy efficiency investment should be recoverable from the savings in energy bills as long as suitable financing is available. The use of microcredits in the developing world has recently reduced the problem of lending to poor people. Perhaps some similar form of crediting could help people save in their energy costs in Europe.

Surprisingly few of the responses included descriptions of strategic planning on a national level to advance energy efficiency. Instead a great number of separate programs and initiatives were cited. This is striking given the importance of energy efficiency at EU level and also in the political discourse in the member states.

Some of the problems with regulation seem to be resolvable by mere good governance. The problems caused by erratic policy changes, for instance, could be avoided by better planning. In general, the question of too little or too much regulation and subsidies is, of course, a more complicated one. In any case, any regulation and subsidies should be designed so that they send the correct signals. Golove and Eto [35] have argued that there are three economically sound rationales for governments to intervene:

- to counteract the effects of market failures,
- to reduce transaction costs, and
- to help individuals help themselves.

Many of the policy measures in place now do not correspond specifically to any of these three rationales. In these cases one should evaluate whether money and effort could be more efficiently used elsewhere to promote energy efficiency. On the other hand, many effective policy measures are still missing from some of the countries. For example many countries lack voluntary energy auditing and conservation programs for the construction industry and building owners. This would seem to be a risk-free and quick policy to adopt, and therefore a good place to begin for countries with few policies to start with.

Germany reported that the government pays attention to energy efficiency in its own building investments such as social housing projects. This would seem to be a very direct way for governments to promote energy efficiency and should be considered for adoption in other countries.

In some of the new member states there are great difficulties in deciding about measures applied to apartment buildings because of underdeveloped housing company practices. For example, in some cases the owner of a single apartment can stall improvement projects in the entire building. Many such problems could be solved by applying management practices that are in general use in housing companies in other countries.

At present, consumers are reported to have problems obtaining information about energy efficiency, technology and finding the right products for their particular circumstances. This could be facilitated perhaps by devising products and creating business models whereby improvements could be purchased as complete packages on a turnkey basis. The role of government could be to provide neutral information and recommendations.

Also, gathering the information on the different products available in the marketplace to one place, e.g. a website, where consumers could evaluate and compare them, would help with the arduous process of going through the myriad products usually provided by small and medium-sized companies.

Finally, it is noteworthy that not many mentioned any specific training efforts to improve the skills of the people implementing the energy efficiency improvements, even though the lack of skills was a commonly cited barrier to further improvements. This seems like a clear avenue for development.

4.2. Conclusion

The countries have very different potentials for energy savings, depending on the size and condition of the housing stock. In total, 88 TWh/a could be saved in single family houses by the year 2020 and 58 TWh/a in apartment buildings, totaling 146 TWh/a. By 2030 respective figures are 169 TWh/a for houses and 110 TWh/a for apartments, totaling 279 TWh/a for all dwellings. In relative terms the potential represents around 10% by 2020 and 20% by 2030 of present heating energy consumption.

The results presented are valid with the price levels at the time of the study and the effective interest rate of 10%. No sensitivity analyses for neither interest rates nor energy and renovation prices were included, as they would be complicated undertakings affecting not only payback periods but also the inclusion and exclusion of the various improvements. Such analyses are, however, an obvious avenue for further research.

All the countries report the status of the implementation of EPBD as complete or nearly complete. A very commonly reported problem was that the improvements in energy efficiency are hindered by the lack of effect on property prices. Another problem cited in all the reports was the low priority for energy efficiency improvements among the consumers. Other commonly cited barriers included:

- lack of information on energy efficiency, especially the lack of trusted information,
- insufficient or lax regulation and the lack of supervision and enforcement,
- lack of coordination and information flow between the actors in the housing market,
- low awareness about labelling, technology, etc., and
- poor training or lack of skills of the people who implement energy efficiency measures.

The most commonly reported public policy measures in use were related to information dissemination and partial public funding of energy efficiency retrofits. Regulations, ecological taxation, subsidies for renewables and R&D activities were also commonly cited.

Acknowledgements

The work was carried out within the project IDEAL EPBD (Improving Dwellings by Enhancing Actions on Labelling for the EPBD) supported by Intelligent Energy Europe program. The authors are grateful to partners and individuals for collecting and providing national data.

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PUBLICATION IV

Estimating exergy prices for energy carriers in heating systems: Country analyses of exergy substitution with capital expenditures

Energy and Buildings 43, pp. 3609–3617.

Energy and Buildings 43 (2011) 3609–3617

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Estimating exergy prices for energy carriers in heating systems: Country analyses of exergy substitution with capital expenditures

A. Müller[a,*], L. Kranzl[a], P. Tuominen[b], E. Boelman[c], M. Molinari[d], A.G. Entrop[e]

[a] Vienna University of Technology, Institute of Power Systems and Energy Economics, Energy Economics Group, Gusshausstrasse 25-29/373-2, 1040 Vienna, Austria
[b] VTT Technical Research Centre of Finland, Building Services and Indoor Environment, P.O. Box 1000, 02044 VTT, Espoo, Finland
[c] EU Committee of the Regions (in a personal capacity), Formerly with the Delft University of Technology, Climate Design Group, Delft, The Netherlands
[d] KTH Royal Institute of Technology, School of Architecture and the Built Environment, Department of Civil and Architectural Engineering, Brinellvägen 34, 1004 Stockholm, Sweden
[e] University of Twente, Faculty of Engineering Technology, Department of Construction Management and Engineering, P.O. Box 217, 7500 AE Enschede, The Netherlands

ARTICLE INFO

Article history:
Received 12 December 2010
Received in revised form
16 September 2011
Accepted 24 September 2011

Keywords:
Exergy
Energy prices
Buildings
Heating

ABSTRACT

Exergy represents the ability of an energy carrier to perform work and can be seen as a core indicator for measuring its quality. In this article we postulate that energy prices reflect the exergy content of the underlying energy carrier and that capital expenditures can substitute for exergy to some degree.

We draw our line of argumentation from cost and technology data for heating systems of four European countries: Austria, Finland, The Netherlands, and Sweden. Firstly, this paper shows that the overall consumer costs for different heating options, widely installed in those countries, are in the same range. In this analysis we derived an overall standard deviation of about 8%. Secondly, additional analysis demonstrates that the share of capital costs on total heating cost increases with lower exergy input. Based on the data used in this analysis, we conclude that for the case of modern cost effective heating systems the substitution rate between exergy and capital is in the vicinity of 2/3. This means that by reducing the average specific exergy input of the applied energy carriers by one unit, the share of capital costs on the total costs increases by 2/3 of a unit.

1. Introduction

A variety of technological options exists for converting different energy carriers to useful energy, heat and finally into the energy service of a comfortable room temperature. Historically, the mix of fuels changed from biomass towards oil, gas and coal during industrialization [1]. During the same period, efficiency and emission standards of heating systems as well as comfort levels increased strongly. On the one hand modern heating solutions include systems like thermal solar collectors and heat-pumps. On the other the thermal insulation and air-tightness of buildings are continuously improved, which enables us to render energy sources more economical (see e.g. [2,3]).

The characteristics of these different heating systems lead to different cost structures, regarding capital costs, operating costs and energy costs. The energy costs of energy carriers can differ considerably, as can the quality of energy carriers. One of the core indicators measuring the quality of an energy carrier is its exergy content. It is reasonable to postulate that, when buying energy, people are interested in the portion of the energy capable of performing work for them, namely exergy, and not unusable forms of energy. Therefore, one of our hypotheses is that in a well-functioning energy market with ample choices the price of an energy carrier does reflect its exergy content rather than its energy content. Thus it can be expected that low-exergy energy carriers (e.g. low-enthalpy heat) have a lower price level. However, for a given end use such as heating, the total cost of energy carrier and capital investments necessary to provide the energy service should be about the same for all systems routinely installed, given that the systems provide a similar comfort level and market distortions are negligible. Based on these premises, we state the following hypotheses:

- The total heat generation costs for widely installed systems are generally on an equal level within a country or region regardless of the energy carrier, and
- the prices of well-established energy carriers in the marketplace reflect the exergy content.

The first proposal for using exergy as a criterion for cost allocation was presented in 1932 by Keenan, cited by Lozano and Valero [4], who suggested that the production costs of a cogeneration plant should be distributed among the products (work and heat) according to their exergy. Since then several concepts to contemplate the

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Abbreviations: CHP, combined heat and power; DH, district heat.

* Corresponding author. Tel.: +43 158801370362.
E-mail address: mueller@eeg.tuwien.ac.at (A. Müller).

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doi:10.1016/j.enbuild.2011.09.034

Nomenclature

$T_{\text{comb. products}}$	temperature of combustion products (K)
T_0	temperature of the ambient environment, dead state (K)
i_{ex}	exergy factor, dimensionless
e_{ex}	annual exergy content of energy carriers (MWh/yr)
e_{en}	annual energy content of energy carriers (MWh/yr)
c_{en}	variable price for energy carrier excluding taxes (€/kWh)
$c_{en,tax}$	energy related taxes (€/kWh)
$f_{en,tax}$	specific energy tax rate, dimensionless
I_{hs}	investment cost (€)
$c_{O\&M}$	operation and maintenance costs (€/yr)
C_{fix}	annual fixed costs (€/yr)

Greek letters

α	capital recovery factor (yr^{-1})
$\varepsilon_{\text{combustion}}$	exergetic efficiency of an ideal combustion process, dimensionless

exergy losses of processes and the exergy content of energy carriers have been developed; they are commonly summarized by the term “thermoeconomics”.

Thermoeconomics, introduced by Tribus and Evans [5], combines the second law of thermodynamics with economics by applying the concept of cost to exergy, in order to achieve a better production management with a more cost-effective operation. Within this concept, second law analysis methods based on cost accounting are used to determine actual product cost and provide a rational basis for pricing [6]. Deng et al. [6] also note that to a certain extent, multiple methodologies with different theories and nomenclatures cause confusion and impede the development of thermoeconomics. Based on the achievements of predecessors, Valero et al. [7] developed the structural theory of thermoeconomics, which provides a general mathematical formulation using a linear model and encompasses all the thermoeconomic methodologies developed up to now, and is considered as standard formalism of thermoeconomics [8,9].

Currently, relevant concepts in the field of thermoeconomics are exergy accounting, exergetic cost, exergoeconomics and the concept of exergy prices. Exergy accounting converts the inflow of physical resources into their equivalent exergetic form. Having a homogeneous exergetic basis paves the way for an evaluation of the efficiency of each energy and mass transfer between numerous sectors of society and enables a quantification of the irreversible losses and an identification of their causes [10–14]. In the exergy cost approach, as applied by Xiang et al. [15], the term exergy cost is used as a representation of the units of external resources used (and depleted) to produce a specific product. However, this concept does not explore costs in a monetary meaning. Valero [16] states that the exergetic cost or the cumulative exergy consumption are, in fact, the same concepts as embodied exergy. Valero proposes a logical chain of concepts for connecting physics with economics. Exergoeconomic analyses consider exergy in allocating the (monetary) production costs of a process to the different products it produces. A general methodology for this kind of analysis was presented by Tsatsaronis in 1985 [17], and was later called the exergoeconomic accounting technique [18]. Finally, the concept of exergetic prices or exergy prices calculates the specific monetary prices of energy carriers based on their exergy content instead of their energy content. Such analyses have, for instance, been performed by Wall [19] and Hepbasli [20].

As this brief overview already reveals, it is important to realize that scholars do not always clearly distinguish between processes of cost and price formation and that the terms “cost” and “price” are used in multiple ways in different sources. Valero [16] defines the term “cost” in the physical sacrifices of resources, and argues, that a strongly related money prices would then reflect past resource depletions. Sciubba [11] proposes that it is not capital that ought to measure the value of a product, but exergetic content, because ‘economic systems are eco-systems that function only because of the energy and material fluxes that sustain human activities’. He advocates that the monetary ‘price tag’ (expressed in e.g. \$ or €unit^{-1}) should be calculated on the basis of the extended exergetic content (expressed in kJ unit^{-1}) of a good or service, corrected for environmental impact. Lozano and Valero [4] highlight the need to use exergy to rationally assign costs. They state that the only rigorous way of measuring the physical production cost is the second law of thermodynamics and not its market value, as it provides a unique way to identify, allocate and quantify the inefficiencies of realized processes which are at the basis of cost and resource consumption.

In this article, we distinguish between the terms “price” and “cost”. We define energy prices in accordance with the common economic theories as the result of supply and demand intersections on energy and resource markets. Thus, they reflect the relation of supply and demand for different energy carriers. Heating related energy costs are the expenses that consumers have to pay for a heating system. This includes fixed costs (investments, operation and maintenance), energy taxes and costs for energy carriers. The latter are represented by energy prices (in a market driven economy) and energy related taxes.

2. Methodology

2.1. Exergy content of energy carriers

The forms of energy at the disposal of our economy can be classified according to their exergy content, that is, their ability to perform potentially useful work. For energy carriers of extra superior quality such as electricity, the exergy factor is set to 100%, chemical energy carriers such as oil, gas and biomass count as superior and do have a exergy factor in the vicinity of 95% [20,21]. The exergy content of heat depends on the temperature of the energy carrier and the temperature level of applicable ambient (dead state). Chemical energy is a much-used basis for primary energy conversion, often through combustion. The temperature levels that can be reached in such combustion processes determine the amount of the chemical exergy that in practice can be converted into thermal exergy. In other words, in combustion processes there is always a certain amount of unavoidable exergy loss due to the limited degree of achievable temperature levels. The exergetic efficiency $\varepsilon_{\text{ex,combustion}}$ of an ideal combustion process is determined by the second law of thermodynamics, and depends basically on the absolute temperature levels of combustion $T_{\text{combustion}}$ and of the environment T_0 (see Eq. (1)). Thus, the highest achievable exergetic efficiency of a combustion process indicates the amount of “in practice maximum usable” exergy (i.e. exergy content minus unavoidable exergy losses).

$$\varepsilon_{\text{ex,combustion}} = \frac{e_{\text{ex,heat}}}{e_{\text{ex,fuel}}} = (1 - T_0 \cdot T_{\text{combustion}}^{-1}) \qquad (1)$$

A maximum exergy of 85% can be derived for a fully oxidized combustion, assuming $T_{\text{combustion}} \approx 2000$ K and $T_0 \approx 300$ K. In contrast, the exergy content indicate that chemical energy could in principle be converted into other forms of energy by up to ~95%. The difference defines the exergy destruction that is unavoidable

Table 1
Exergy content of the energy carriers analysed in this paper.

Energy carrier (temperature level)	Temperature level	Reference temperature level	Exergy content as used in this paper
Oil, coal, gas	1500 °C	0 °C (−20 °C/+20 °C)	85% (86%/83%)
Biomass	800 °C	0 °C (−20 °C/+20 °C)	75% (76%/73%)
Electricity	–	–	100%
District heat inlet flow	100 °C	0 °C (−20 °C/+20 °C)	27% (32%/21%)

for thermodynamic causes and the highest achievable combustion temperatures with current technologies. Comparing secondary energy carriers such as electricity and district heat solely on the basis of their exergy content would lead to some bias, as it would not include exergy destruction upstream the system boundaries. It would also exclude energy carriers which still contain some exergy that cannot be utilized by any means.

Hence, we also consider the thermodynamic losses associated to the temperature limits imposed by current technology for large scale utilization. For electricity production from natural gas the exergy efficiency is determined by the most efficient available power plants, which today have a net power generation efficiency of 58% and above. Using this approach is reasonable when investigating a specific component or subsystem. Yet, when looking at a broader system, such as an energy supply system for district heating (DH), it may overlook the overall efficiency gains of using surplus thermal energy, such as heat supplied from a cogeneration heat and power (CHP) plant to the DH grid.

For natural gas or oil, combined cycle CHP have a high exergetic efficiency, which depends on the turbine inlet and environmental temperatures, T_{inlet} and T_0. Even in most recent gas turbines, the turbine inlet temperature must not exceed a temperature T_{inlet} of about 1700 K as the hot gas would degrade the turbine blades quickly. Similarly, for coal-fired high temperature processes (e.g. from metal melting), usual temperatures are in the vicinity of 1400–1500 °C. For biomass combustion, the maximum temperature level on which flue gas can be utilized is mainly determined by impurities. Fluidized bed reactors, nowadays one of the most advanced biomass combustion processes, usually operate at temperature levels not above 800 °C for unconverted, solid biomass.

The choice of the reference state, as revealed by Eq. (1) also influences the exergy content of an energy carrier. If the state of the energy carrier is close to the reference state, choosing an appropriate dead state is of crucial importance. Torío et al. [22] concludes that even though several authors propose and performed a dynamic calculation of the exergy content based on the ever changing ambient temperature, most reviewed papers apply a steady-state approach based on seasonal or annual average temperatures. In our case, the seasonal average temperature during the heating period appears to be appropriate. The average outdoor temperature, weighted by monthly heating degree days, are: Vienna (Austria) 4.9 °C, Stockholm (Sweden) 2.3 °C, Amsterdam (The Netherlands) 6.5 °C, and Helsinki (Finland) 0.2 °C. Appling these ambient temperature levels to a heat source with 100 °C, the exergy content would differ by less than 1.7%. Considering the fact that the supply line temperatures are varying themselves and that within the selected countries different climate zones exist, we set the reference temperature to $T_0 = 273\,\text{K}$ (0 °C). Yet, to present the effect of a varying dead state, Table 1 includes the specific exergy content of the analysed energy carriers also for the reference temperature levels of ±20 °C.

Based on the Eq. (1) and the assumptions presented above, we estimate overall values for the highest exergetic efficiencies converting the energy carriers into the desired forms of final energy. As described above, we are using these values as "in practice usable" exergy (i.e. exergy content minus unavoidable losses due to temperature limitation).

2.2. Model framework

Methods and approaches from energy economics and from energy accounting are combined to compare consumer prices and exergy content. Combining these two approaches, we believe, leads to new and interesting insights into the extent to which current energy market prices take into account the exergy content of energy carriers. In doing so, we consider the following critical aspects to this approach:

- The comparison of the analysis in different countries is not straightforward, given the differences in climate, housing stock, adopted technologies and economic conditions. A brief overview of these parameters is given in Section 2.3. We then define a characteristic building type along with common heating systems using different energy carriers to be compared in the analysis.
- Energy related taxes on energy carriers differ in each country and have considerable impact on the outcome of our analysis. Therefore, within the cases prices with and without those taxes are distinguished. However, our figures do not include value added tax (VAT) as it is always placed on top and has no impact on price comparisons within a country.
- Energy prices have shown considerable volatility within the last few years. While price volatility has not been the same for all energy carriers, the level of energy prices strongly affects the ratio of capital to energy costs. We are aware that the reference year for energy prices is of crucial impact as a parameter. In order to not reflect on the strong price volatility of the years 2007 and 2009, the energy price levels of the year 2005 are used in all investigated case studies.

2.3. System boundaries and monetary costs of heat generation

The core idea of this paper is to examine the trade-off between two basic inputs: an energy carrier with its exergy content and the technology for converting it into the required energy service. This trade-off is investigated both from an exergetic, physical point of view as well as from an economic perspective (Fig. 1).

In order to conduct research on the exergy content of energy carriers the system boundaries are drawn around the final consumer, namely a typical reference building for each country. The energy, exergy and financial streams passing through the system boundaries will be analysed. The system boundary has important

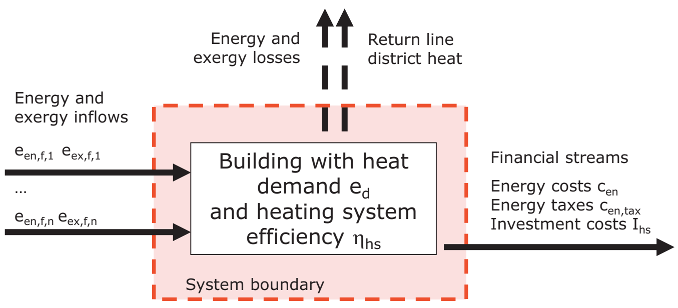

Fig. 1. System boundary used in this work.

implications on the following analysis. Firstly, upstream energy losses (e.g. in the electricity grid or during electricity production) are not considered. Secondly, all financial streams and the underlying prices and costs are based on consumer prices. Finally, upstream infrastructure (e.g. electricity or heating grids) and its related cost structure are not analysed. We assume that the costs of the infrastructure are incorporated in the consumer prices. For grid connected energy carriers a considerable part of the energy price consists of a base price, which is independent of the actual energy consumption. This base price can actually be understood as an element to take into account the up-front investments into the infrastructure.

2.4. *Monetary costs of heat generation*

We distinguished between the following financial flows in this article:

- variable price for energy carrier c_{en} excluding taxes
- energy related taxes $c_{\text{en,tax}}$ based on the energy tax rate $f_{\text{en,tax}}$:

$$c_{\text{en,tax}} \quad [€\text{MWh}^{-1}] = c_{\text{en}} f_{\text{en,tax}} \tag{2}$$

- total fixed costs C_{fix} (Eq. (3)), consist of
- levelized investment costs of the heating system I_{hs} (€), using the capital recovery factor α. For calculation of the levelized investment costs we used a depreciation time (T) of 20 years (lifetime of heating systems) and varied the discount rate i in a range of 0–10% and;
- annual operating and maintenance costs $c_{\text{O\&M}}$ (€/yr), including the annual fixed amounts paid to the energy supply company regardless of the actual energy consumption.

$$C_{\text{fix}} \quad [€\text{yr}^{-1}] = c_{\text{O\&M}} + \alpha I_{\text{hs}} \tag{3}$$

The total specific heating costs c_{tot} (Eq. (4)) are defined by:

$$c_{\text{tot}} \quad [€\text{MWh}^{-1}] = c_{\text{en}} + c_{\text{en,tax}} + C_{\text{fix}} \quad e_{\text{en},f}^{-1} \tag{4}$$

Subsidies and other promotion schemes also have an impact on the competitiveness and total heat generation costs of different heating systems. In our analysis they could have analogous effects to energy taxes. In order to focus on the key issues we do not take into account the impact of subsidies in this study.

To test the first hypothesis, we measure the variability of the total heat generation costs by calculating the standard deviation σ (Eq. (5)) and the relative range R_{rel} (Eq. (6)).

$$\sigma^2 = \frac{1}{\sum_{j=1}^{\text{Countries}} \text{Tech}_j - 1} \sum_{j=1}^{\text{Countries}} \sum_{i=1}^{\text{Tech}_j} \left(\frac{c_{\text{tot},i,j}}{c_{\text{tot,mean},j}} - 1 \right)^2 \tag{5}$$

$$R_{\text{rel}} = \frac{c_{\text{tot,max}} - c_{\text{tot,min}}}{c_{\text{tot,mean}}} \tag{6}$$

with average costs $c_{\text{tot,mean},j}$ within a country j:

$$c_{\text{tot,mean},j} \quad [€\text{MWh}^{-1}] = \frac{1}{\text{Tech}_j} \sum_{i=1}^{\text{Tech}_j} c_{\text{tot},i,j} \tag{7}$$

2.5. *Final exergy consumption and overall exergy factor*

For the second hypothesis, we look at the relation between the exergy input and the share of the energy related costs $c_{\text{en}} + c_{\text{en,tax}}$ on the total heating costs c_{tot}. For our analysis, we define a parameter i_{ex}, the overall weighted exergy factor (Eq. (8)), which represents the ratio between all annual incoming exergy and energy flows considered in the building and its heating system (e.g. including ambient energy for the case of heat pumps).

$$i_{\text{ex}} = \sum_{i=1}^{n} e_{\text{ex},i} \left(\sum_{i=1}^{n} e_{\text{en},i} \right)^{-1} \tag{8}$$

The annual exergy content $e_{\text{ex},i}$ is based on the energy demand $e_{\text{en},i}$ and the energy carrier specific exergy content shown in Table 1. The annual final energy demand $e_{\text{en},i}$ for heating is defined by the heat demand of the building and the efficiency of the heating system.

3. Case studies

3.1. *Analysed data*

Our analysis uses data from Austria, Finland, The Netherlands, and Sweden. These countries show large similarities regarding the physical quality of buildings, energy consumption per capita, gross domestic product per capita. In contrast there are differences in climate, heating system traditions and building stock. In view of the above-mentioned objectives, data for these countries can be seen to provide a robust base for a first comparative analysis.

3.2. *Austria*

For our analysis we selected a common single family house (150 m^2 gross floor area) with an annual heating energy demand of 20 MWh resulting in a specific energy demand of 133 kWh m^{-2} yr^{-1}. This corresponds to a single family house of the construction period 1981–1991 or an older building after related thermal renovation measures. About 40% of single and double family houses in Austria are equipped with an oil heating system, followed by 32% using a biomass based system (mainly wood log). In this buildings segment, gas holds a share of 15%, DH 6%. In the remaining buildings mainly direct electric heating and heat pumps are used for space heating purposes (Statistic Austria [23], own calculation). For the Austrian case study we selected the following heating systems: district heating, heat pumps (air/water; brine/water), biomass heating systems (based on wood log or wood pellets), fossil based heating systems (gas, oil), and direct electric heating.

3.3. *Finland*

The data for the Finnish example building are based on the norm house as it is defined by the Finnish government energy efficiency promotion corporation Motiva in its heating energy calculator. The building represents a typical contemporary Finnish single-family house with a gross floor area of 147 m^2 and an annual energy demand for heating of 20 MWh. This results in a specific heat demand of 136 kWh m^{-2} yr^{-1}. More details are available from Motiva [24]. In single-family houses direct electric radiator heating has the largest share, 44% followed by oil heating (25%) and solid fuels (21%) [25]. In newly constructed single family houses, direct electric heating still holds a share of 40%. The share of heat pumps has risen to 37%, district heat gets a share of 12% [26]. The remaining share is mainly covered by biomass based systems [27]. Therefore the following heating systems were selected for the Finish case study: wood pellets boiler, oil boiler, district heating, heat pumps (air/water, ground/water), direct electric heating, partially storing electric heating.

Table 2
Energy costs, consumer prices and technology data for the heating systems considered in the case studies.

Austria		Wood log boiler	Wood pellets boiler	Natural gas boiler	Oil boiler	District heat	Heat pump air	Heat pump ground	Direct electrical radiator	Electric storage radiator
Variable energy price	€/MWh	23	29	40	40	31	83	83	83	73
Energy taxes	€/MWh	0	0	5	11	0	17	17	17	17
Investment costs	tds. €	10.7	13.6	10.9	10.3	11.1	11.4	16.4	2.6	3.8
O&M costs	€/a	297	352	202	270	443	233	194	21	30

Sources: Own calculations based on data taken from [31–33]. Electricity and natural gas prices represent average prices throughout various suppliers for an annual energy consumption of 20 MWh.

Finland		Wood pellets boiler	Oil boiler	District heat	Heat pump air	Heat pump ground	Direct electrical radiator	Electric storage radiator
Variable energy price	€/MWh	34	33	31	53	53	53	48
Energy taxes	€/MWh	0	14	2	9	9	9	8
Investment costs	tds. €	12.8	10.6	10.1	7.8	13.7	3.0	4.0
O&M costs	€/a	124	96	43	92	126	64	76

Sources: [24,34,35].

The Netherlands		Natural gas boiler	District heat	Direct electric radiator
Variable energy price	€/MWh	38	50	125
Energy taxes	€/MWh	16	23	42
Investment costs	tds. €	11.9	10.6	3.5
O&M costs	€/a	81	50	13

Sources: [36,40]; based on the different components of typical Dutch energy bills: base fee, metering costs, energy taxes, discount on taxes, administration costs; the electricity price represents a typical mix (20 MWh/yr) of night and daytime tariff.

Sweden		Wood pellets boiler	Oil boiler	District heat	Heat pump ground
Variable energy price	€/MWh	34	38	36	65
Energy taxes	€/MWh	0	32	0	24
Investment costs	tds. €	12.4	10.7	19.8	15.8
O&M costs	€/a	323	215	120	161

Investment costs of central heating systems include boiler costs and the heat distribution costs inside the building (5500 €). Assumed exchange rate: 9.28 SEK/€ (due to high volatility of the exchange rate in the last few years, direct comparison should be made with caution). For electricity and natural gas, the energy price corresponds to an annual consumption of 20 MWh.

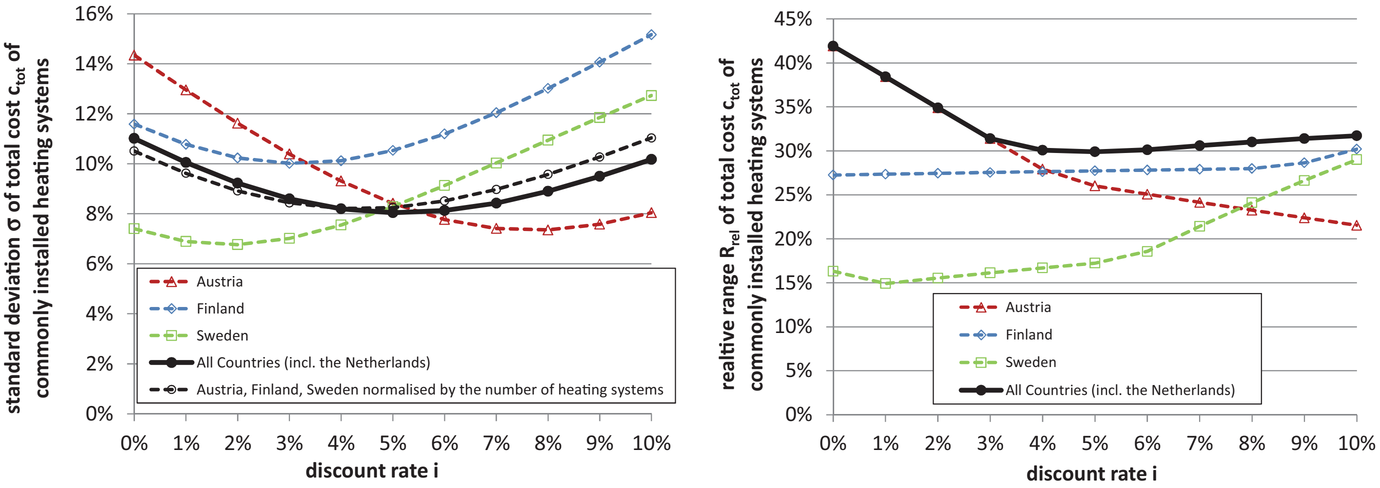

Fig. 2. Standard deviation and relative range R_{rel} of total heating costs c_{tot} of heating systems commonly installed in the analysed building types.

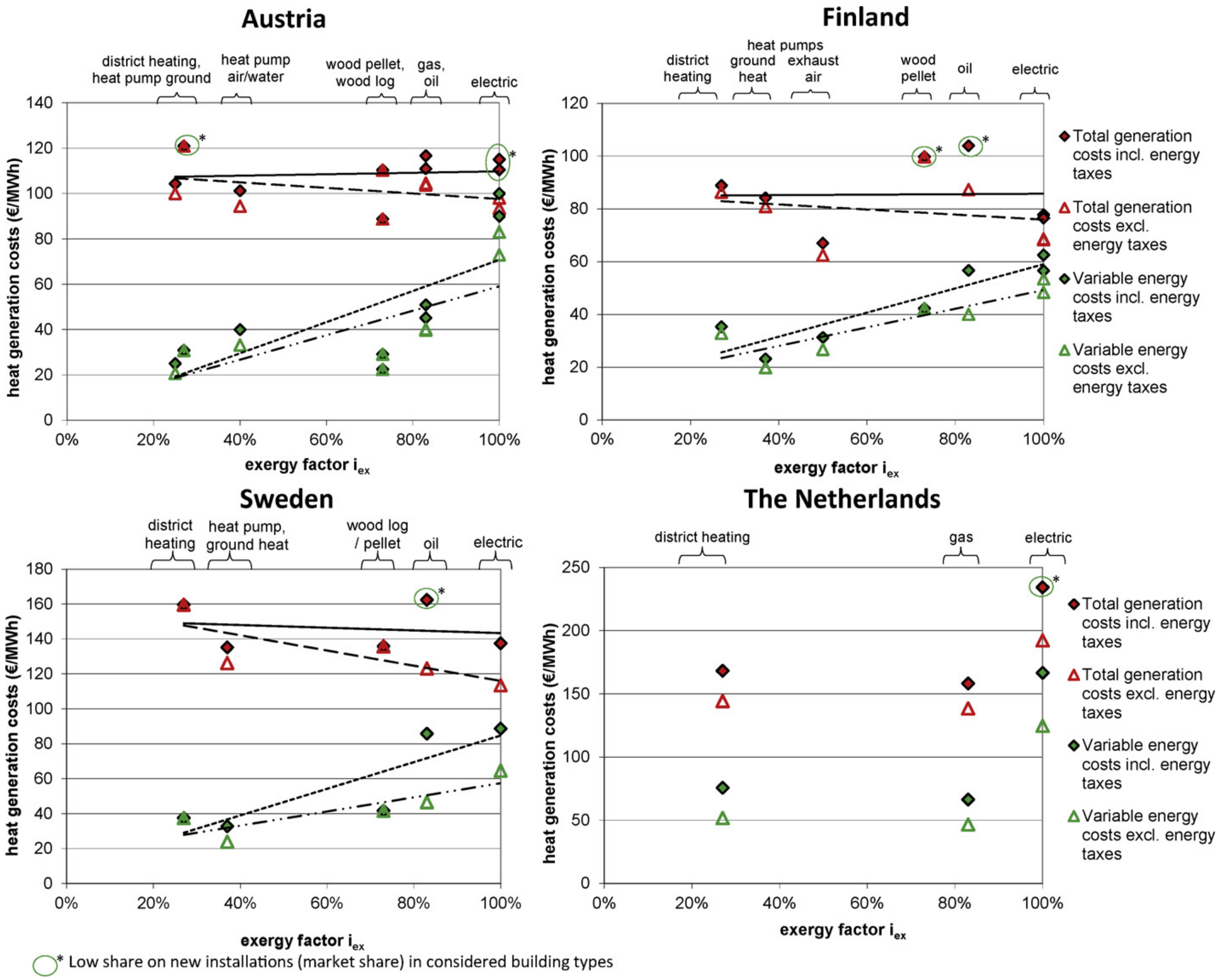

Fig. 3. Components of heat generation costs vs. exergy factor for various heating systems for the countries analysed in this studies, based on a discount rate of 5%.

3.4. The Netherlands

The Dutch example building is a typical row house built between 1980 and 1988. The houses have in general a gross floor area of 89 m^2, the average annual energy demand for heating of these buildings results to 14.7 MWh/yr, or 164 kWh m^{-2} yr^{-1}. Additional information can be found at SenterNovem [28]. Since the nineteen sixties, the most common energy carrier for space heating is natural gas (∼85%). 10% of all dwellings are connected to district heating; a small fraction of the building stock uses electric energy for space heating. Therefore, the following heating systems were selected for the Dutch case study: district heating, natural gas boiler, electric heating.

3.5. Sweden

The Swedish model building is a standard single family house built in the nineteen nineties with a gross floor area of 140 m^2 and an annual heat demand of 14 MWh/yr (101 kWh m^{-2} yr^{-1}) [29]. In small houses, i.e. one- and two-dwelling buildings, heat is provided mostly by means of biomass (∼30%), heat pumps (∼25–30%) and direct electric heating (25%), while district heating accounts for only 12% [30]. In newly constructed buildings, the shares of direct electric heating (water based heat distribution system) and biomass are in the range of 35%. Heat pumps hold a share of about 20%, DH gets about 8% [29]. Based on this distribution the following heating systems have been selected for the Swedish case study: district heating, oil boiler, wood pellets, direct electric heating, and heat pumps. Despite their common use in previous decades, oil boilers are basically not installed in Sweden anymore. As it holds for Finland as well, the use of natural gas is strongly constrained by the lack of a wide-spread natural gas grid.

Table 2 lists the input data that have been used for the heating systems investigated for our case studies. Prices are averages for 2005; the variable energy prices exclude taxes.

4. Results and discussion

Based on the data shown in the previous section, we calculate indicators to test our hypotheses. To do so, an estimation of the underlying discount rate has been calculated. Empirical studies provide evidence that households do not apply all available cost-effective energy efficiency technologies. Therefore literature often suggests that households use high discount rates in energy-related decisions (see e.g. Feldmann [37]). In contrast, Howarth and Sanstad [38] conclude that 'market failures related to asymmetric information, bounded rationality, and transaction costs are major contributors to the so-called "efficiency gap."' We pursue their line of argumentation. We expect market failures to be small in the area analysed within this paper. This is, because the chosen heating systems, their costs and performances are well known, as they are commonly installed. Furthermore, it was not analysed whether or not a decision to install a heating system had been taken, but if it had been, the kind of technology adopted is of interest. Finally, as all four countries are generally relatively wealthy, availability of capital is not expected to be a major obstacle. We therefore expect the discount rate to be somewhere in the lower range. Based on a depreciation time of twenty years (approximately the lifetime of heating systems), the discount rate has been varied in a range of 0–10%.

Results shown in Fig. 2 support the first hypothesis. The overall costs of well-established heating systems are within the same range in each country. Depending on the discount rate applied, the standard deviation of total heating cost is in the range of 8–11%, calculated based on all countries. The minimal dispersion stems from applying a discount rate of 5%, resulting in standard deviation of 8%. On the level of the individual countries, this discount rate results in relative ranges R_{rel} between 17% (Sweden) and 28% (Finland). The estimated standard deviation is in a range of 8.3% (Sweden) to 10.5% (Finland), as shown in Table 3.

Table 3
Statistical dispersion of total heating costs c_{tot} of most common heating systems per country based on a discount rate of 5%.

	Relative range R_{rel}	Standard deviation σ
Austria (excl. district heat and electr. radiators[a])	26%	8.4%
Finland (excl. biomass and oil boilers[a])	28%	10.5%
Sweden (excl. oil boilers[a])	17%	8.3%
The Netherlands[b]	–	–
All countries (incl. The Netherlands)	30%	8.0%
Austria, Finland, Sweden (normalized by the number of heating systems)	30%	8.2%

[a] Low market shares in the considered building types.
[b] Direct electric heating is not common (anymore), district heating: tariff structure based on total heating costs of natural gas based boilers.

Yet, these results also suggests that the costs might not be the only decision criteria and others, such as availability of energy carriers, past decisions (tradition), convenience differences, individual preferences and, at least for the case of air source heat pumps, diffusion barriers of new technologies, influence the investment decision as well. Based on a discount rate of 5%, the national results for the total costs and the energy related costs, both with and without taxes, are shown in Fig. 3. The x-axis represents the overall exergy factor as defined by Eq. (8). The y-axis indicates the cost components based on Eqs. (2)–(4). The slope of the corresponding regression lines can be understood as a rough indicator to which extent these components of the heat generation costs are based on the exergy content of the energy carriers.

To test the second hypothesis, the share of investment costs on the total heating costs has been calculated. The results shown in Fig. 4 support the hypothesis that there is a strong relation between investments needed to supply the desired useful heat and the exergy factor i_{ex} of the applied energy carrier or carriers. Major digressions can be explained by taking into account the drawn system boundaries. Since we used the price structure of retail consumers, at least some part of the upfront investments do account for variable energy costs. This is particularly evident for the tariff structure of DH in Sweden and The Netherlands. The

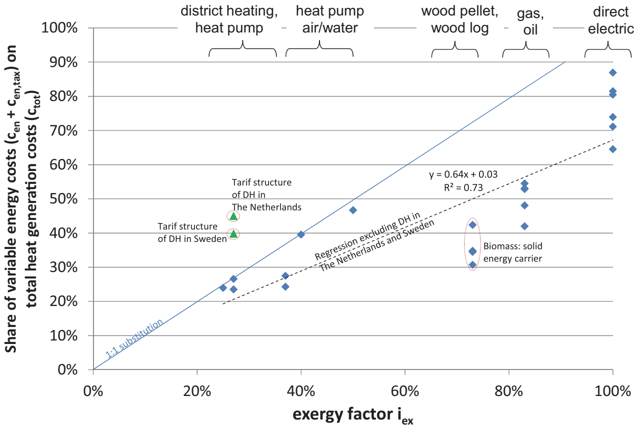

Fig. 4. Share of variable energy costs on total heat generation costs for all technologies and countries analysed.

Netherlands has regulations regarding the maximum consumer price of DH, stating that the fares should not be higher than for natural gas heating. The energy bills of comparable houses and households connected to the gas grid or DH grid should therefore be the similar. Nevertheless, when we regard the exergy factor, due to this tariff system the DH energy price is relatively high compared to natural gas, as initial investment costs are included in the variable cost components. This is the case for the Swedish price data as well. A significant share of investment costs is included in the energy price as opposed to the infrastructure related price components. Another group of outliers are the biomass technologies, especially wood log boilers. Due to the system boundaries drawn in this study, these systems are using a raw energy carrier compared to the other technologies, which again means, that all the necessary purification, ash handling and other comparable processes, which take place upfront for the other technologies, have to be done within the chosen system boundaries and by doing so increasing the investment costs of the installed system.

The conducted regression results in a capital-expenditures-to-exergy substitution rate of 64%. Furthermore, the data support the plausible assumptions that the value and consequently, the energy price of a hypothetical energy carrier with a very low exergy content would be virtually zero. In turn, the effort and value would have to be invested into the heat supply technology.

5. Conclusions

This analysis has shown that the total costs of heating systems widely installed are, compared on a national level, in the same range, resulting in a standard deviation of 8–11%. Furthermore we have shown that there is a close correlation between the specific energy related costs and the average exergy factor of the applied energy carriers. This shows that the lower the exergy factor, the higher the investment and capital needs for making use of this low-exergy energy source.

This can also be formulated in terms of the possibility to substitute exergy with capital and hence reduce the consumption of high-exergy resources by additional capital input.[1] For the cases studied here, this supports the proposition that exergy and capital can be substituted for each other to some extent. Based on the data used in this analysis, we conclude that for the case of current, from an economical point of view, relatively efficient heating systems the substitution rate between exergy and capital is in the vicinity of 2/3. This means that by reducing the average specific exergy input of the applied energy carriers by one unit, the share of capital costs on the total costs increases by 2/3 of a unit.

Several open questions are left for further research. In particular they refer to the following issues:

- extending the sources of energy carriers and systems (e.g. thermal solar collectors and micro cogeneration systems),
- extending the system barrier (e.g. including the capital costs for gas or DH network),
- extending the exergy concept to the exergy needed for an investment (e.g. boiler, DH network, etc.).

The results of this analysis and the proposed approach, as well as further research on this topic, could be used to provide policy recommendations on how to adjust energy carrier taxation as well as other policy instruments so as to stimulate the use of low-exergy carriers to meet low-exergy demands in buildings.

Acknowledgements

This publication was enabled by action C24 (www.costexergy.eu) of COST, a European framework enabling international cooperation between scientists conducting nationally funded research (www.cost.esf.org) as well as IEA ECBCS Annex 49 (www.annex49.com).

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PUBLICATION V

Low energy building market trends in Northern Europe

Proceedings of the International Heating, Ventilation and
Air-Conditioning Conference, pp. 39–44, Tongji University,
Shanghai, China; 6–9 November 2011.

LOW ENERGY BUILDING MARKET TRENDS IN NORTHERN EUROPE

P. Tuominen*, R. Holopainen, P. Ala-Kotila and G. Cao

VTT Technical Research Centre of Finland,
PL 1000, 02044 VTT, Finland

ABSTRACT

The market for low energy buildings is developing fast in the Northern Europe. The objective of this study was to analyze the market low energy buildings in the region by surveying key stakeholders about the issue.

Two sets of surveys were conducted in Northern European countries: one questionnaire was aimed at individuals and families considering building a new house to find out their willingness to build a low energy house, and a second one at experts to map the barriers and drivers existing in the market. This paper presents preliminary findings for four participating countries.

The study confirms that builders are generally interested in low energy buildings and that experts see growth in the market segment in the future. The continuing fast development of the industry can be expected with confidence if the present sentiment prevails.

KEYWORDS

Energy efficiency, Low energy buildings, Market, Survey, Consumer

INTRODUCTION

The market for low energy buildings is developing fast in the Northern Europe driven to a large part by national policies aiming at energy conservation and the mitigation of the climate change. Energy efficiency has become a central theme in the energy policies of both the European countries and the European Union (EU).

Indeed, improving energy efficiency is regarded by the European Commission (EC) as a key element in the Community energy policy. It is described by the Commission as the most effective way to improve security of energy supply, reduce carbon emissions, increase competitiveness and stimulate the development of markets for new energy-efficient technologies. EC (2006) reports that the households sector has been estimated to represent 27 % of the energy savings potential by the year 2020.

If the recently announced legislative and regulatory programs (EC 2010) concerning energy efficiency in buildings are carried out, we are to expect drastic changes in the real estate market. The new EU regulations aim at making near zero energy buildings the norm in new construction by 2020.

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* Corresponding author email: pekka.tuominen@vtt.fi

However, the market situation varies from one country to another depending on factors such as consumer interest, availability of information, trends in construction etc. The objective of this study was to analyze the market low energy buildings in the Northern Europe by surveying key stakeholders about the issue. The work is still in progress but a summary of main findings is reported for countries where preliminary results are available.

RESEARCH METHODS

The data was collected by performing two sets of questionnaires: the first questionnaire was aimed at individuals and families considering building a new house to find out their willingness to build a low energy house, and the second one at experts to map the barriers and drivers existing in the market. The study targets eight Northern European countries. In four countries the studies have been completed or nearly completed: Estonia, Finland, Lithuania and Poland. The study is still underway in four more countries: Denmark, Latvia, Norway and Sweden. A summary of the main findings is given for first four countries where preliminary results are available.

Questionnaires were carried out in all participating countries and were similar in each country apart from parts which needed some country specific modification. The research teams in each country decided on the execution of the surveys. The results of the questionnaires were sent to the VTT Technical Research Centre of Finland in Excel format. VTT collected the data and placed it into a database run with Digium software for analysis and reporting.

Customer survey – Builders

Customer survey was targeted at private individuals, who were building a single family house. The main purpose of the builder survey was to find out the interest to build low energy house and what options builders considered and into which result did they arrive.

The target group, referred henceforth to as ‘builders’, was mostly land owners who had no building permit or who had a permit but had not started building yet. For finding the respondents the help of local authorities, architects, product suppliers, organizations and fairs was used.

Expert survey

The purpose of the expert survey was to find out the amount of low-energy houses, level of costs, stage of development of the business, experiences of the industry and market situation in general. The target group for expert survey, referred henceforth to as ‘experts’, was different stakeholders, such as representatives of the industry, authorities, researchers and organizations. The questionnaires were distributed through workshop, symposiums, conferences and emails, depending on the country.

RESULTS

Two major results give a picture of the market situation in the countries studied so far. Figure 1 shows what is perhaps the main result from the experts survey: how the market for low-energy buildings is predicted to develop in the foreseeable future in each country. Overall, the experts believed that there will be growth in future, with the Estonian and Finnish experts being the most optimistic ones and Lithuanian and Polish least. Similarly, figure 2 shows the possible main result from the builders survey: how many see low-energy construction as a realistic alternative. In Estonia, Finland and Lithuania most builders consider it to be realistic, whereas in Poland a slight majority is sceptical of low-energy buildings.

The body of responses collected with the questionnaires is too large for a detailed account of results to be given here. Rather, a summary of main findings is presented for each country. For the full results, the reader is directed to the upcoming project report (VTT 2011).

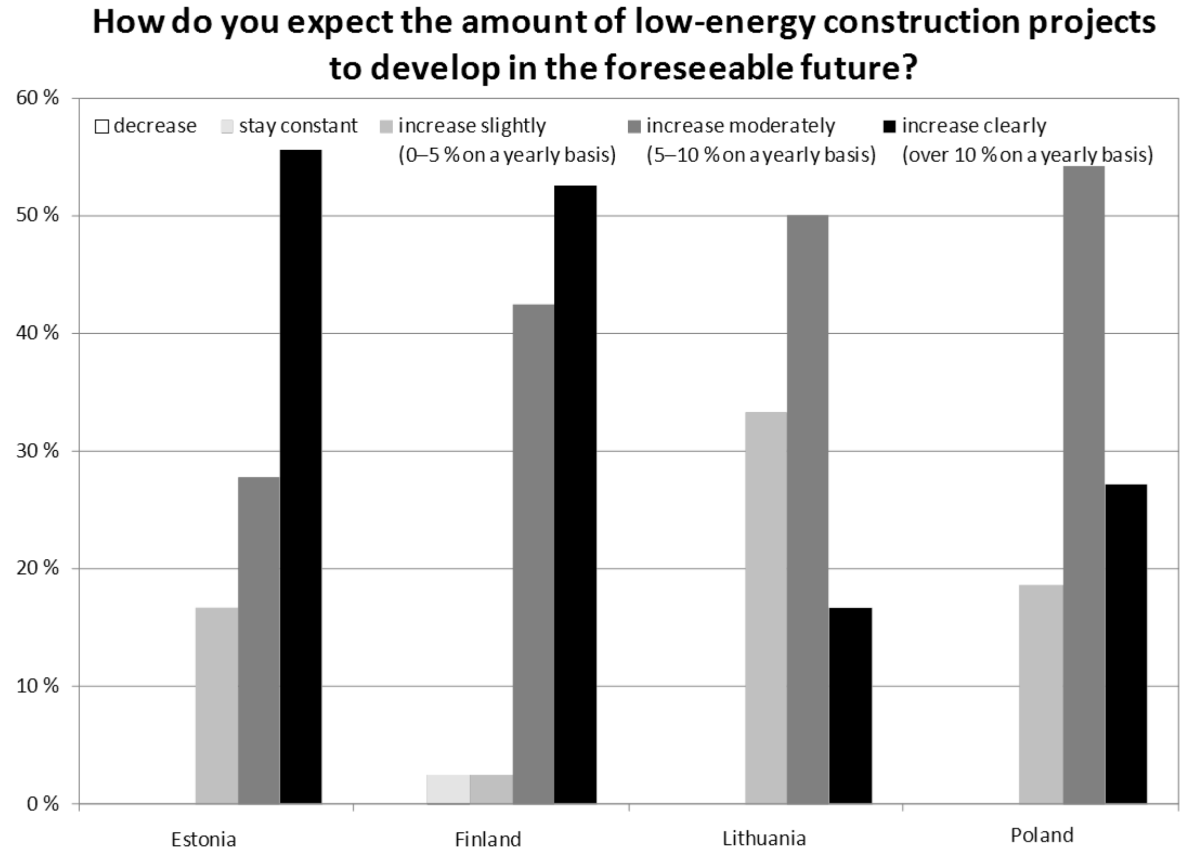

Figure 1. The future development of low-energy construction projects as forecast by the experts surveyed.

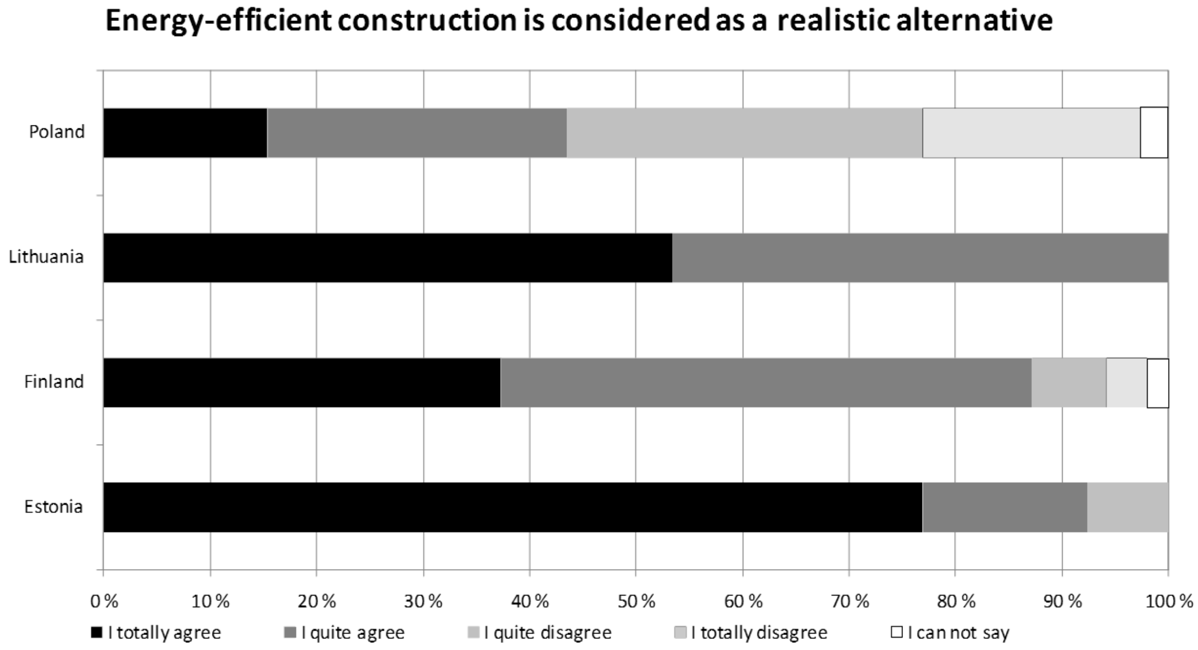

Figure 2. The surveyed builders’ views on considering energy efficient construction.

Estonia

The heating energy demand of newly erected building has been mostly decreasing while the electricity demand has been increasing or stayed constant during the last 10 years. During the last five years the amount of low-energy construction projects has been increasing moderately and in 2009, based on the surveyed experts' estimates, about 20 per cent of all the dwellings built were very low-energy houses. In the foreseeable future they believe that the number of these projects will increase clearly (more than 10 %/a). In Estonia the cost level of low-energy construction services and products are expected mostly to get lower or to stay constant.

In the experts' opinion, low energy building projects seem to have encountered more problems than traditional construction. Nevertheless, low-energy construction is a clear market trend in Estonia. The demand of low energy buildings in the public sector was seen as an important driver towards low energy construction.

According to the surveyed builders, Estonians tend to want their house individually planned. House are mainly built using subcontractors. In general builders consider energy-efficient construction as a realistic alternative. In Estonia people building houses are generally aware of the concepts of low-energy and passive houses. Zero-energy house and energy positive house were not, however, familiar for all.

Finland

Heating energy demand in newly erected buildings has been mostly decreasing while the electricity demand has been clearly increasing for the last 10 years. During last five years the amount of low-energy construction projects was perceived to have increased moderately in the expert survey, and in 2009 about 45 per cent of all the dwellings built were very low-energy houses according to average opinion of the experts. In the foreseeable future, the amount of these projects is expected to increase moderately (more than 5 %/a).

In the expert's view companies in Finland mostly do not offer or plan to offer in the near future building products for low-energy construction. Moreover, they tend to lack the right expertise and knowledge to construct low-energy buildings. However, companies reported plans to recruit employees with that knowledge.

Finnish builders were mostly interested in buying prefabricated houses but with customization. They build their house mainly using subcontractors. In general builders seem to consider energy-efficient construction as a realistic alternative. In Finland builders are generally aware of low-energy house and passive house concepts. Zero-energy houses and energy positive houses, on the other hand, were not familiar for all.

Lithuania

Heating energy demand of newly erected building has been decreasing. At the same time the electricity demand has been clearly increasing. During the last five years the amount of low-energy construction projects has been increasing slightly and in 2009 about 15 per cent of all the dwellings built were very low-energy houses. In foreseeable future the amount of these projects are expected to increase slightly (less than 5 %/a).

The experts expected the cost level of low-energy construction services and products to rise. Generally speaking, the experts believe that low energy construction has faced more problems than traditional construction. Nevertheless, low-energy construction is rising as a marketing trend in Lithuania. The demand of low energy buildings by public authorities was seen as an important driver in the market towards low energy construction.

Lithuanian builders want their house nearly always individually planned. They tend to build their house using subcontractors or by building it by themselves. All of the builders surveyed see energy-efficient construction as a realistic alternative. In Lithuania builders didn't all know what the low-energy or passive house is and the zero-energy house and energy positive house was even more unknown.

Poland

Heating energy demand of newly erected building has been mostly decreasing while the electricity demand has been clearly increasing during the last 10 years. In foreseeable future the experts believe the amount of energy efficient construction to increase moderately (more than 5 %/a). The cost level of low-energy construction services products is expected mostly to get lower.

According to experts, low energy construction has faced clearly more problems than traditional construction. However, low-energy construction is a rising marketing trend in Poland. The demand of low energy buildings by public authorities was seen important driver the market towards low energy construction.

The experts say that some companies in Poland already offer building products for low-energy construction, but only few of those were planning to increase their supply of those products. Only some companies have the right expertise and knowledge to construct low-energy buildings, but many were planning to recruit employees with that knowledge. Companies see working with energy efficient buildings slightly important for the image. In general low-energy products are available in Poland.

Polish builders want their house mostly individually planned. They build their house using subcontractors and. Polish builders mostly didn't consider energy-efficient construction to be a realistic alternative. In Poland builders knew what the low-energy house is the passive house concepts were but zero-energy house was not that familiar and energy positive house was even less familiar.

Norway

In Norway the opinions about heating energy demand of newly erected building were really divided – the experts did not agree whether the trend was rising or diminishing. Electricity demand has clearly been increasing during the last 10 years. In foreseeable future the amount of energy efficient construction is expected to increase moderately (more than 5 %/a).

In Norway the cost level of low-energy construction services and products is expected mostly to get lower. Low-energy construction encounters still problems more than traditional construction. However low-energy construction is seen as a marketing trend in Norway by the experts. The demand of low energy buildings by public authorities was seen as an important driver the market towards low energy construction.

Companies in Norway offer building products for low-energy construction and most of them are planning to increase their supply of those products. However only some companies have the right expertise and knowledge to construct low-energy buildings, but almost all are planning to recruit employees with that knowledge. Companies see working with energy efficient buildings important for the image. In general the low-energy products are available for private individuals if they know where to look for them.

DISCUSSION

The expert surveys show that there is nearly universally an expectation of growth for the market of low energy buildings. Nevertheless, at present, whether companies offer products aimed specifically at low energy construction varies greatly from country to country. Moreover, there is no great expectation of growth in the number of related products offered. Majority of companies do, however, take the issue into account when recruiting.

The builders in general seem to be prepared to consider low-energy buildings as an option, with the exception of Poland, where about half of the builders are sceptics. Builders are usually familiar with the concepts of low-energy and passive buildings, but not so much with zero energy and energy positive houses.

CONCLUSION AND IMPLICATIONS

The study confirms that builders are generally interested in low energy buildings and that experts see growth in the market segment in the future. It appears, though, that companies are not yet planning to develop their product lines to answer to the shifting markets. They do, however, tend to take it into account in recruiting. The continuing fast development of the industry can be expected with confidence if the present sentiment prevails.

ACKNOWLEDGEMENTS

The work was carried out within the NorthPass project (Promotion of the Very Low Energy House Concept to the North European Building Market) supported by the Intelligent Energy Europe program of the European Commission.

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Series title and number

VTT Science 117

Title	**Assessing energy efficiency potential in the building stock** Method for estimating the potential for improvements and their economic effects
Author(s)	Pekka Tuominen
Abstract	Buildings, representing more than a third of global energy consumption, have long remained one of the focal points for the efforts to increase energy efficiency. The residential sector in particular has had more energy-related policies put in place than any other sector in the IEA countries. Therefore, the question which policies will have the greatest effect over time is very relevant to the policymakers. The main objective of this thesis is to develop a method for calculating the en-ergy efficiency potential of the building stock and to assess the economic effects of the realization of the potential in terms of changes in GDP, employment and external costs. Even though the method is meant to be applicable to different building stocks, the Finnish building stock was mostly studied as the method was developed over time. Similar but more limited analysis was also conducted for a number of EU member states. During the course of the study, a calculation tool called REMA was developed based on the methods used. The purpose of REMA is to allow conducting similar analyses in the future with relative ease in a systematized way. REMA is a bottom-up engineering model of energy use in the building stock. Future developments are estimated using annual rates of new construction, renovations and removals from the building stock. The selected approach entails selecting representative building types, also called archetypes, for estimating the energy consumption in different segments of the building stock. The scenarios calculated concerning the Finnish case indicate that a few per-cent rise in annual construction and renovation investments can decrease total primary energy consumption 5–7% of the country by 2050 compared to a baseline scenario. On the short term a slight decrease in the level of GDP and employment is expected. On the medium to long term, however, the effects on both would be positive. Furthermore, a significant drop in harmful emissions and hence external costs is anticipated. Overall, a clear net benefit is expected from improving energy efficiency. For other EU countries studied, typically energy savings of about 20% were estimated to be achievable by 2030 with cost-effective renovation investments in the building stock analysed. Overall, major economically sound energy efficiency potentials were identified, but the realization of these potentials is rather slow due to the limited renewal rates present in building stocks.
ISBN, ISSN, URN	ISBN 978-951-38-8372-0 (Soft back ed.) ISBN 978-951-38-8373-7 (URL: http://www.vttresearch.com/impact/publications) ISSN-L 2242-119X ISSN 2242-119X (Print) ISSN 2242-1203 (Online) http://urn.fi/URN:ISBN:978-951-38-8373-7
Date	December 2015
Language	English, Finnish abstract
Pages	52 p. + app. 52 p.
Name of the project	
Commissioned by	
Keywords	Energy efficiency, energy policy, energy economics, building stock
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111

Julkaisun sarja ja numero

VTT Science 117

Nimeke	**Rakennuskannan energiatehokkuuspotentiaalin arviointi** Menetelmä rakennuskannan energiatehokkuusparannusten ja niiden taloudellisten vaikutusten arviointiin
Tekijä(t)	Pekka Tuominen
Tiivistelmä	Rakennukset edustavat noin kolmasosaa maailman energiankulutuksesta ja ovat siksi pitkään olleet yksi teollisuusmaiden keskeisimmistä energiatehokkuusparannusten kohteista. IEA:n jäsenmaissa erityisesti asuinrakennuksiin on menneinä vuosina kohdistettu enemmän julkisen vallan energiatehokkuustoimenpiteitä kuin millekään toiselle talouden sektorille. Näin ollen yhteiskunnallisen päätöksenteon kannalta keskeinen kysymys on, mitkä vaihtoehtoisista toimenpiteistä ovat pitkällä aikavälillä tehokkaimpia. Tässä väitöskirjassa päätavoitteena on kehittää menetelmä, jolla voidaan määrittää rakennuskannan energiatehokkuuspotentiaali ja arvioida sen taloudelliset vaikutukset BKT:hen, työllisyyteen ja ulkoiskustannuksiin. Menetelmä on tarkoitettu käytettäväksi erilaisten rakennuskantojen analysointiin. Menetelmän pohjalta tehtiin tutkimuksen kuluessa rakennuskannan energiamalli REMA, jolla samankaltaisia laskelmia voidaan tehdä systemaattisesti suhteellisen helposti. REMA on bottom-up-tyyppinen fysikaalinen rakennuskannan energialaskentamalli. Rakennuskannan tuleva kehityskulku arvioidaan uudisrakentamisen, korjausrakentamisen ja purkamisen vuosittaisten määrien perusteella. Energiankulutuslaskenta perustuu rakennuskannan merkittäviä osia edustavien tyyppirakennusten käytölle. Tässä väitöstutkimuksessa lasketut Suomea käsittelevät skenaariot osoittavat, että muutaman prosentin lisäys vuosittaisiin rakentamis- ja kunnostusinvestointeihin voi vähentää maan kokonaisprimäärienergiankulutusta 5–7 % vuoteen 2050 mennessä verrattuna perusuraan. Lyhyellä aikavälillä on odotettavissa lievä BKT:n ja työllisyyden pudotus, mutta keskipitkällä ja pitkällä aikavälillä vaikutukset molempiin ovat positiivisia. Lisäksi on odotettavissa huomattava haitallisten päästöjen ja siten ulkoiskustannusten pieneneminen. Kaikkiaan toimenpiteiden arvioidaan synnyttävän selkeän nettohyödyn. Muissa tutkituissa EU-maissa tavallisesti noin 20 %:n energiansäästö oli saavutettavissa tutkitussa rakennuskannassa kustannustehokkailla korjausrakentamistoimilla vuoteen 2030 mennessä. Tutkimuksessa tunnistettiin siis huomattavia taloudellisesti järkeviä energiatehokkuuspotentiaaleja, mutta niiden toteutumisen vauhti on varsin verkkainen, koska rakennuskanta uudistuu hitaasti.
ISBN, ISSN, URN	ISBN 978-951-38-8372-0 (nid.) ISBN 978-951-38-8373-7 (URL: http://www.vtt.fi/julkaisut) ISSN-L 2242-119X ISSN 2242-119X (Painettu) ISSN 2242-1203 (Verkkojulkaisu) http://urn.fi/URN:ISBN:978-951-38-8373-7
Julkaisuaika	Joulukuu 2015
Kieli	Englanti, suomenkielinen tiivistelmä
Sivumäärä	52 s. + liitt. 52 s.
Projektin nimi	
Rahoittajat	
Avainsanat	Energiatehokkuus, energiapolitiikka, taloudelliset vaikutukset, rakennuskanta
Julkaisija	Teknologian tutkimuskeskus VTT Oy PL 1000, 02044 VTT, puh. 020 722 111

Assessing energy efficiency potential in the building stock

Method for estimating the potential for improvements and their economic effects

Buildings, representing more than a third of global energy consumption, have long remained one of the focal points for the efforts to increase energy efficiency. The main objective of this thesis is to develop a method for calculating the energy efficiency potential of the building stock and to assess the economic effects of the realization of the potential in terms of changes in GDP, employment and external costs. The scenarios calculated concerning the Finnish case indicate that a few percent rise in annual construction and renovation investments can decrease total primary energy consumption 5–7% of the country by 2050 compared to a baseline scenario. On the short term a slight decrease in the level of GDP and employment is expected. On the medium to long term, however, the effects on both would be positive. Furthermore, a significant drop in harmful emissions and hence external costs is anticipated. Overall, a clear net benefit is expected from improving energy efficiency.

ISBN 978-951-38-8372-0 (Soft back ed.)
ISBN 978-951-38-8373-7 (URL: http://www.vttresearch.com/impact/publications)
ISSN-L 2242-119X
ISSN 2242-119X (Print)
ISSN 2242-1203 (Online)
http://urn.fi/URN:ISBN:978-951-38-8373-7