A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Doctor of Philosophy

ENERGY EFFICIENCY POTENTIAL FOR SPACE HEATING IN HUNGARIAN PUBLIC BUILDINGS. TOWARDS LOW-CARBON ECONOMY

Supervisor: Prof. Dr. Diana Ürge-Vorsatz, Central European University, Hungary
External supervisor: Dr. Tamás Csoknyai, Faculty of Engineering, University of Debrecen, Hungary

PhD Committee:
Prof. Dr. Ruben Mnatsakanian, Central European University, Hungary
Prof. Dr. Alan Watt, Central European University, Hungary
Dr. Tudor Constantinescu, Executive Director of the Buildings Performance Institute Europe (BPIE)

Katarina KORYTAROVA

September, 2010

Budapest

Notes on copyright and the ownership of intellectual property rights:

(3) For bibliographic and reference purposes this thesis should be referred to as:

Korytarova, K. 2010. *Energy efficiency potential for space heating in Hungarian public buildings. Towards a low-carbon economy.* Doctoral thesis, Department of Environmental Sciences and Policy, Central European University, Budapest.

Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Furthermore, this thesis contains no materials previously written and/or published by another person, except where appropriate acknowledgment is made in the form of bibliographical reference, etc.

Katarina KORYTAROVA

THE CENTRAL EUROPEAN UNIVERSITY

ABSTRACT OF THESIS submitted by:
Katarina KORYTAROVA
for the degree of Doctor of Philosophy and entitled: Energy efficiency potential for space heating in Hungarian public buildings. Towards a low-carbon economy.

Month and Year of submission: September, 2010.

Impacts of climate change as well as depletion of energy sources and disruptions in energy supply call for significant energy savings as well as greenhouse gas emission reductions. According to IPCC buildings provide large mitigation potential at low costs, especially in economies in transition and developing countries. The aim of the dissertation is to determine energy savings potential for space heating in public buildings in Hungary, one of the economies in transition. The dissertation also aims to assess risks of suboptimal retrofit applied at a large scale and to estimate the related "lock-in effect". The potential is determined based on two types of modelling approaches: first, a well-established component-based approach where the potentials of individual more efficient building components are summed up through supply curve method; and second, a rather novel, performance-based approach. The risks and opportunities as well as the lock-in effect are examined in through scenario analysis, which is based on the performance-based model. The results of the comparison of the results of the two modelling approaches, first of its kind in time of writing, shows significant difference between the potential determined by component- and performance-based approach. This comparison also shows that the performance-based approach is a flexible modelling tool. The calculation of the potential in both approaches is based on average specific heating energy requirements for eight types of public buildings, based on a set of energy audits conducted in Hungarian municipal buildings. Scenario analysis implies that although the rate of retrofit is important in determining the total potential, it is the level of energy performance the buildings are retrofitted, which is detrimental to the size of the potential. The analysis shows that if the existing public building stock is retrofitted at an accelerated rate but only partially, the resulting potential will be only slightly higher than if buildings are retrofitted to the level of high-performance buildings at a natural rate of retrofit, requiring much higher investment. Moreover, gradual retrofit to passive house standard at natural rate of retrofit leaves more room for further renovation even after 2030 and thus the resulting energy savings in 2050 would be higher. Further, if passive energy standard is gradually applied to the whole building stock, several times higher energy savings can be reached than if the partial retrofit is applied to the same building stock. The difference between these two cases, the lock-in effect, accounts for about 44% of the 2030 baseline energy consumption. This amount will be locked-in for several next decades if suboptimal retrofit is supported on a large scale. Thus, in order to use the public funds most effectively, high-performance retrofit should be preferred to suboptimal retrofit at a large scale.

Keywords: energy efficiency, public buildings, energy savings potential, performance-based approach, lock-in effect

---

Acknowledgements

I would like to thank to my supervisor Prof. Dr. Diana Ürge-Vorsatz for providing me support during my PhD studies, especially in mainstreaming the most important research ideas as well as well as challenging questions and suggestions for furthering the research.

I am very greatful to my external supervisor, Dr. Tamás Csoknyai from Faculty of Engineering, University of Debrecen (formerly: Faculty of Architectural Engineering, Budapest University of Technology and Economics) for the nummerous consultations, ideas for brainstorming, technical advise as well as detailed comments on the drafts of the dissertation.

I would like to thank also to Dr. Alexandra Novikova (currently at Climate Policy Initiative, DIW) for nummerous consultations and sharing of the residential model with me, József Feiler (Office of the Parliamentary Commissioner for Future Generations) for professional motivation during my research period, Bence Huba and Energy Centre (Energia Központ) for providing me the right conditions for processing UNDP/GEF energy audits, Orsolya Korsos (currently at Development Directorate of the Ministry of Environment and Water in Hungary) and Dorottya Hujber (currently at Energia Közpönt) for transforming the relevant data from over hundred Hungarian energy audits into my English database, Prof. Dr. Alan Watt and Prof. Dr. Ruben Mnatsakanian, Dr. Brandon Anthony, Sergio Herrero-Tirado, Andrew Butcher, as well as other faculty members, colleagues and university staff for support throughout the PhD programme, as well as to Central European University and Centre for Climate Change and Sustainable Energy Policy for provision of suitable research facilities and funding. I would also like to thank to József Fucskó (MAKK), Péter Nagy (energy manager at Nyíregyháza), Zoltán Kiss (D-ÉG Kft.), Stefan Lechtenböhmer (Wuppertal Institute for Climate, Environment and Energy), Prof. L. D. Danny Harvey (University of Toronto), Istán Kovacsics (EGI Contracting Engineering Co. Ltd.) for their consultations, provision of valuable data, information and support in the research. Finally, I am thankful to my family and friends for support during the studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations

ABC	Atmospheric black clouds
BAU	Business-as-usual (scenario)
BEMS	Building Energy Management System
CBA	Cost-benefit analysis
CEA	Cost-effectiveness analysis
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CoEU	Council of European Union
DAI	Dangerous anthropogenic interference
EC	European Communities
EPBD	Energy Performance of Buildings Directive (2002/91/EC)
EU	European Union
ESD	Energy Service Directive (2006/32/EC)
GDP	Gross Domestic Product
GEA	Global Energy Assessment
GEF	Global Environmental Facility
GHGs	Greenhouse gases
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KSH	Központi Statistikai Hivatal [Hungarian Central Statistical Office]
LEED	Leadership of Energy and Environmental Design
OECD	Organisation for Economic Cooperation and Development
ppm	Parts per million
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
VLEB	Very low energy building

CHAPTER 1. INTRODUCTION

This chapter first introduces the environmental problem of climate change and the urgent need to reduce current levels of GHGs emissions. The current research shows that buildings can deliver large energy and CO_2 emission reductions at low costs. This chapter then presents the object of the study – the public sector in Hungary, as well as the research aim, objectives and research questions. At the end of the chapter the outline of the dissertation is presented.

1.1 Climate change – a problem and solutions

Melting of the Arctic and glaciers, droughts and floods and numerous extreme events observed in the past decades are evidence that climate change is occurring. With high probability the climate change observed today is a result of increasing concentration of greenhouse gases (GHG) with the most rapid rise occurring since 1970 (SEG 2007). Major increase in the GHGs levels is attributed to the increased use of fossil fuels. The current level of 379 ppm CO_2 (in 2005, Ramanathan and Feng 2008) is according to experts approaching the levels of dangerous anthropogenic climate change (also called dangerous anthropogenic interference, DAI), when the many changes triggered by increased average surface temperature of more than 2ºC above pre-industrial levels can cause irreversible changes in the ecosystem, also called "tipping points" (Ramanathan and Feng 2008, SEG 2007).[1] IPCC suggests that the 2ºC correspond to 445-490 ppm of CO_2 (Table 3.10, Fisher *et al.* 2007), however, there is still discussion on the exact level of GHG emissions that do not present a danger to humanity. To keep within the IPCC's range of $CO_{2\text{-}e}$ concentrations, the GHGs have to be reduced by 50-85% by 2050 compared to current (2000) levels (see Tables 3.5 and 3.10 in Fisher *et al.* 2007), with majority of the reductions coming from the industrialized

[1] Tipping points include Arctic sea ice loss, melt of Greenland ice sheet, thawing of permafrost and tundra loss, further desertification of Sahara region, significant disruption of El Niṅo –Southern Oscillation and other (for more detail see SEG 2007).

countries. This means that in the short term CO_2 emissions should be reduced by 20-40% by 2020 relative to 1990 levels (Box 13.7 in Gupta *et al.* 2007). Moreover, the CO_2 emissions have to peak between 2000 and 2015 (Fisher *et al.* 2007). These IPCC findings led to a commitment of several countries to decrease the global GHGs to levels which will hinder dangerous climate change. EU set a target of avoiding 2ºC warming compared to pre-industrial levels levels (EC 2007), which was further supported by a commitment to reduce the GHGs emissions by 20% by 2020 compared to 1990 levels (CoEU 2007). The Group of Eight (G8) committed to limit average global temperature rise above 2ºC above the pre-industrial levels, however they have not managed to commit to a more concrete target yet (EurActive 2009). However, new evidence suggests that even these commitments, although challenging, may not prevent dangerous climate change. Although so far only 0.76ºC of warming has been observed, Ramanathan and Feng (2008) claim that due to the masking effect of some aerosols, in reality, the Earth is already committed to a warming of 2.4ºC (1.4ºC-4.3ºC) above the preindustrial surface temperature. Thus, the current mitigation proposals aimed at GHG concentrations of 450 ppm will not help avoiding the already committed warming of 2.4ºC (Ramanathan and Feng (2008). The mitigation policies can "only" limit the extent of exceeding this committed warming (Ramanathan and Feng 2008).[2] Others claim that 450-490 ppm is not enough to prevent DAI. Based on paleoclimate data Hansen *et al.* (2008) state that the society is already in a dangerous zone and thus we should reduce our emissions concentrations below 350 ppm if severe damage is to be prevented.

Moreover, the fossil fuels are limited, energy prices increase and the demand for energy grows as well. Countries are more dependent on fewer energy suppliers which poses risk to

[2] Schellnhuber (2008) opposes to Ramanathan and Feng (2008) by claiming that with strong mitigation action under the G8 lead and clean air policy the warming can be kept under 2ºC (Schellnhuber 2008). Nevertheless, his scenario, which excludes the masking effect of the aerosols overshoots the 2ºC and only then is brought back down under this threshold. This would however mean that some irreversible processes may already start and thus is not a suitable path.

their energy security. If the current trends continue in the future (i.e. trends in the World Energy Outlook 2005 Reference Scenario), oil demand and the related CO_2 emissions will continue to grow rapidly over the next 25 years (IEA 2006). Extending this scenario further shows that CO_2 emissions will be almost 2.5 times the current level by 2050 (IEA 2006). At the same time, several scientists point out that the society has reached the peak oil and is approaching the peak of natural gas and coal (e.g. Aleklett *et al.* 2010). Countries largely dependent on energy imports are vulnerable to disruption in energy supply which may in turn threaten functioning of their current economic structure. The EU imported 54% of its energy sources in 2006 (EC 2008c) and was projected to increase even further by 2030 (EC 2006a). Reducing its import dependency EU is one of the main goals of the 20-20 by 2020 target – this legislative package is believed to reduce the expected imports of energy by 26% compared to the development before the 20-20 initiative (EC 2008c).

The discussion on the necessary GHG emission reductions as well as the increasing dependency on energy imports shows the urgency to envision and facilitate a transition towards a low-carbon future.

The AR4 of IPCC shows that on the global level there is an economic potential for GHG mitigation of 16-31 Gt $CO_{2\text{-eq}}$ at the cost below 100 US$/t $CO_{2\text{-eq}}$ by 2030 (Table 11.3, Barker *et al.* 2007), which is 30-50% of the global $CO_{2\text{-eq}}$ baseline emissions in 2030 (Barker *et al.* 2007)[3]. Much of this potential (15-30% of 2030 baseline emissions, 9.3-17.1 Gt CO_{2e}) can be realized at costs below 20 US$/t CO_{2e} (Table 11.4, Barker *et al.* 2007). The largest cost-effective potential is reported in the building sector (5-6 Gt $CO_{2\text{-eq}}$), followed by transport and energy supply and conversion (Table 11.4, Barker *et al.* 2007). The most recent McKinsey study on global GHG abatement potential reports total global potential for GHG reduction of

[3] Based on bottom-up, sectoral studies.

38 Gt $CO_{2\text{-eq}}$ at the cost up to 60 Euro/t $CO_{2\text{-eq}}$, which would mean reduction in GHG emissions of 55% compared to the 2030 baseline (McKinsey 2009a).[4] According to the report this would correspond to the GHG concentration of 480 ppm and keep an increase in average surface temperature just below 2ºC (McKinsey 2009a). Combining these results with the urges from the climatologists described earlier implies that even more action may be needed to avoid DAI.

Ambitious reduction targets entail additional costs. Stern estimates that the stabilization at concentration levels of 500-550 ppm of CO_{2e} (approximately 450 ppm of CO_2) would cost around 1% of the projected GDP (Stern 2007). IPCC reports that the mitigation costs to achieve the stabilization level of 445-535 ppm of CO_{2e} is less than 3% of the global GDP in 2030 (Table SPM 4, IPCC 2007). The examined stabilization level of 480 ppm CO_{2e} in McKinsey global study would entail total additional investment 810 billion EUR per year, which is approximately 1.3% of the projected 2030 global GDP (McKinsey 2009a). However, the costs of inaction and subsequent adaptation are much higher than these estimates – 5-14% of the global GDP (Stern 2007).[5] At the same time, the more the deep reductions are postponed, the more ambitious reductions would be needed within the following periods which would increase the cost of mitigation action (Meinshausen *et al.* 2009).

While deep reductions are necessary for stabilization of GHGs levels, large reductions can be achieved already today at very low costs. Buildings represent a sector with one of the largest cost-effective potential - 29% of the 2020 world's buildings' baseline emissions can be reduced cost-effectively (Levine *et al.* 2007). While the residential sector is a major contributor to the global building-related CO_2 emissions (McKinsey 2009a), the tertiary sector is an important player in mitigation effort due to its spillover effect through the building users.

[4] Which corresponds to 10% below the 1990 levels (McKinsey 2009a).
[5] Stern (2007) estimates the costs of BAU climate change to be 5-7% of the global GDP for market impacts, and 11-14% if the non-market impacts (environmental damage and loss on human lives) are included.

However, the tertiary sector (including public sector) is much less understood than the residential sector. Nevertheless, public buildings should play an exemplary role in energy efficiency (EC 2006b, 2008b, 2010) due to their potential educational and awareness raising effect among the population. Also the new recast of the Energy performance of buildings directive (EPBD; EC 2010) has even more pronounced the importance of this sector and set more ambitious goals for the public buildings than for other buildings. However, without proper information on energy use and potential for energy savings one cannot create a viable strategy on how to reach these goals. This is even more needed in the economies in transition where it is assumed that large inefficiencies exist especially in public sector. Therefore, this study will investigate the energy efficiency potential in the public sector in one of the transition economies in Central Europe. In particular, countries of the Visegrad group are of interest, as they are a rather homogenous group and the results of the analysis could be applied to all of them (provided country specific data is supplied). Hungary, one of the economies in transition and one of the countries of the Visegrad four group, was chosen for the study from a practical reason – it is probably one the only country of the V4 region where over thousand energy audits of municipal buildings was collected.[6] The next section provides an introduction to the Hungarian public sector in terms of energy consumption and CO_2 emissions.

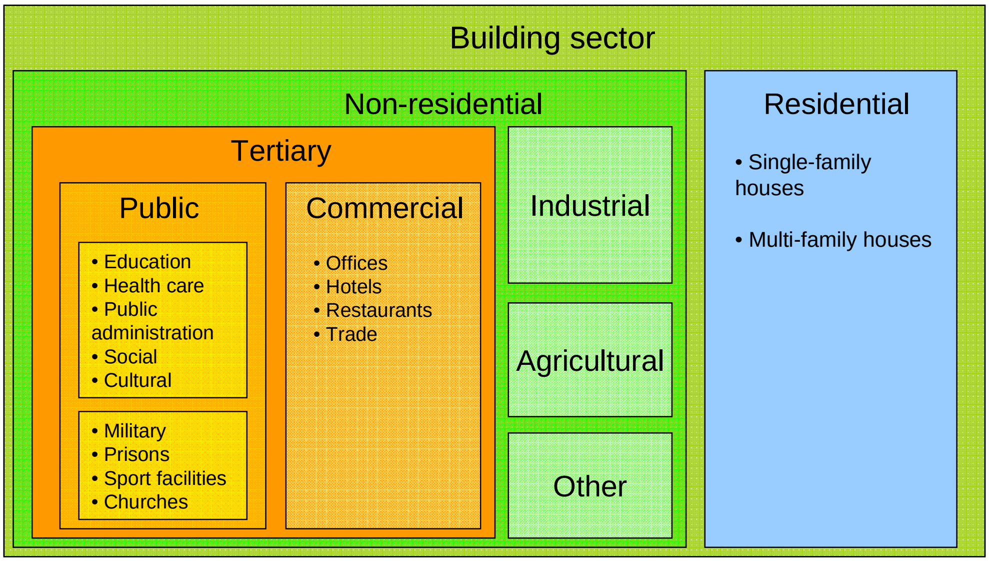
1.2 The public sector in the context of Hungarian energy consumption and CO_2 emissions

The public sector is a sector which consists of buildings that offer public services, such as education, health and social care, public administration and culture. This sector includes buildings of both national and municipal authorities, while most of the public buildings are

[6] The energy audits were collected under the UNDP/GEF project "Hungary Public Sector Energy Efficiency Project' in 2000-2007. For more, see section 4.2.

municipally owned. The public sector, together with the commercial sector, is a part of the tertiary sector (also called the service sector; in the US the tertiary sector is called the commercial sector despite the fact that it includes also public buildings). The tertiary sector falls under the category of non-residential buildings which includes tertiary, agricultural and industrial buildings. The tertiary sector is often also called the Commercial/Institutional sector (e.g. in UNFCCC statistics). The division of the building sector into its subsectors is shown in Figure 1.

Figure 1 Building sector and its subsectors



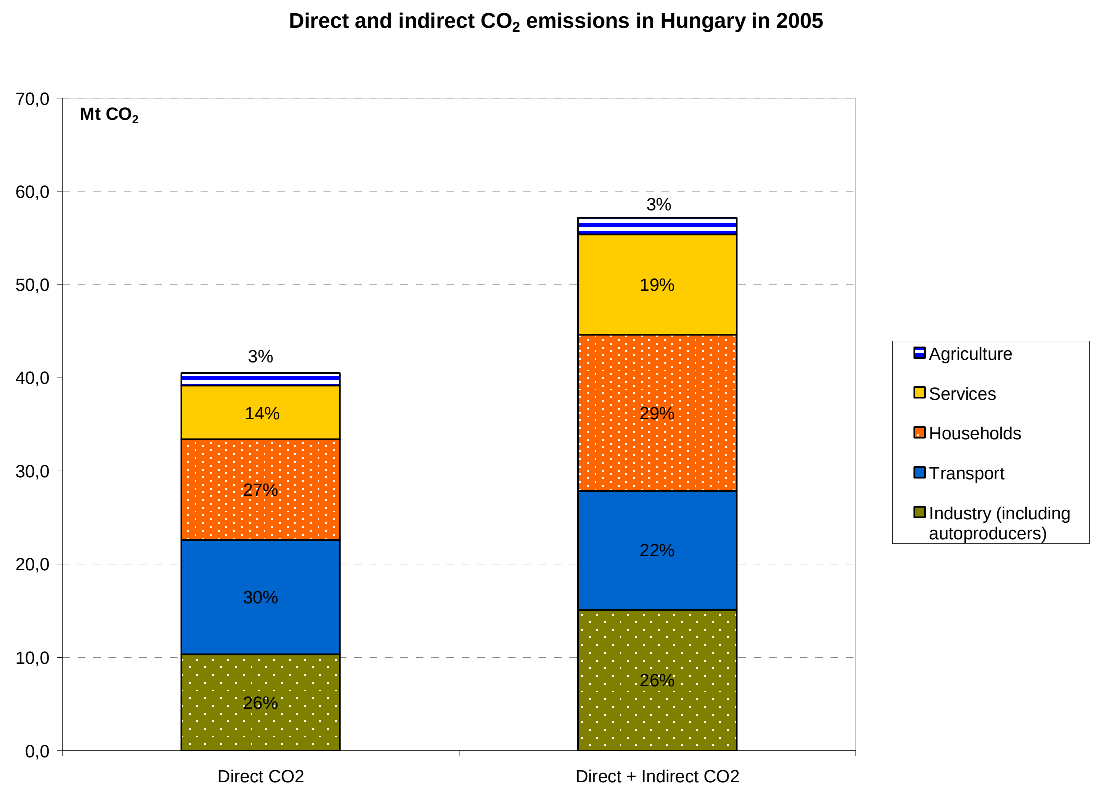
With a more than 60% share of Hungarian GDP and employment (67% share of gross value added, 65% share of employment in 2008, KSH 2009a, b)[7] the tertiary sector plays a key role in the Hungarian economy.

The public sector is usually reported in national and international statistics as part of the tertiary sector and thus, separate data on the public sector is limited. Nevertheless, the situation in the tertiary sector partly reflects the main trends in both the public and commercial sector. The Hungarian tertiary sector is responsible for 14 % of total national direct CO_2 emissions (ODYSSEE 2009), i.e. the emissions from direct combustion of fuels in

[7] Commercial services accounted for approximately 44% and public services for 23% of the Hungarian gross value added in 2008 (KSH 2009a) and for 32% and 33% on the total employment in 2008, respectively (KSH 2009b).

this sector. This shows that emissions in the tertiary sector are about half of the emissions in the residential sector (based on NIR 2009 submission v1.3). When the CO_2 emissions related to the use of district heat and electricity are included (so called indirect emissions, i.e. emissions produced in heat and power plants), the share of the tertiary sector in total emissions rises to 19% (ODYSSEE 2009, see Figure 2).

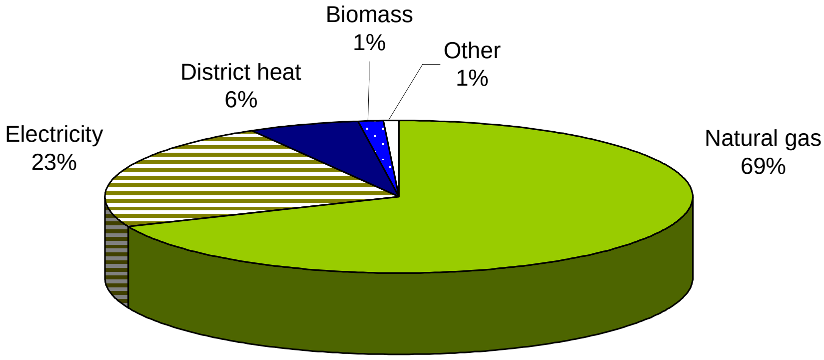
Figure 2 CO_2 emissions in Hungary by sector (2005)



Source: ODYSSEE (2009)

According to IEA (2008b) the total final energy in the Hungarian tertiary sector is approximately 155 PJ in 2005. Natural gas accounts for the majority of the total final energy consumption (almost 70%), while electricity for 23% and district heat for 6% of the final tertiary energy use (based on IEA 2008b, see Figure 3).

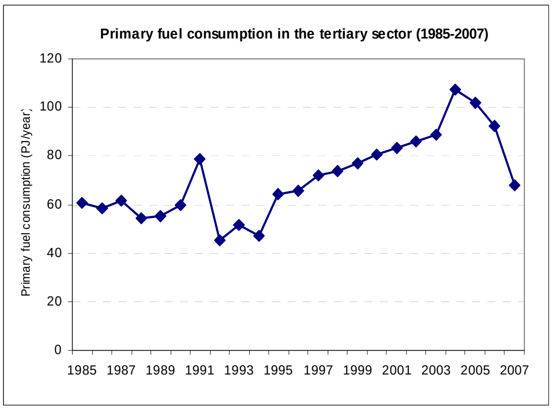
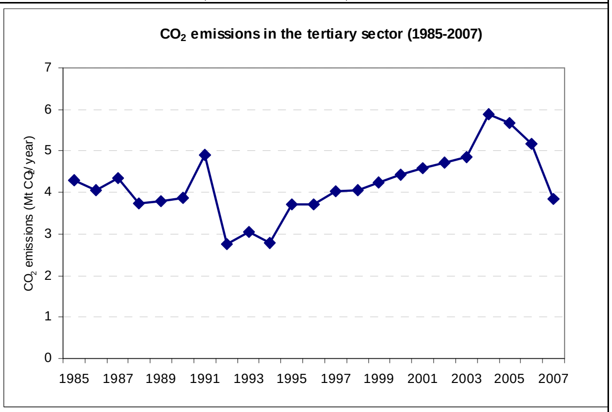
Figure 3 Energy use in the Hungarian tertiary sector in 2005 (%, TJ)



Source: IEA, 2008b. Energy Statistics of the OECD countries.

Based on NIR (2009) the total direct fuel consumption in tertiary sector has increased by 12% in the period 1985-2007. Direct CO_2 emissions follow a similar trend in this period (Figure 4).

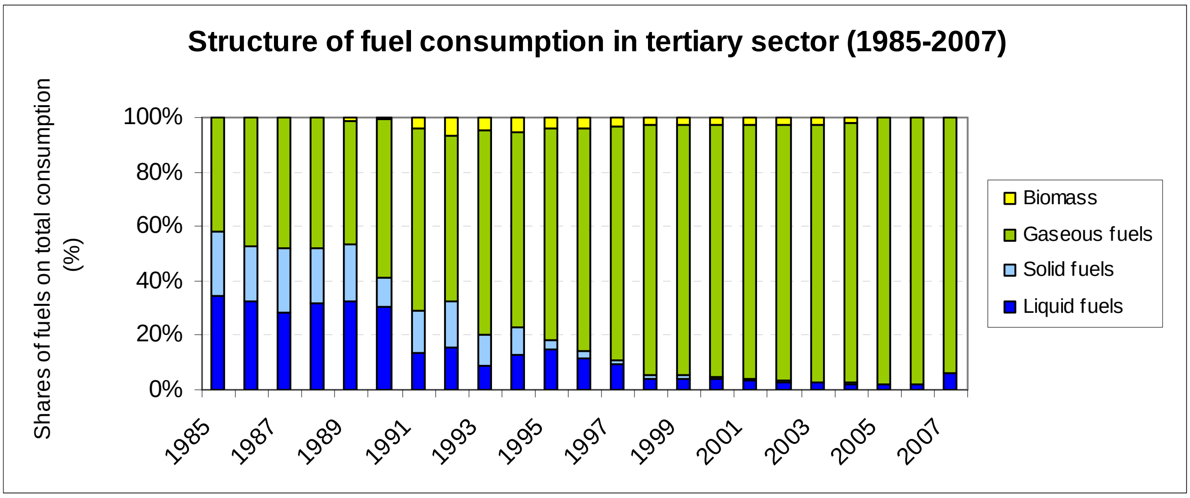
Figure 4 Primary fuel consumption and CO_2 emissions in the Hungarian tertiary sector 1985-2007

<table>
<tr><th>Primary fuel consumption (1985-2007)</th><th>CO_2 emissions (1985-2007)</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Source: NIR 1985-2007, based on NIR 2009 submission v1.3

Most of this increase is due to an increase in consumption of natural gas. Natural gas has become dominant primary energy fuel, having substituted oil and coal consumption almost completely in the last twenty years (Figure 5). In total, Hungarian tertiary sector accounted for about 5.69 Mt (direct) CO_2 emissions in 2005 (NIR 2009).

Figure 5 Fuel consumption in the Hungarian tertiary sector 1985-2007



Source: NIR 1985-2007, based on NIR 2009 submission v1.3

In general, space heating is a dominant end-use in the tertiary sector (Blok 2007). Water heating usually accounts for a small share of the total energy consumption; however, it can be significant in the health care, kindergarten and social sectors, as well as hotels. Space heating and hot water are supplied in the Hungarian tertiary buildings by natural gas, district heating and in small proportions also by electricity (e.g. by HVAC systems – heating, ventilation and air conditioning), coal, oil and firewood. This study is focused on what is currently the most significant end use in public buildings – space heating - and the main two energy sources used for the heat supply: natural gas and district heating.

1.3 Research aim, objectives and research questions

Aim: The aim of this study is to investigate the potential for mitigation of CO_2 emissions in public buildings in Hungary with a special focus on space heating.

To fulfill the research aim the following objectives shall be met and the related research questions are answered:

Objective 1: To assess scenarios of possible development of energy use and CO_2 emissions in the Hungarian public sector for space heating for low-energy future.

Research questions related to Objective 1:

1. What is the optimal path towards significant reduction of energy use in the Hungarian public buildings up to 2030 considering the best available technologies on the market?
2. What are the implications for energy use if the whole building stock is retrofitted by 2030 to a suboptimal level?
3. What is the potential lock-in effect of such suboptimal accelerated retrofit in the Hungarian public buildings sector?
4. What are the implications for energy use in the Hungarian public buildings of slow diffusion of best available technology?

Objective 2: To estimate the CO_2 mitigation potential for space heating in Hungarian public buildings through a component-based approach and to identify the least-cost abatement technologies.

Research questions related to Objective 2:

1. What are the main abatement technology options in the public sector in the area of space heating that can be applied in case of Hungary?
2. What is the estimated CO_2 mitigation potential of the individual mitigation options in the Hungarian public sector and what are the costs of these technologies?
3. What is the combined mitigation potential of the examined technologies as a function of their costs?

Objective 3: To estimate the total CO_2 mitigation potential in the Hungarian public sector related to space heating when taking a systemic, performance approach to building construction and renovation.

Research questions related to Objective 3:

1. What are the lowest possible energy performance levels that can be achieved by improving energy efficiency in Hungarian public buildings and what are their costs?
2. What is the total CO_2 mitigation potential of the Hungarian public sector when the buildings are constructed or renovated to high levels of energy performance?

Objective 4: To compare the potential computed as the sum of the individual mitigation technologies, through a component-based method and the potential calculated through performance method.

Research questions related to Objective 4:

1. What is the potential estimated through the energy performance-based approach in relation to the component-based technology approach?
2. What are the advantages and disadvantages of the performance-based and component-based approach based on the research and what are the implications for policy design?

1.4 Scope of the dissertation research

The focus of the dissertation is energy efficiency potential for space heating. The focus of the research is based on the so-called “Trias energetica” strategy, where reduction of energy demand is the priority area for any energy strategy (Lysen 1996, Joosen and Blok 2001), here applied to buildings. Only when the energy demand is reduced, renewable sources should be used to cover the majority of the remaining demand. Finnaly, the energy efficiency of the fossil-based supply technologies, which supply the rest of the demand, should be improved. In the dissertation renewable technologies are not considered and supply-side technologies outside of the building (district heating) are considered only as an exegenous input data.

The current research focuses on space heating, not on water heating. Water heating could be important from the energy efficiency point of view in some public subsectors, such as hospitals and buildings of social care. The research does not deal with losses in relation with mechanical ventilation systems, as currently only limited number of public buildings have mechanical ventilation. Both potential in water heating and ventilation in the public sector should be investigated in further research.

The dissertation focuses on the public buildings for which data on number of buildings and energy features are available. Thus, some building types (such as military buildings, prisons, churches and sport facilities) were excluded. The research focuses on public buildings due to the role this sector should play in energy conservation efforts (EC 2006b, EC 2010).

1.5 Structure of the dissertation

The dissertation consists of eight chapters. Chapter 1 provides the introduction to the environmental problem that the dissertation is addressing which leads to the aim of the research, its objectives and research questions. Chapter 2 presents the theoretical framework in which the research is nested and presents the recent studies focused on determining mitigation and energy saving potential in the building sector. Chapter 3 introduces the methodological frameworks used in the research – the so-called component-based framework and the performance-based approach. In this chapter the two approaches are described and compared and the contribution of the current work to their development is presented. The construction of the building projections and baseline energy use is described in Chapter 4.

Chapter 5 describes the individual abatement technologies and presents the results of the component-based modelling approach. Chapter 6 details the construction of the performance-based model and shows its results in comparison to the component-based approach. Chapter 7 presents a further analysis based on the performance-based approach – three scenarios showing different pathways into low-energy future, which are compared to a business-as-usual scenario. Chapter 8 brings conclusions and recommendations for policy making as well as for further research.

CHAPTER 2. CONCEPTUAL FRAMEWORK

In all fields of public policy policy makers must be well informed in order to design effective policies and measures. In the area of climate policy this is especially so, as the impacts of climate change are not easily predictable and even if they are predictable, the time frame is very large. Nevertheless, the scientific evidence presses the international community and individual countries to act now. Climate policy makers need reliable tools, which can simulate the changes in the society needed for significant GHG reduction efforts and which can estimate the costs of such actions. The knowledge of the expense to mitigate climate change would help politicians set [realistic] targets (Tol 2000) for future mitigation action. This section briefly describes the theoretical approaches behind using such decision support tools and focuses on the role of models in climate policy-making.

2.1 The basis for policy design support tools: the quest for rationality

Using support tools for policy making is based on the *rationality* approach to decision-making (Parsons 1995: 271). This approach is based on the notion of economic rationality (or rather its rejection) and bureaucratic rationality. The economic rationality is based on the notion of *Homo economicus*, i.e. the calculating self-interested individual (Parsons 1995: 272), principle on which modern economics is based. However, decision-making rarely conforms to this notion due to imperfect information leading to gaps in rationality. Thus, the decision-makers should be provided the information they need to make effective choices. The notion of bureaucratic rationality comes from sociological theories of organization and industrial society. Noteworthy are the foundations laid by Weber and Simon: Weber's notion of effective bureaucratic decision-making; and Simon's recognition of ineffectiveness of decision making in institutions, simultaneous belief of its improvement by the use of rational techniques and computers in problem-solving (Parsons 1995: 273-281). However, Lasswell rather claims that these technologies used by policy sciences should offer us ‘freedom’ (more choices), rather than rationality (limitation of choices) (Parsons 1995: 283). Others criticized optimism of rational decision-making and rational analysis as such (e.g. Lindblom, cited in Parson 1995:284-287).[8] In this section we focus on the analysis for decision-making (*ex ante* analysis), as this is most relevant to the proposed research (as opposed to *ex post* evaluation of existing policies and programmes, Parsons 1995: 399). Despite criticism, most of the policy analysis thinkers acknowledge the need for some kind of ‘rational’ analysis in decision-making.

Simon suggests that facilitating problem-solving involves substitution of a complex reality with a more simplified model, which decision-makers can use to solve the problems of attaining their goal(s) (Parsons 1995: 355). The framework for rational policy analysis can be expressed in terms of a cycle of five key stages: formulation of the problem, identification and screening of the alternatives, forecasting (predicting the future environment), modelling (building and using models to determine the impacts) and evaluation (comparing and ranking the alternatives) (Quade in Parsons 1995: 397).

2.2 Policy design support tools in the field of environment with a special focus on climate policy

Natural scientists have been conducting research focusing on natural science of climate change for the last century. But the economic, political and institutional issues have only begun to be considered since the 1990s (Nordhaus and Boyer 2000:4). Since then several tools have been developed to assess the economics of GHG mitigation. The following text describes selected tools which are assumed most relevant for assessing the options for dealing

[8] E.g. Lindlom advocates a more incremental adjustment in the policy making (Parsons, 1995: 286-287).

with climate change: cost-benefit analysis (CBA), cost-effectiveness analysis (CEA) and other decision-supporting modelling tools.

2.2.1 Cost-benefit analysis (CBA)

CBA was invented in the 19th century by Jules Dupuit but started to be used in policy contexts only in the 1930s. The basis of CBA lies in the theory of welfare economics (Edwards-Jones *et al.* 2000). In CBA the costs and benefits of different alternatives are calculated and the net benefits of different alternatives are compared. The option with the maximum net benefit [for the society] will be preferred (Parsons 1995: 400). The economists often use *social CBA* to judge whether a policy option should be adopted or not (SEG 2007). Currently, CBA is used for evaluation of planned projects and policies.[9] This can be attributed among other things to the fact that it addresses efficiency of resource allocation and a wide variety of impacts can be included and compared in the same measurement units (Hanley *et al.* 2001). Nevertheless, this is not an advantage when assigning monetary value to environmental goods as the prices and costs and utility of these goods is difficult to quantify (Parsons 1995: 402). Despite the fact that CBA has improved significantly over years, the main *limitation* of the CBA is its assumption of total substitutability of natural capital by man-made capital, which makes it still inadequate for evaluation of long-term policies affecting environmental assets (SEG 2007:64). Another weakness of CBA is that it is up to the evaluators to decide which impacts will be included and which not (Kraft and Furlong 2007). This leaves room for manipulation of the inputs in order to achieve the desired outcomes, a phenomenon known as `institutional capture` (Hanley *et al.* 2001). CBA is also

[9] For instance, CBA is currently used as the main tool for evaluation of large investment projects that apply for co-financing from the EU’s funds (ERDF, Cohesion fund etc) (EC 2008a), which can be supplemented by CEA, multi-criteria analysis or environment impact assessment for environmental projects.

criticized for discounting future benefits of e.g. environmental action to insignificant present value which leads to shifting the financial burden onto future generations.[10]

2.2.2 Cost-effectiveness analysis (CEA)

Cost-benefit analysis is not suitable as a solely decision-making support tool in cases when it is very difficult to estimate the value of the costs or benefits, e.g. in the area of human life or environment. Unlike CBA, CEA is useful in evaluation of such policies and projects where the benefits are difficult or even impossible to evaluate in monetary terms while the costs can be estimated with a higher confidence (EC 2008a). The CEA allows the decision makers to exclude options which are technically in-efficient, while other options are ranked by cost-effectiveness and their implementation will depend on the limitations of the budget (EU 2008a). The advantage of the CEA is that it requires no measurements of the value of intangible benefits [...]; it simply compares different [...] alternatives that can produce these benefits in terms of their relative costs (Kraft and Furlong 2007). This way the CEA practically by-passes the need for monetarization of the benefits of the applied measures, and thus the controversy linked to it, for which CBA is criticized (especially in fields like health care and environment). With the help of this tool, one can ask which alternative brings most benefit (e.g. CO_2 emission reduction) per monetary unit of investment.

2.2.3 Modelling tools in climate policy making

In the last twenty years several modelling groups emerged around the world to come up with tools of economics, mathematical modelling, decision theory and related disciplines (Nordhaus and Boyer 2000) in the area of climate change. One of the earliest dynamic economic models of climate change was the DICE model (a Dynamic Integrated model of

[10] "The benefits of […] slowing or halting global climate change are real and often substantial, but they occur so far in the future that discounting the benefits to today's valued tends to minimize them in a cost-benefit calculation. In contrast, the cost of […] dealing with climate change can be quite large and they will be paid for in today's dollars" (Kraft and Furlong 2007).

Climate and the Economy), introduced in 1994. It presented economics, carbon cycle, climate science and impacts in a highly aggregated model that allowed a weighting of the costs and benefits of taking steps to slow climate change (Nordhaus and Boyer 2000). Since then, modelling tools experienced many developments – the models have been adjusted to include technological progress, uncertainty in both economic development and energy demand, as well as the climate responses to increased carbon concentrations. The International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) have been the steering wheel in modelling the climate change impacts, mitigation measures and their costs (see e.g. Levine et al. 2007 and IEA 2006, 2008c). In addition, a recent report by Sir Nicolas Stern provided another momentum for further mitigation potential research. The report shows that the cost of inaction is significantly higher than the cost of mitigation measures that can be implemented today (Stern 2007).

2.2.3.1 Types of models, comparison and analysis

The modelling tools, which aim to assess the mitigation potential and the costs of mitigation efforts, can be divided into three main groups: a. top-down approaches (economy-based models with linkage to energy); b. bottom-up approaches (technology-based models); c. hybrid models (which combine the elements from the two previous approaches); d. integrated assessment models (IAM)[11].

While top-down models look at the interactions of the energy system with other parts of the economy on the basis of observed historic behavior, bottom-up models usually focus on the sector in consideration solely, but in much more detail. This allows the latter to specify the technologies as they are currently available on the market and thus are more precise on the technological characteristics of the abatement options and their costs. However, in the

[11] IAMs are complex models combining economic and biophysical systems set in long-term perspective.

bottom-up models the interactions with the other economic sectors are only assumed in terms of exogenously fed energy prices, discount rates and anticipated price changes for certain abatement technologies due to technology learning.

The main theoretical difference between these two types of models is that while the top-town models assume perfect markets (markets maintain equilibrium of supply and demand), the bottom-up models count on market imperfections and barriers and they assume that there exists room for efficiency improvement on the market. The assumption behind top-down modelling of perfect markets implies that the current state of the economy is most possibly efficient and if there were cost-efficient measure these would have already been implemented (and thus included in the baseline) and/or market barriers exist that would raise their costs (Hoogwijk *et al.* 2008). Thus, the top-down models typically result in lower mitigation potential than the bottom-up studies. However, due to barriers in the market energy consumers often do not act rationally and use more energy than under perfect conditions. Therefore the bottom-up studies usually result in large cost-effective potential, which can be realized upon removal of the barriers or provision of the necessary information to the energy users. On the other hand, the bottom-up models are criticized for their technological optimism about low-cost abatement potentials (Wing 2006). Bottom-up models are claimed to underestimate the costs, which is believed to be a result of not incorporating the responses from other economic sectors (Blesl and Remme 2005) and their usage of low discount rates[12] (Koopmans and te Velde 2001). Due to this reason, there is an "efficiency gap" between the efficiency projected by the bottom-up models and the real efficiency in the market (efficiency perceived by market agents) (Mantzos and Capros 1998). The market agents (such as consumers, companies, governments) do not always act in the most cost-efficient way as the

[12] For instance, in the bottom-up analysis in the study described by Blok *et al.* (2001) discount rate of 4% is used for all economic sectors, while in the top-down analysis, sector specific discount rates ranging from 8-17.5% were used to reflect different time preference of the actors (12% for the service sector).

bottom-up models predict – market agents maximize welfare or profit, while the models maximize energy system.[13] Such agent-based simulations can be rather represented in the TD models. This is why some BU models started to include also macroeconomic feedback (Koopmans and te Velde 2001). On the other hand, the top-down models are considered to rather overestimate the costs (Blesl and Remme 2005) due to the lack of technological specification of abatement options (Blesl and Remme 2005). That is why currently some TD models include technology details (Koopmans and te Velde 2001). A study on emission reduction opportunities in the EU-15 through both top-down and bottom-up analysis by Blok *et al.* (2001) shows the main differences: while the bottom-up analysis is more detailed in the abatement options, especially for demand-side energy efficiency, the top-down model (PRIMES) provided more details on the energy supply side (Blok *et al.* 2001). Moreover, the bottom-up analysis considered only the abatement options, whereas the top-down model considered also structural changes and the interaction between energy and economy (Blok *et al.* 2001).

Table 1 Comparison of top-down and bottom-up models

	Top-down models	Bottom-up models
Concept and term	Economic-based	Engineering-based
Period of projection	Long-term	Short- and medium-term
Treatment of technological change	Trends rates (exogenous)	Set of technical options
Motive force in the model	Responses of economic groups via income and price elasticities	Responses of agents via discount rates
Perception of the market in the model	Assumption of perfect markets (and information)	The models count with market imperfections and barriers
Abatement costs	Higher (than BU)	Lower (than TD)
Potential efficiency improvement	Usually low as TD assume that all negative cost opportunities have been utilized	Opportunities for negative cost opportunities are identified

Source: Based on IPCC (2001: 489-490) and Novikova (2008).

[13] The views on reason behind the efficiency gap differ – some claim it to market failures (limited information or mismatch between the receiver of the information on efficiency and energy end-users), others to non-market failures (uncertainty over energy price development makes it risky to invest into energy efficiency improvements) (Koopmans and te Velde 2001).

The bottom-up models are more suitable for a single sector analysis of mitigation potential at a country level in a short and medium term. This is one of the reasons why a bottom-up model was chosen for the analysis of the mitigation potential and its costs in Hungarian tertiary buildings sector. Another reason is that most of the reviewed studies have used a bottom-up modelling for mitigation analysis in the building sector (e.g. Joosen and Blok 2001; NOA 2003; Novikova 2008; McKinsey 2007a, see more in Section 2.1). In addition, top-down models require simulation of economic interplay, which is usually solved by programming-assisted modelling, and is not feasible within the current study. Despite its own modelling complexities of energy flows, the proposed bottom-up model can be performed in an Excel application and does not require programming skills.

All tools designed to aid decision making share several common challenges – the choice of discount rate, uncertainty linked to energy prices, rate of technology learning and the related cost of technologies and timing of implementation of the abatement options. All these can affect the cost-effectiveness of various options (see Section 4.1.1).

2.2.3.2 Review of models used for climate policy design in the world with a focus on the V4 countries

Among the most recognized bottom-up models are MARKAL, TIMES, MESSAGE and ERIS. TIMES is actually an update of MARKAL. ERIS includes technology learning. Well-known examples of top-down models are DICE and RICE and MACRO. In Europe the GEM-E3 and POLES models are used for assessment of mitigation potential (Clapp *et al.* 2007). Among the most widely used hybrid models are MARKAL-MACRO (and other of MARKAL extensions) and PRIMES. MARKAL-MAKRO is a bottom-up based model extended by a macroeconomic application, which enables interactions between the energy system and the rest of the economy to be reflected in the costs of the mitigation options. PRIMES is a hybrid model combining both BU and TD elements. While MARKAL-MACRO has been used world wide for (mainly) national energy and climate policy analysis, PRIMES has been used for energy policy-making in the European region. More information on these models can be found in Annex II, Table 63.

Besides TD and BU models, so-called Integrated Assessment Models have been developed and used in energy and climate policy analysis. These are very complex models combining economic and biophysical systems. An example of such a modelling tool is the MERGE model, which provides a framework for assessing climate change long-term management proposals (Kypreos 2005).

In the Visegrad region several different models have been used for the purpose of energy and climate policy. The Czech republic has been using the MARKAL model for energy projections and for identification of climate change mitigation options and the evaluation of climate change policies since the late 1990s (e.g. Tichý 1997). MARKAL was further used for emission projections in the Czech National Allocation Plan I and II (MoE and MIT 2005, 2006) and national energy policies. In addition, energy production optimization model EFOM/ENV was used for preparation of emission projections for the Third, Fourth and Fifth National Communications to the UNFCCC (MoECR 2009).

Slovakia uses MESSAGE for modelling energy balances as a basis for emission projections for the purpose of development of NAP II and the Fourth National Communication to UNFCCC together with other modelling tools (such as BALANCE and IMPACT of the ENPEP package and WASP IV[14]) (MoESR 2005, 2006).

[14] WASP (Wien Automatic System Planning) is an ELECTRIC module of the ENPEP package.

Hungary used ENPEP applications for the Third National Communication to UNFCCC (Systemexpert Consulting 2002). For the development of the NAP II were used the projections from the previous studies and where these did not exist, the projections were prepared by the Ministry of Environment and Water (based on the GDP projections for large, or investment projections of smaller installations) (MEW 2007). Since 2009 Hungary uses a comprehensive bottom-up HUMIT model, which was already utilized for preparation of the Fifth National Communication to the UNFCCC used (HCSD 2009).

Poland used different modelling tools for the Third National Communication including EFOM-PL for energy sector modelling (Polish UNFCCC Executive Bureau 2001). For the Fourth National Communication other set of modelling tools was used: bottom-up MAED model for the forecast of energy end-use, the results of which were used as an input into energy-ecological simulation model BALANCE (MoEPL 2006).

2.3 Application of bottom-up models in mitigation potential research in the building sector

This section provides a review of the state-of-art literature in the area of tertiary buildings in terms of the methodology used and outcomes and identifies the gaps in the existing literature. Finally, this chapter describes which of these gaps will be covered by the proposed study.

2.3.1 Review of bottom-up studies on mitigation potential in building sector, with special focus on public/tertiary buildings

There is an increasing number of studies aiming to quantify achieved energy savings or CO_2 mitigation potential in tertiary/public buildings. These can be classified into four types:

Studies that focus on individual tertiary buildings and present how the energy savings or CO_2 reductions were achieved.[15]

a. Studies focusing on selected subsectors of the tertiary sector (at national level).
b. Comprehensive studies covering the whole tertiary (or non-residential) sector (national level).
c. Studies where tertiary buildings are treated together with other buildings within single buildings sector (sectoral, national or cross-country studies).

Although a large number of studies exist that describe the application of abatement options in individual tertiary buildings and the achieved energy savings (e.g. Energie-Cités 2000, GreenBuilding project described by Pillen *et al.* 2007, Itard *et al.* 2008, Hegger *et al.* 2008, Richarz *et al.* 2007, Veronica 2008), and there are some which look at only a selected number of tertiary subsectors (Gaglia *et al.* 2007, Georgopoulou *et al.* 2006, NOA 2003)[16], only a small number of studies focus on the whole tertiary sector in detail, or its subsectors – the public and commercial sector. For instance, Layberry and Hinnelis (2007) focus on the whole non-residential sector.[17] This is one of the most detailed study in terms of tertiary building types classification in the literature (55 building types), which can be managed thanks to a robust computer model. Some of the studies examine the tertiary sector separately but in much less detail than the residential sector due to lack of data for the tertiary sector (e.g. Joosen and Blok 2001, Szlávik *et al.* 1999, Petersdorff *et al.* 2005). Several studies treat residential and tertiary buildings together under the single category "building sector". Reasons for this can be different, most often lack of data or robustness of the study (such robust studies

[15] The studies describing individual buildings usually report on the energy savings achieved and do not aim to estimate mitigation potential.
[16] Gaglia *et al.* (2007), Georgopoulou *et al.* (2006) and NOA (2003) cover education, health care, office buildings, hotels and other commercial buildings. Coverage of the "other commercial buildings" is not specified.
[17] Some studies, especially in the UK and German literature, treat tertiary buildings within the non-residential buildings, which include tertiary, industrial and agricultural buildings (e.g. Layberry and Hinnelis 2007). This has to be considered when the outcomes of different studies are compared.

as the world's building assessment of Levine *et al.* (2007) or global assessment of the potential of all economic sectors by McKinsey (2007)). None of the reviewed studies examine energy savings potential in the public sector in a comprehensive way.

The text below discusses different aspects of studies focusing on estimation of mitigation potential in the building sector. These include also studies focused on residential buildings where relevant. The following aspects are discussed:

- the type of model used and methodological approach
- the set of measures covered
- results in terms of estimated CO_2 mitigation/energy savings potential and its cost

- ***Type of model used and methodological approach***

The majority of the reviewed mitigation potential studies in the field of buildings use bottom-up modelling for estimation of the mitigation potential. Most of these studies use a component-based approach – the potential is estimated incrementally by assuming implementation of individual abatement technologies based on cost-effectiveness. The total potential is then calculated with help of so-called "cost curve" method, method that prevents double-counting of the potential when applying the interrelated measures (see Section 4.1). Only few studies include also abatement levers based on performance – e.g. McKinsey (2007) in terms of retrofit to the level of 70 kWh/(m^2.a) and 20 kWh/(m^2.a). Layberry and Hinnelis (2007) and Jensen *et al.* (2009) are among the first studies which use a performance-based approach in a simplified manner (for more see Chapter 6).

The reviewed studies differ in several methodological assumptions, such as choice of baseline, projection period, discount rate, assumption on technology learning etc. (see Chapter 4). While some studies compare the mitigation potential to a frozen efficiency scenario (such as Joosen and Blok 2001, Petersdorff *et al.* 2005, McKinsey 2007a, 2008), other studies use a business-as-usual scenario (such as Gaglia *et al.* 2007, Ürge-Vorsatz and Novikova 2008, Novikova 2008, McKinsey 2009a, Vatenfall 2007). The goal of the studies is mainly the estimation of the mitigation potential and identification of the most cost-effective abatement options. However, some studies have different aims - Layberry and Hinnelis (2007) investigate whether and how the target of 60% reduction in CO_2 emissions can be achieved in the UK non-residential sector by 2050 compared to baseline, while Petersdorff *et al.* (2005) examine mitigation potential of EPBD and its extended version. Different types of modelling tools are also employed in studies – for instance Novikova (2008) uses a spread sheet modelling tool where a detailed technology database is applied to a sectoral baseline for 5 types of residential buildings. Layberry and Hinnelis (2007) use an extensive computer NDCM model encompassing 55 different building types of non-domestic sector, Joosen and Blok (2001) use a detailed technology database GENESIS which is applied to their bottom-up energy model. Petersdorff *et al.* (2005) use a so-called Building Environment Analysis Model (BEAM), which projects residential and non-residential building stock for 210 basic building types in Europe.[18] Szlávik *et al.* (1999) uses a hybrid model ENPEP with specific technology information. The study on global mitigation potential of McKinsey (2009) uses the so-called Global 2.0 model, which is predominantly based on bottom-up modelling (ten sectors), though it uses top-down estimates for the remaining (three) sectors.

- ***Set of measures covered***

Most of the studies cover technologies which include high-performance building envelope components, improved efficiency of heating systems, heat controls and reduction of hot water demand for the existing buildings and low-energy and passive house standard for the new

[18] BEAM model includes 210 basic building types which consider different factors, such as architecture, size, age and thermal quality.

construction.[19] Specific measures applied to tertiary sector include: improvement of BEMS for space heating and cooling and improved cooling system (Joosen and Blok, 2001; Levine *et al.* 2007); heat recovery improvement in ventilation system, energy monitoring and control system (e.g. by energy performance contracting, as well as optimized air-conditioning system (McKinsey 2007a). In addition to improved HVAC, commissioning and cogeneration are considered in Levine *et al.* (2007) (see Table 2).

- ***Results in terms of estimated CO_2 mitigation/energy savings potential and its cost***

The resulting total technical potential differs among the studies given coverage of different energy saving measures and projection period. However, the studies report similar figures of the level of cost-effective potential. The IPCC's Fourth assessment report (Levine *et al.* 2007, described also in Ürge-Vorsatz and Novikova 2008) estimated on the basis of 80 studies focusing on residential and tertiary buildings that about 29% of the 2020 world's building-related baseline CO_2 emissions can be mitigated at negative costs. The economic potential in the transition countries[20] is estimated as up to 37%, which is higher than in industrialized countries (up to 25%) (Ürge-Vorsatz and Novikova 2008). The result of this comprehensive study is further supported by several other recent studies. For example cost-effective mitigation potential is estimated as 20% of the baseline 2020 emissions in German building sector (McKinsey 2007a). Hungarian residential buildings can achieve 29% reduction of baseline CO_2 emissions by 2025 at negative costs, while the total technical potential accounts for 51% (Novikova 2008). Lechtenböhmer *et al.* (2005) reports that the tertiary sector[21] in the EU-25 can reduce their GHG emissions by 30% by 2020 through cost-effective measures

[19] In this section only technologies relevant for space and water heating are noted, and such abatement options which may be interrelated with the space and water heating options.
[20] Under the economies in transitions the authors understand: Hungary, Russia, Poland, Croatia, Latvia, Lithuania, Estonia, Slovakia, Slovenia, Malta, Cyprus, Poland and the Czech Republic (Ürge-Vorsatz and Novikova 2008).
[21] Tertiary sector and services covers in this study public buildings, offices, shops, warehouses and agricultural premises (Lechtenböhmer *et al.* 2005).

compared to 1990 level. Vattenfall (2007) reports that world's buildings have the potential of 26% reduction of their emissions by 2030 in a cost-effective manner. The most recent global study by McKinsey (2009) shows that 21% of the 2030 baseline global building-related emissions can be reduced cost-effectively.

From the older studies it is important to mention study on mitigation potential in Hungary by Szlávik *et al.* (1999) which reports cost-effective potential of 31% by 2030 in the building sector (covering residential and communal sector). For more examples of the studies see Table 2.

The potential in the tertiary sector is usually smaller than in the residential: for instance, the technical potential in the tertiary sector is 40% of the residential sector in Greece (Georgopolou *et al.* 2006) and half of the world's residential potential reported in Vattenfall (2007).

The most cost-effective technology option in the world's building sector is efficient lighting (Levine *et al.* 2007, Ürge-Vorsatz and Novikova 2008). In the residential buildings in Hungary, the most cost-effective options are efficient lighting and heating and water demand controls (Novikova 2008). According to McKinsey (2007) the most cost-effective options relevant to tertiary sector include efficient electric equipment and lighting, followed by ventilation drive system, improvement of heat recovery in ventilation systems, energy monitoring and control systems (e.g. by energy performance contracting) and insulation in office and educational buildings to the level of 70 kWh/m^2. The most cost-effective measures in the global building sector in the study of McKinsey (2009) are efficient lighting, efficient water heating and appliances and retrofit of the building envelope in existing buildings.

The largest potential in the world's building sector in the economies in transition stems from fuel-related savings such as building envelope insulation and window exchange, which are followed by efficient lighting and appliances (Ürge-Vorsatz and Novikova 2008).

At the global level the measure with the largest potential are so-called "new building packages" which include improved design and orientation of the new buildings taking advantage of passive solar technologies, complemented by high quality mechanical ventilation and efficient water heating technology (McKinsey 2009a). The second largest potential is in retrofit at two levels (to about 54 and 35 kWh/(m^2.a) respectively) (McKinsey 2009a).

For the buildings sector (including both residential and tertiary buildings) the single option with the largest potential is a holistic upgrade of insulation and heating in residential buildings built before 1979 to the level of 70 kWh/m^2 per year (McKinsey 2007a).[22] In the residential buildings fuel switch and improvement of the building envelope offer the largest potential (Novikova 2008). Passive houses for new construction and optimized air-conditioning systems showed also a significant potential at low cost (20-100 Euro/t CO_2) (McKinsey 2007a). Joosen and Blok (2001) report that improving energy performance of existing buildings, building energy management system (BEMS) for space heating and cooling and improved cooling systems have a large reduction potential in the service sector (Joosen and Blok 2001). Table 2 provides a summary on the main outcomes of the reviewed literature.

[22] Note that the McKinsey (2007) considers renovation of residential buildings in two levels – up to the 70 kWh/(m^2.a) and up to the level of 20 kWh/(m^2.a) (close to passive house standard). This way retrofit to the passive level entails higher additional costs as if such retrofit was calculated as one measure.

Table 2 Summary of relevant reviewed mitigation studies in the building sector

Study	Sectoral coverage	Most cost-effective options	Options with the largest potential	Mitigation potential as a share of baseline (%)**	Cost-effective potential as a share of a baseline (%)
Relevant studies in individual countries					
Szlávik *et al.* (1999)	Residential and communal buildings (Hungary)	1. Individual metering of hot water; 2. water flow controllers; 3. windows retrofit	1. Building insulation; 2. window retrofit; 3. window replacement	Technical potential: 45% of the 2030 baseline.	31% of 2030 baseline.
Georgopoulou *et al.* (2006)	Tertiary buildings (Greece)***	NA	1. efficient lighting; 2. BEMS; 3. roof ventilators	Technical potential: 27% of 2010 baseline.	25% of 2010 baseline
Gaglia *et al.* (2007)	Non-residential buildings (Greece)	Not reported in terms of cost of CO_2 avoided.	1. BEMS in offices and hotels; 2. efficient lighting in offices; 3. Ceiling fans;	Examined energy saving potential in different scenarios until 2010.	NA
Layberry and Hinnelis (2007)	Non-residential buildings (UK)	Not investigated	1. improved space heating system; 2. efficient lighting; 3. efficient appliances and space cooling	Investigated whether 60% reduction in CO_2 emissions by 2050 can be achieved	NA
McKinsey (2007)	Residential and non-residential**** (Germany)	1. 1-W stand-by for electronics and office equipment; 2. Innovative detergents; 3. Efficient refrigeration for retail	1. Holistic insulation in residential buildings to level of 70 kWh/m^2; 2. Heat recovery in tertiary ventilation system; 3.efficient white goods	Technical potential: total 22% of 2020 baseline.	19% of 2020 baseline.
Novikova (2008)	Residential buildings (Hungary)	1. Efficient lighting; 2. reduction of low power mode consumption for TV and PC equipment; 3. Water saving fixtures	1. Roof insulation; 2. Wall insulation; 3. Fuel switch (biomass)	Technical potential: 50% of 2025 baseline.	29% of 2025 baseline.
EU studies					
Joosen and Blok (2001)	Residential and service sector (EU-15)	Service sector: 1. Efficient TV appliances; 2. efficient refrigerators and freezers; 3. Efficient lighting	Service sector: 1. Window retrofit; 2. wall insulation; 3. BEMS	Technical potential of service sector (no cost cap): 18% of 2010 frozen efficiency baseline.	12% of 2010 frozen efficiency baseline.
Lechten-böhmer *et al.* (2005)	All economic sectors (EU-25)	NA	1. Space heating demand reduction through low energy retrofit and new construction, optimized heating technology; 2. efficient appliances; 3. process	Technical potential of tertiary sector: 45% of 2020 baseline.	30% of 2020 baseline.

Study	Sectoral coverage	Most cost-effective options	Options with the largest potential	Mitigation potential as a share of baseline (%)**	Cost-effective potential as a share of a baseline (%)
			heat and cooking		
Petersdorff *et al.* (2005)	Residential and tertiary (New EU MSs)	1. Roof insulation; 2. wall insulation; 3. floor insulation	1. window replacement; 2. wall insulation; 3. roof insulation	Technical potential of implementing EPBD and its extensions: 18-62 Mt CO_2 by 2010	NA
Global studies					
Levine *et al.* (2007), Ürge-Vorsatz and Novikova (2008)	Residential and tertiary buildings (world, here focus on TE)	EIT*: 1. efficient lighting and controls; 2. Water and space heating controls; 3. Retrofit of building components	EIT: 1. replacement of building components; 2. efficient lighting; 3. efficient appliances	Technical potential in EIT (<100 USD/t CO_2): 26-47% of 2020 baseline. Economic potential: 13-37% of 2020 baseline.	EIT: 29% of 2020 baseline.
Vattenfall (2007)	Residential and commercial buildings (world)	Commercial sector: 1. Better insulation and improved heating/ventilation; 2. more efficient water heating; 3. efficient AC	Commercial sector: 1. Better insulation and improved heating/ventilation; 2. efficient office appliances, 3. efficient AC	Technical potential below 40 €/t CO_2 for commercial sector: 27% of 2030 baseline.	27% of 2030 baseline.
McKinsey (2009)	Residential and commercial buildings (world)	1. Efficient lighting, 2. water heating, 3. efficient residential electronics	1. Efficient new building, 2. efficient retrofit, 3. Efficient lighting	Technical potential in buildings at 60€/t CO_2: 38% of 2030 baseline.	21% of 2030 baseline.

* EIT – Economies in transition, including Hungary.
** If not noted otherwise.
*** The paper describes separately both tertiary and residential buildings.
**** They include residential, commercial, public and buildings used in agriculture.

2.3.2 Identification of the research challenges and gaps

As demonstrated by the previous section, there is a number of mitigation studies on tertiary buildings, however, these are not as numerous as residential studies and are less detailed. There are several reasons for this:

- Residential buildings constitute a larger portion of the building stock than the tertiary buildings and consequently they account for a larger share of the national energy consumption and CO_2 emissions.[23]
- Unlike residential building stock, which is relatively more uniform in terms of architecture, tertiary sector consists of numerous heterogeneous subsectors and even within these the architecture differs substantially and thus, classification of these buildings is difficult.[24]
- Data on size and quality of the building stock in tertiary sector is limited. Surveys in the tertiary sector are non-regular or incomplete, unlike surveys of residential buildings, which are usually part of regular household censuses. For instance, in the UK the NDSM survey on non-residential building stock is available only for 2004 (Layberry and Hinnells 2007), the survey on non-residential building stock and energy consumption in Germany is available only for years 2005 and 2007 (Gruber and Schlomann 2009). In Hungary surveys on public sector are available for 2000 and 2003-2007 (KSH 2000, 2003-2007). However, there is no comprehensive survey on all commercial buildings, and the data is rather limited and scattered.

In addition to incomplete building stock data, there are also other challenges hindering modelling of the tertiary sector (with focus on space heating modelling):

[23] On global scale residential buildings account for 62% of the total building sector, while the commercial and public buildings account for 38% (McKinsey 2009a).
[24] Layberry and Hinnelis (2007) constructed a model which distinguishes 55 building types of non-residential buildings in the UK. This is the most comprehensive building stock model found in the literature. However, such a detailed typology necessitates a complex and powerful modeling tool.

- Limited knowledge of the floor area and volume of the commercial buildings, their age structure and overall thermal quality,
- Limited data on energy usage of the commercial buildings and their energy consumption trends.
- In many cases, the total energy consumption for the tertiary sector reported by the official statistics is treated as a residual sector (e.g. as "Other" in the UNFCCC National Inventory Reports) which includes the differences that occur in the energy balance after accounting for the main economic sectors. In some cases, the tertiary sector is reported together with residential, or within non-residential sector together with agricultural and industrial buildings. This makes it difficult to disaggregate this group into the different subsectors, especially where the dynamics and trends in energy use and CO_2 emissions are very different from one another (e.g. public and commercial subsectors), which is especially important for calibration of the baseline.
- There is no coordinated approach in reporting this sector for international comparison. And thus, the coverage of the buildings within this sector in different studies varies depending on objective and data availability. While some studies focus on non-residential buildings (including tertiary, industrial and agricultural buildings), other focus on only selected types of buildings within tertiary sector (e.g. NOA 2003, Gaglia *et al.* 2007, Georgopoulou *et al.* 2006). This makes it difficult to compare the potentials in tertiary sector.

The main gaps in the current literature on mitigation potential in tertiary/public buildings are the following:

- There is a limited number of studies that determine mitigation potential in tertiary sector.
- The tertiary sector is often treated together with residential buildings.

- If the tertiary sector is treated separately, public and commercial buildings are often not distinguished.
- The tertiary sector is often modeled without consideration of the variety of different building types within the tertiary sector (Joosen and Blok 2001, Szlávik *et al.* 1999).
- Moreover, in several cases future development of the tertiary sector is projected based on the expectations of the value added in the service sector and its energy intensity rather than the development of the building stock (e.g. in Joosen and Blok 2001, Szlávik *et al.* 1999). This is mainly justified by lack of data. However, such modelling is uncertain due to: a. uncertainty linked to projections of GDP growth, b. Uncertainty related to decarbonization of GDP growth, especially in the economies in transition.
- The specific energy consumption is available only for a limited number of building types and countries.
- Most of the studies focusing on estimation of the mitigation potential in the tertiary buildings, and building sector in general, determine potential based on a component-based approach and do not take into account the synergic effect that occurs through holistic approach to retrofit.

Discontinuity in both the building stock and energy use reporting not only makes modelling of tertiary energy use uncertain but also disables periodic monitoring of energy use and evaluation of the applied energy efficiency measures in the sector. Fortunately, a large collection of energy audits (including both building characteristics and energy use data) exists in Hungary for the public sector. The audits were collected within a UNDP/GEF project ‘UNDP/GEF Hungary Public Sector Energy Efficiency Project‘ in 2000-2007 (further ‘UNDP/GEF audits‘). The current research distinguishes eight main public sector subsectors and specific energy use for each type is calculated based on the UNDP/GEF audits and other sets of audits (Nagy 2008 and Csoknyai 2008a). This data fills in the information gap for public buildings and can be used in other countries in the region as well.

The focus of the current research on public buildings is given by both the availability of the building statistics and energy consumption data for public buildings as well as by the limited availability of the energy use data for the commercial buildings. This way narrowing the research to public buildings contributes to a higher precision of the determination of the energy saving potential. Focus on the public sector is even more pronounced by the important role of the public sector in promoting energy efficiency among public which is highlighted in the Energy Service Directive 2006/92/EC (Article 5; EC 2006b), as well as in the Energy Performance of Buildings Directive (EPBD) 2002/91/EC (Article 5 (3); EC 2002) and its recast proposal (Article 9; EC 2008b).

Furthermore, the energy use in the public buildings is modeled through projection of energy use based on building projections of each building type using the real energy use data from UNDP/GEF energy audits. This approach eliminates the uncertainty linked to projections bound to GDP growth forecasting.

Moreover, the current study not only looks at the potential in terms of the individual abatement technologies, but also investigates mitigation potential based on energy performance of the buildings. This way the study results in potential assessed from two different perspectives. The following section describes the main features of both approaches.

In addition, the current study provides an updated and a more detailed insights into the energy savings potential for space heating in the Hungarian public building sector since the study of Szlávik *et al.* (1999). The mentioned study treats the whole communal sector as a whole without specifying the differences in terms of heating demand among the different subsectors within the sector (health care, public administration etc.).

Last but not least, the proposed research complements the study of Novikova (*Forthcoming*) which focuses on electricity savings potential in the Hungarian tertiary sector. Both studies together with the research of Novikova (2008) on residential buildings cover the majority of the building sector in Hungary (except for industrial and agricultural buildings) and contribute to informing the decision-makers on mitigation potential in the Hungarian buildings and its costs.

2.4 Two approaches in bottom-up mitigation potential research: component-based and performance-based approach

Component-based approach is widely applied approach for modelling energy savings and mitigation potential in the building sector. More recently, an alternative, performance-based approach has been used. In this section the main features, advantages and disadvantages of both approaches are described.

2.4.1 Component-based approach

The component-based studies determine energy saving potential as a sum of potentials of different building components (e.g. efficient windows and boilers, wall insulation). This approach uses the so-called ‘cost curve method’ for calculating the total combined potential of the interrelated abatement options and thus avoids double-counting. The result is a cost supply curve which shows the potential of different abatement options in terms of costs (see Figure 9 in Chapter 3).

The supply curve paradigm was adopted to characterize the potential costs and benefits of energy conservation in the early 1980s (PIER and CEC 2003, Attachment V) and since then it has been applied in numerous studies, both in the field of energy conservation and GHG mitigation (see above). Most of the reviewed studies use incremental component-based approach to estimate mitigation potential (such as Joosen and Blok 2001, Levine *et al.* 2007, McKinsey 2007a, Novikova 2008, McKinsey 2009a). This approach is widely used also due to the fact that currently most of the building codes use prescriptive values for the building components (Laustsen 2008).

Advantages

The main advantage of this method is that the mitigation potential is adjusted for the effects of overlapping options that are targeted at the same base case technologies and segments and thus, double-counting of potential is avoided (PIER and CEC 2003, Attachment V, p. ii). In addition, the supply curve allows effective presentation of the "combined results of individual measures analyses into a simple graphical format that is intuitively easy to understand", despite the fact that these studies involve a large number of different technologies and practices (PIER and CEC, 2003, Attachment V, p. ii). The advantage of the component-based approach is that it clearly identifies the most cost-effective abatement options while it separately shows those which exceed given cost threshold.

Disadvantages

One of the main weaknesses of the component-based approach is that while estimating the combined potential of the individual technologies, the component-based approach is unable to capture the synergy effect, which occurs when a building is renovated in a holistic way (Novikova *et al.* 2009). This is due to the fact that the cost curve method "rarely consider[s] buildings as integrated systems" (Levine *et al.* 2007). For instance, most of the technology-based analyses "do not account for the secondary savings from lower heating system replacement costs after existing buildings have been retrofitted with shell improvements" (Koomey 1998). Including such considerations would have increased the cost-effectiveness of the individual options and renovation of the building as a whole. This can be done through consideration of integrated building design[25], which "not only can generate savings that are greater than [those] achievable through individual measures, but can also improve cost-effectiveness" (Levine *et al.* 2007). It is doubtful that due to consideration of individual components only, the purely component-based models are capable of capturing all synergy effects, trade-offs and solutions based on integrated design for such complex systems as buildings. "Studies relying solely on component estimates may underestimate the abatement potential or overestimate the costs, compared with a systems approach to building energy efficiency" (Levine *et al.* 2007). Harvey (2006) proves that with an integrated approach, (i) the cost of saving energy can go down as the amount of energy saved goes up, and (ii) highly energy-efficient buildings can cost less than buildings built according to standard practice (cited in Levine *et al.* 2007).

Another weakness of the component-based approach, is that the building components ordered in the resulting cost curve by order of cost-effectiveness may be misunderstood by the decision- and policy-makers. Using this approach can lead to a situation when the decision-makers will implement only the cost-effective abatement options without considering more expensive, but similarly important and complementing abatement options. This can lead to suboptimal retrofit and underutilization of the available potential. Implementing only cost-effective options means that the building is retrofitted only partially and this can lead to locking the emissions (and energy used) for several next decades in until the buildings are retrofitted again, also called the "lock-in effect". In other words, if the building is not

[25] Integrated design process is defined as "a process in which all of the design variables that affect one another are considered together and resolved in an optimal fashion" (Lewis 2004 cited in Harvey 2006). Together with the most efficient equipment available, optimization of the equipment operation and commissioning, savings of 35-50% can be achieved (Harvey 2006).

renovated to the lowest possible level at once, the energy use of the building is locked-in on a sub-optimal level for several upcoming decades. This can take 30-40 years in the OECD countries (Laustsen 2008), and about 30-50 years in Hungary (Csoknyai 2009). Partial retrofit based on implementation of only the most cost-effective measures may also lead to incremental changes to the building (e.g. the external wall first is insulated and only several years later the windows are replaced), instead of a complex retrofit of all building components at the same time. However, only "simultaneous insulation of walls, exchange of windows and renovation of heating systems provide better thermal performance and less risk of fabric damages" (Zöld and Csoknyai 2007). Further, "missing one or two items from these will not result in energy saving, moreover the risk of fabric damages may become higher" (Zöld and Csoknyai 2007). McKinsey (2007) also stresses that "complete renovation of old, inefficient buildings yields greater improvement than just applying standards to individual parts of buildings".

Another weakness of the component-based approach is the selection of technical options considered in the cost curve. This can affect the extent of the total potential. Further, grouping of different abatement options may influence the cost-effectiveness of the options (Fleiter *et al.* 2009) and thus may change the order of the measures on the curve. On the other hand, if the retrofit of a building towards the level of very low energy building (VLEB) is split into several phases (e.g. McKinsey 2007a, this measure was split into 2 levels – 70 kWh/(m^2.a) and 25 kWh/(m^2.a)), the cost-effectiveness of the more ambitious level may decrease significantly.

2.4.2 Performance-based approach

The performance-based approach determines the potential in terms of the energy performance of the whole building and not of the individual components as in the case of the component-based approach. In the mitigation scenario the energy efficiency of the whole building is improved, irrespective of the potential and costs of the individual components. This approach leaves the choice of the components up to the designer provided that the required performance level is achieved. In the last decade, several countries/regions started to use performance-based requirements in their building codes (Hui 2002, Lausten 2008), including the European Union. In addition, some European countries (the UK, Netherlands, Denmark, Germany and France) have recently stipulated their long-term plans to decrease the CO_2 emissions and energy use in building sector by setting minimum requirements in terms of energy performance of a building (Thomsen *et al.* 2008, see Chapter 6). Despite these movements in the building policy towards the performance-based regulation in the time of writing there are only few studies based on this approach – Jensen *et al.* (2008), Harvey (2009), the recent work started under the Global Energy Assessment (GEA) (see Ürge-Vorsatz 2010) and Petrichenko (2010).

Advantages

The main advantage of the performance-based approach in terms of legislation is that it first gives flexibility to the designer, which promotes innovation and new techniques in energy efficiency building design (Hui 2002), and second, ensures that the total energy use of the building is not exceeded above the set boundaries. The main advantage in terms of modelling mitigation and energy saving potential is its relative simplicity compared to component-based modelling. This is because the potential of different options does not overlap and thus there is no necessity to use the cost curve method of incremental adjustment of heat demand after implementing every measure.

Disadvantages

The main disadvantage of this approach in terms of implementation of the results of the modelling into reality in the form of performance-based minimum requirements is that the model does not show the technical characteristics of the building components that should be set as obligatory in the building code. Nevertheless, these technical parameters can be calculated subsequently using building design software (e.g. BauSoft in Hungary). Thus, along with the greater flexibility, the designers gain more responsibility over the design and construction process. The performance-based approach necessitates using powerful computer-based models to optimize the utilized components in terms of performance and costs, and a deeper understanding of building principles (Lausten 2008). The trend in the world is to move towards a greater use of building energy simulation and modelling techniques to express building energy performance (Hui 2002). Thus, a higher level of skill is required from the designers and users to demonstrate the code compliance (Hui 2002). Nevertheless, the current trend in building codes is that even if the building code relies primarily on the performance-based approach, it also usually stipulates technical parameters of several building components. This provides a guideline for the designers and planners to come up with a suitable set of measures and technical systems so as to comply with the minimum performance level requirements for the building as a whole.

This approach requires all entities involved in the design and construction process to work together, which in turn needs a new way of thinking to be included in the technical university curricula and construction business processes.

2.5 Lock-in effect

One of the main problems of energy efficiency measures in buildings is that if they are not performed to the highest efficiency level, high share of the building's energy will be used for the next several decades until the building is renovated again, and the related CO_2 emissions are locked-in in the infrastructure. This phenomena, so-called "lock-in effect", occurs especially in infrastructure of long lifetimes, such as buildings and power plants. The longevity of such energy infrastructure prolongs the operation of obsolete technologies, and other impediments cause suboptimal choices to be made when technologies do finally turn over (Unruh 2002, Brown *et al.* 2007). Lock-in effect, which occurs in several countries, which do not impose strict criteria for their building renovation programmes, is linked to a path-dependency theory (David 1985 and Arthur 1989 cited in Petrichenko 2010). The theory implies that decision-makers prefer using a dominant, but not the most efficient technology even if a new and more efficient technology exists (Altman 2000, cited in Petrichenko 2010).[26] Introduction of the more efficient technologies and their uptake on the market is hindered by several market barriers and high initial costs, yet not influenced by technology learning. At the same time, the most cost-efficient energy savings occur during the replacement of the old technology, or during the renovation of the building as such (Bastian *et al.* 2009: 270). Thus, any governmental building renovation programme should provide incentives for the most efficient technologies on the market. This support should target only the initial phase of phasing-in of such a technology, so that the path-dependency is avoided in the future. High efficiency performance-based regulation and targets makes it possible to avoid this path-dependence, and supports innovation, as the designers will search for the technologies that fulfil the performance criteria at the least cost.

Up to this date only few studies aimed to quantify the lock-in effect, all of which have been conducted only recently: GEA study described in Ürge-Vorsatz (2010), Petrichenko (2010) and study of Ürge-Vorsatz *et al.* (2010). Overview of the results of these studies and comparison to the results of the dissertation research can be found in Chapter 8. Note, that these studies are performance-based energy efficiency studies focusing on scenarios. Yet, none of the studies calculates the cost-effectiveness of the different scenarios, except for the dissertation.

[26] For detailed theoretical overview of the lock-in effect and path-dependency theory, see Petrichenko (2010).

Summary

Provision of the right information is necessary for effective decision-making. In energy and climate policy making the following support tools are being used: cost-benefit analysis (CBA), cost-effectiveness analysis (CEA) and different modelling tools. These modelling tools are widely used for calculating mitigation and energy savings potential and we can distinguish top-down, bottom-up and hybrid models, as well as integrated assessment models (IAM). The main theoretical difference between the top-down and bottom-up models is that while the top-down models assume close-to-perfect efficiency of the economy, the bottom-up models assume large inefficiency on the market due to existence of numerous barriers and imperfect information of the decision makers. Another, practical, difference is that while the top-down models usually look at several sectors of the economy, and thus include the interaction of energy systems with the rest of the economy, the bottom-up models usually focus on one or few selected sectors. This is a clear advantage of the top-down models. Nevertheless, the bottom-up models, on the other hand, include more technology details than their top-down counterparts. Hybrids are models which include elements from both top-down and bottom-up models.

Most of the models and modelling tools used currently for determining energy saving and mitigation potential in the building sector are bottom-up, technology-rich models. Most of these studies rely on a component-based approach. The chapter provides an overview of the relevant mitigation studies in the building sector with special focus on tertiary buildings. The main gaps identified in the literature are: lack of detailed studies of tertiary sector, lack of data on specific energy consumption in tertiary sector and usage of an incremental, rather than holistic approach to building renovation. The current study addresses these gaps by employing the results of the UNDP/GEF energy audits and by complementing the component-based analysis by a performance-based approach to modelling energy saving potential. The main

advantages of the performance-based approach are that it provides the designers with flexibility to choose the appropriate components, which leave more space for innovation (Hui 2002), and this approach ensures that the energy consumption of the whole building given by the building regulation is not exceeded. This, however, requires utilization of powerful software, as well as tight cooperation between the designers and builders during the whole process of construction from the planning stage till commissioning. This chapter also introduces the term “lock-in effect“, the problem when suboptimal retrofit is preferred over a high-efficiency retrofit based on the principles of passive house standard technology.

CHAPTER 3. RESEARCH DESIGN AND METHODOLOGY

Chapter 3 introduces the research design, describes the sources for data collection and presents the formulas used in the process of determination of energy saving and mitigation potential and its costs.

3.1 Research design

The research is oriented around the central aim of the dissertation - to determine the energy efficiency potential in the Hungarian public buildings. The potential is examined in four scenarios and through two different types of modelling approaches: component-based and performance-based.

The scenarios aim to examine the strategies to achieve the largest potential and point out the risks that may arise when the long-term impacts of some strategies are ignored.

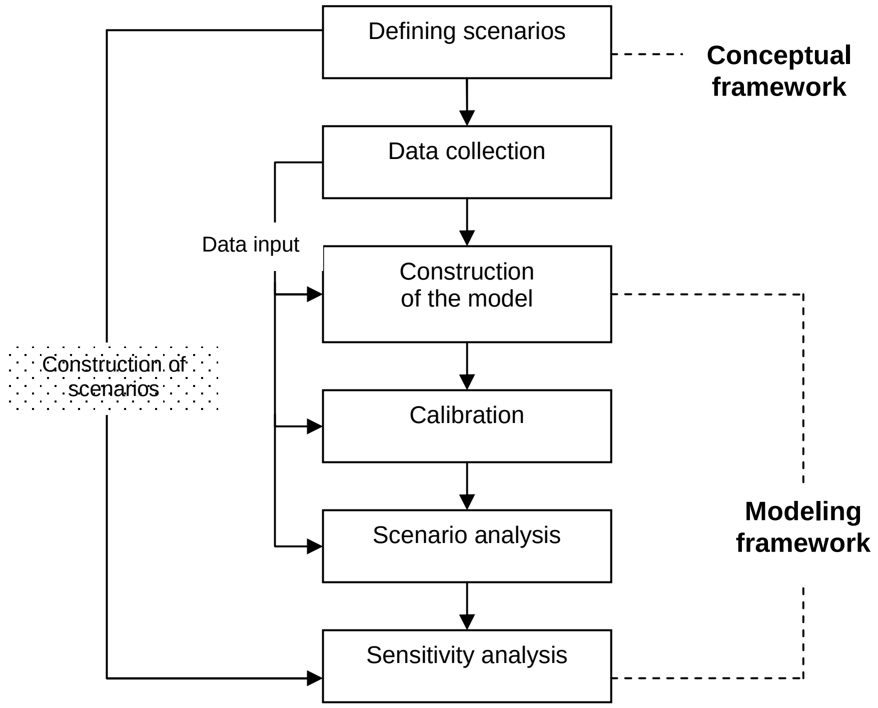
The analysis of the two modelling approaches aims to determine which methodology is more appropriate to capture the total available potential while considering such complex systems as buildings.

While the first approach determines the potential based on implementation of individual energy efficiency options, the latter investigates the potential based on the lower energy consumption of the building as a whole. The resulting potentials of the two approaches are compared.

3.1.1 Research framework

The research methodology consists of these main steps: conceptualizing scenarios for low-energy future; data collection which feeds in different parts of the modelling framework and modelling framework itself. The main parts of the modelling framework are – construction of the model, calibration, scenario analysis. Finally, the results of the model are checked in sensitivity analysis (see Figure 6). Modelling framework is described in detail in Figure 7.

Figure 6 Research methodology



3.1.1.1 Conceptualizing scenarios for low-carbon future

The aim of the scenarios is to compare four different pathways into the future and identify the best alternative in terms of the extent of potential and the cost-effectiveness.

These pathways include:

- *Business-as-usual (BAU) scenario* – simulates the current practice of slow renovation of the existing public buildings. Currently only those buildings are renovated where either one of the building systems is outdated or when the building envelope does not properly fulfill its function. The buildings are renovated mainly only partially (purely exchange of heating system, window exchange or wall insulation) depending on the most severe damage, here called “partial retrofit“. This partial retrofit results into energy savings of less than one third of the original final energy use of the building. In the BAU scenario it is assumed that gradually the buildings will be renovated to the level of the Hungarian Building code of 2006 (specified below).

- *Suboptimal accelerated scenario* – currently there are several programs that provide support for renovation of the existing buildings. However, the conditions for receiving the financial support are rather weak and thus, the building is retrofitted only partially (less than 30% energy savings). This scenario simulates a hypothetical situation when the whole existing public building stock is retrofitted to the level of partial retrofit by 2030.
- *Passive 1% scenario* – simulates a gradual change of the BAU towards a passive retrofit (70-80% energy savings). In other word, the buildings are retrofitted at current, slow pace, though, to a much more efficient standard than the current practice.
- *Passive accelerated scenario* – provides a gradual transition towards the passive retrofit at an accelerated pace. This scenario is the most ambitious and would require a long-term policy.

One of the objectives of the scenario analysis is to estimate the extent of the so-called “lock-in effect“, i.e. the opportunity to reduce final energy use lost when buildings are renovated only partially. The extent of the “lock-in effect“ is given by the difference between the most ambitious and the suboptimal scenario.

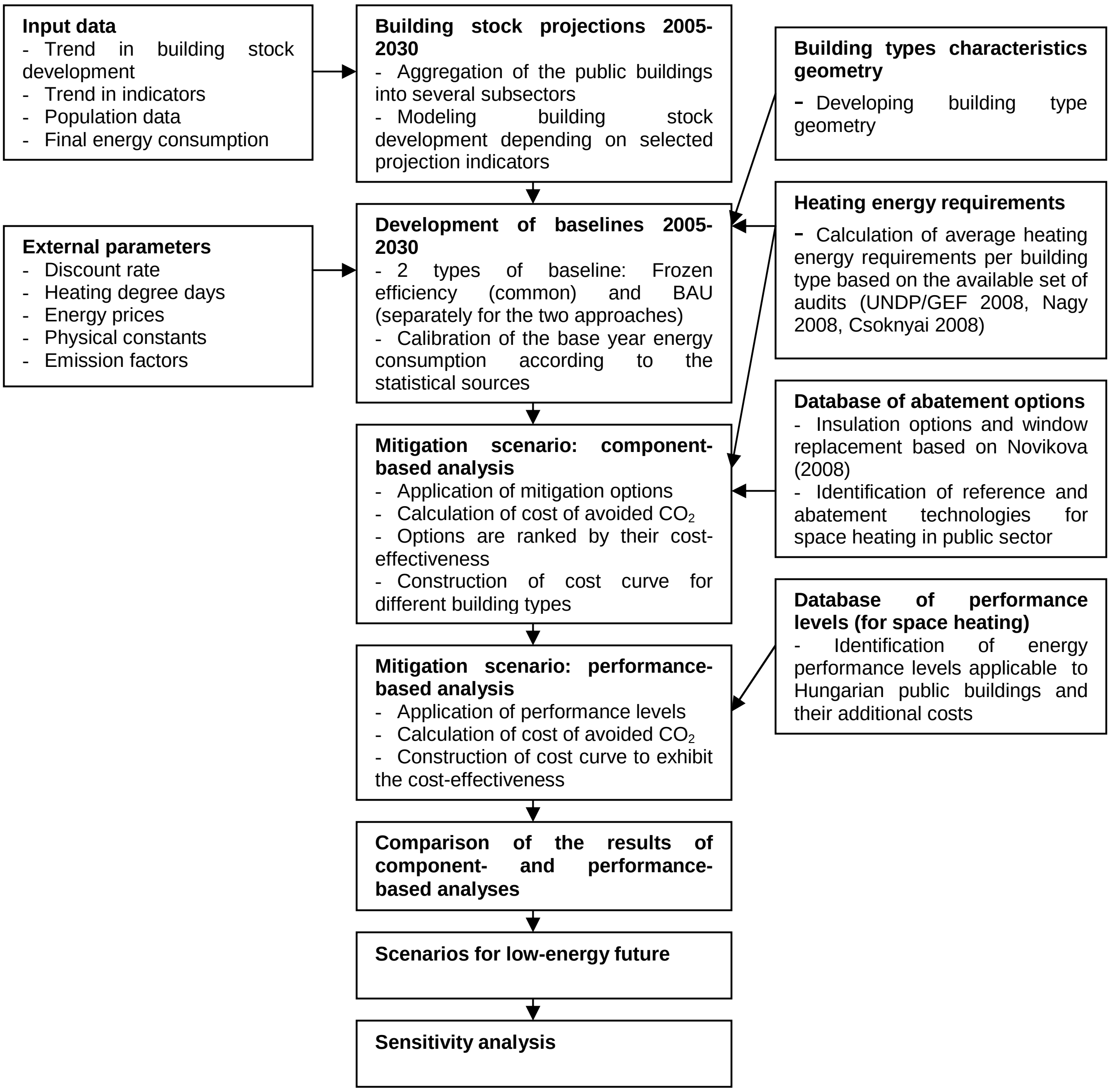
3.1.1.2 Modelling framework

The modelling framework for determination of energy saving potential in the public sector is derived from the modelling framework for the residential model developed by Novikova (2008). The residential model is a component-based model with a simple performance-based framework for new construction.[27] In the public sector model the building projections and building types are modified according to the data availability and specifics of the public sector. The heating energy requirements are based on the real data collected from the 'UNDP/GEF Hungary Public Sector Energy Efficiency Project' (further referred to as UNDP/GEF audits). The technology options concerning insulation of building shell and windows replacement are based on Novikova (2008) and the measures concerning heating system and temperature management are based on current product catalogues and expert consultations. The public sector model is focused on energy efficiency options, thus does not include measures based on renewable energy. All underlying assumptions which feed into the building stock projections, space heating modes, building types characteristics and energy consumption of these types as well as basic assumptions for the model, such as energy prices, are adjusted to the public sector. The base year is 2005.

The modelling framework is not only adjusted to the public building sector, but also extended to include an alternative approach to construct the mitigation scenario – performance-based approach. Although Novikova (2008) included simple performance-based analysis for the new construction, the performance-based model in the public model is significantly enhanced to allow a gradual phase-in of different energy performance levels, both for the new construction and retrofit of the existing buildings. The cost analysis in the performance-based model is also further developed to fully account for all investment beyond the baseline. The performance-based model is then further developed in order to conduct scenario analysis.

[27] In Novikova (2009) all new buildings are assumed to be built as passive houses from the start of the mitigation action without any transition period.

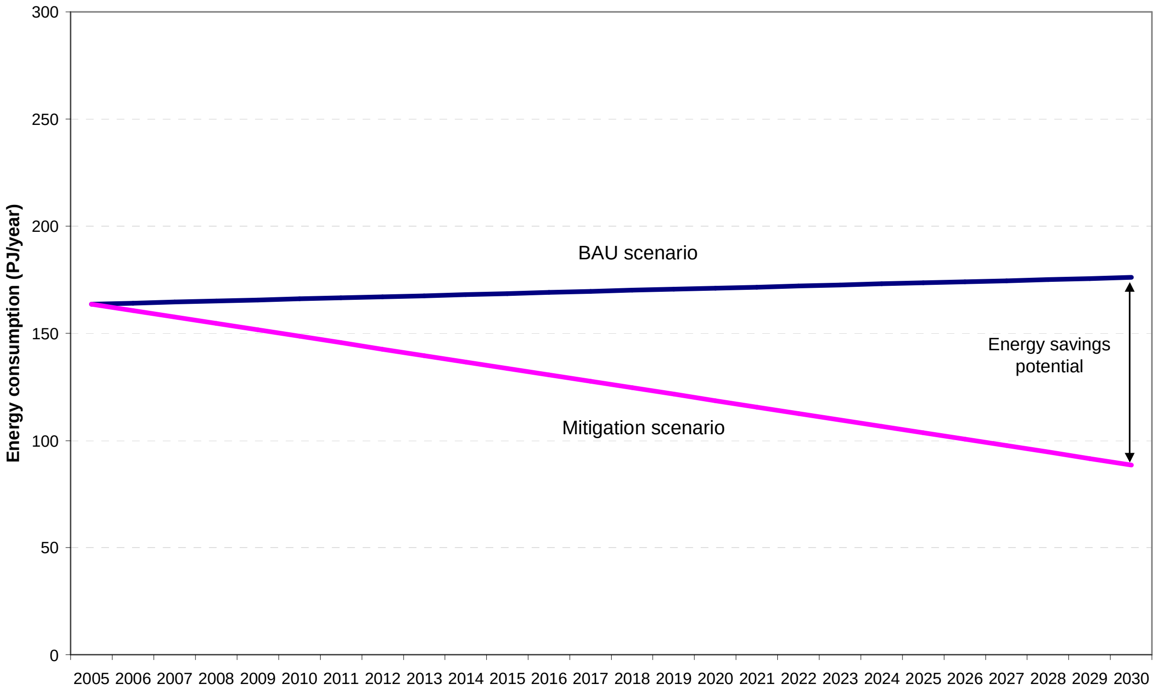
Figure 7 Modelling framework for estimating mitigation potential for space heating in Hungarian public buildings utilizing both component- and performance- based approach



The framework (Figure 7) shows the main methodological steps in the current research. First, the building types are classified and the building stock is projected. Then, heating energy requirements are calculated based on a set of energy audits (UNDP/GEF 2008, Nagy 2008 and Csoknyai 2008a) and these are subsequently fed into the projections of the baseline scenario. In the model two types of baseline scenario are constructed: i. a baseline scenario common for both modelling approaches (component- and performance-based approach) with no change to energy efficiency assumed, the so-called 'frozen efficiency scenario') and ii. business-as-usual (BAU) scenario which is constructed separately for each modelling approach. The aim of the frozen efficiency scenario is to provide an additional check for the consistency of the two modelling approaches. The frozen efficiency scenario is described in a detail in Chapter 4. The results of the mitigation scenario are compared to the BAU scenario which is based on a more realistic assumptions than the frozen efficiency scenario and plotted in a single graph. The BAU scenario incorporates the valid policies in the Hungarian public building sector in 2009.[28] BAU scenario used in the dissertation includes implementation of the requirement of the 2006 Hungarian Building code (Ministerial order No.7/2006 published in Magyar közlöny 2006) for new construction and combination of partial retrofit and retrofit to the level of 2006 Building code in the existing buildings built until 1990 at natural rate of retrofit. The base year energy consumption is calibrated to the energy data available for tertiary sector from statistical sources. The building stock, building types, building stock projections and frozen efficiency scenario, as well as the main assumptions of the modelling framework are common for both modelling approaches (component- and performance-based). Then the BAU and mitigation scenarios are constructed separately in each of the two analyses, resulting in two types of BAU and mitigation scenarios. Both mitigation scenarios are compared to the respective BAU scenarios of the relevant modelling approach. Comparison of the mitigation and BAU scenario shows the effect of implementation of mitigation measures against the expected trend represented by the BAU scenario (Figure 8).

[28] Thus, it for example does not consider the recast of the EPBD directive, which was adopted only in May 2010. Thus, this policy is part of the mitigation scenario.

Figure 8 Example of relation between the BAU and mitigation scenario and the energy savings potential



In the component-based mitigation scenario is constructed by applying abatement options from the technology database incrementally to the baseline. The combined potential of the individual options is calculated with the help of the cost curve method. For each building type, cost curves are constructed based on the cost-effectiveness of the abatement options. And finally, an aggregate cost curve for the whole public sector is constructed.

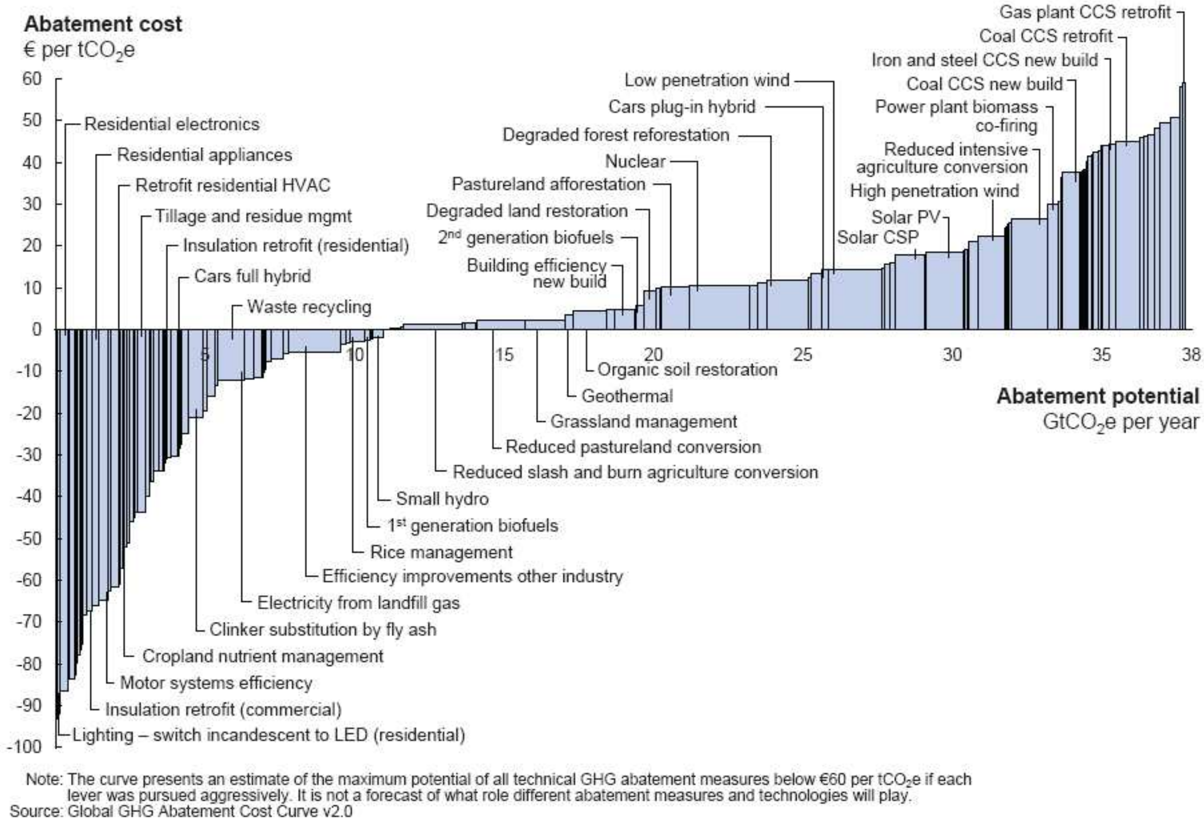
In the performance-based analysis the mitigation scenario is constructed in such a way that different energy performance levels are applied to the baseline. This analysis does not require cost curve method for accounting for the energy saving potential, nevertheless, the results of the performance-based analysis are presented in form of a cost-curve graph for each building type in order to clearly visualize the cost-effectiveness of these levels for different building types.

Then, the results of both analyses are compared and discussed. Next, the performance-based modelling framework is used to construct several mitigation scenarios. The main aim of the scenarios is to find the best pathway towards a low-carbon future as well as to point out the risk of the "lock-in effect" when implementing sub-optimal retrofit to the majority of the existing building stock. Finally, sensitivity analysis is conducted based on the most ambitious performance-based scenario (Passive accelerated scenario). In the following section the methodological background of the two approaches is described.

3.1.1.2.1 Component-based modelling framework

The component-based analysis used in this study is based on the cost curve (also called supply curve) method. This method makes it possible to account for energy saving potential of different energy efficiency technologies in such a way that the overlapping potential of interrelated technologies is avoided. This process involves a number of iterations when the baseline demand is decreased by the energy saving potential of the previous technology. The resulting combined potential of all technical options is ordered by cost-effectiveness in a so-called 'cost curve' (for an example, see Figure 9). The curve presents the energy saving or mitigation potential of each technology and its costs. The part of the curve below the horizontal axis shows the technologies which can be achieved at net negative costs (Blok 2007:212). The potential which can be achieved at zero or negative cost is called *cost-effective potential*. This means that the initial investment costs necessary for implementation of these technologies are offset by the energy costs savings achieved over the lifetime of the technologies. The shape and slope of the cost curve depends on several factors, which are discussed later in this chapter.

Figure 9 Global GHG abatement cost curve until 2030



Source: McKinsey (2009a)

Note: The supply curve depicts the different technologies, their reduction potential (horizontal axis) and their costs (vertical axis) (Blok 2007: 211) in a single diagram. Each step represents one technology.

In order to rank the options by cost-effectiveness, cost of avoiding the CO_2 emissions (EURO/t CO_2) has to be determined. This cost depends on the annualized (sometimes referred to as "levelized") additional investment costs, energy costs saving and the CO_2 emissions avoided by implementing the respective abatement option. Similarly one can calculate the cost of conserved energy (CCE; EUR/kWh or EUR/MWh). The total savings or impacts mitigated are calculated incrementally with respect to the measures that precede them (PIER and CEC, 2003, Attachment V, p. 3). This means that for those efficiency measures, which are interactive, for any measure applied after the most cost-effective one (the first in order), the energy efficiency potential decreases. And thus, in a typical energy efficiency supply curve, the sector's total end-use consumption is reduced with each unit of energy efficiency that is acquired. This means that the total end-use energy consumption is recalculated after application of each additional measure and thus, reducing the baseline energy available to be saved by the next measure (PIER and CEC, 2003, Attachment V, p. 3). This way double-counting for overlapping potentials of interrelated measures is avoided.

Besides the limitations discussed in Chapter 2, there are two further limitations of the method in terms of methodology: first, the cost curve methodology requires iterative calculations or powerful software to perform the calculations, which is barrier to small-scale users with restricted budgets. Second limitation in terms of methodology is fast development on the market with energy efficiency technologies in terms of their technical properties and costs, which is difficult to encompass by the model.

3.1.1.2.2 Performance-based modelling framework

The performance-based approach considers the energy performance of a building as a system. Instead of considering its individual building components, this approach examines the efficiency improvements of the building as a whole. And thus it can be considered as an alternative approach to the component-based modelling.

Performance-based analysis is a reaction to the growing importance of performance-based regulation, building codes in particular. Such regulation rather than prescribing minimum standards for each building component considers the performance of the building as a system.[29] Performance-based building energy code sets a maximum allowable energy consumption level (e.g. in kWh/(m^2.a)) without specification of the methods, materials, processes to be employed to achieve it and it is designer's task to present a design solution together with appropriate predictive evidence of its energy behaviour (Hui 2002). This means

[29] Performance can be understood as "objectively identifiable qualitative or quantitative characteristics of the building which help determine its aptitude to fulfill the different functions for which it was designed" (CIB 1988 in Hui 2002).

that the performance-based modelling for the purpose of estimating energy saving potential does not need to model the relationship of the U-values to the overall energy use of the building. This is left to the designer, who with the help of specialized software has to find the optimum balance between the quality of different components and their costs to meet the required energy performance.

The first attempts to include performance-based elements into energy modelling in the building sector can be traced back to simple analysis of Jensen *et al.* (2008) and Novikova (2008). [30] Both Jensen *et al.* (2008) and Novikova (2008) use a performance-based approach for modelling energy use in the new construction. While Novikova (2008) applies a single performance level in Hungary starting immediately, without a transition period, Jensen *et al.* (2008) apply different building standards in different time horizons according to the long-term commitments and plans of five EU member states[31] – thus with a transition period. This scenario is then compared to another where no transition is assumed and the committed energy performance levels are applied from 2009. Along with the current research a similar research for the global building stock has been conducted under Global Energy Assessment (GEA) based on the performance approach. The aim of the GEA research is to develop scenarios under changing rate of retrofit and energy performance level of retrofit and new construction up to 2050 (e.g. see Ürge-Vorsatz 2010). This model assumes also a transition period between the current state of the global building stock and the future high-performance energy intensity of the stock (Ürge-Vorsatz 2010). The models of Novikova (2008) for new construction, Jensen *et al.* (2008) and Ürge-Vorsatz (2010) are Excel-based models.

[30] Also Although Layberry and Hinnelis (2007) apply some kind of performance-based analysis in their non-residential model, however, it is not known how important role the performance-based approach plays in the study. Further, Harvey (2009) constructed a generic performance-based model
[31] United Kingdom, The Netherlands, Germany, France, Denmark.

Table 3 Overview of the methodological basics for the current performance-based studies in the building sector

Study	Country/ Region	Sector(s)	Transition period	Model
Novikova (2008)	Hungary	Residential	No	Excel-based
Jensen *et al.* (2008)	5 EU MSs	Residential and non-residential	2 scenarios: 1. scenario: No 2. scenario: Yes	Excel-based
Ürge-Vorsatz (2010)/GEA	World	Residential and non-residential	Yes	Excel-based

The current model uses the performance-based approach both for new construction and existing buildings in Hungary. Different levels of energy performance of buildings are applied in different time horizons in such a way that the passive house level of performance is achieved gradually. This allows a transition period for development of the passive house market in Hungary of around 10 years which is in accordance with the current capacity of the market (Szekér, personal com., 2009).

The modelling framework for the performance-based analysis developed in the current research is similar to the one used for component-based analysis except that the set of individual technology options are replaced by a set of energy performance levels and their costs. The energy performance levels are based on the current state of the development of different performance levels in Hungary and assumptions on the trend into the future.

In the baseline scenario of the current performance-based model all new buildings are assumed to be built according to the 2006 Hungarian Building code (Ministerial order No.7/2006 published in Magyar közlöny 2006).[32] The existing buildings are assumed to be retrofitted to two performance levels: partial retrofit and a higher level of 2006 Building code. Over time the higher level of performance is increasing its share on the existing building stock which is renovated every year. The mitigation scenario is based on a gradual phase-in of a

[32] This assumption for the new construction is same as in the baseline of the component-based model.

passive house standard to both new construction and existing buildings, while during the transition period implementation of performance levels of 30 and 60 kWh/(m^2.a) for space heating are assumed.

3.1.1.3 Scenario analysis

The four scenarios are constructed utilizing the performance-based modelling approach. This approach allows changing the assumptions in the scenarios without the necessity of iteration. The performance-based model allows straightforward calculation in the spreadsheet application.

The differences in the scenarios are in the extent of retrofit of the existing building stock, i.e. the rate of retrofit and the level of retrofit, i.e. the performance level to which the buildings are renovated. Other assumptions are same for all scenarios.

Each scenario shows the results in form of a cost curve graph and the different steps of the cost curve show the different building types. Each scenario is compared to the base scenario – the BAU scenario[33], which is the common basis for all scenarios. Finally, all scenarios are presented in a single combined graph.

The difference between the most ambitious scenario (Passive accelerated scenario) and the least ambitious scenario (Suboptimal scenario) provides the quantification of the "lock-in effect".

[33] Later referred to as BAU_{perf}.

3.1.1.4 Sensitivity analysis

Sensitivity analysis is performed for the main scenario of the performance-based model. The aim of the sensitivity analysis is to show the effect of selected assumptions on the final results, i.e. on the total cost-effective potential and on the order of the energy efficiency options in terms of cost-effectiveness. In the dissertation research the following assumptions are considered in the sensitivity analysis: change in energy prices and change in discount rate. It is expected, that the rise in energy prices will increase the cost-effective potential. On the other hand, increase of the discount rate should lower the cost-effective potential. Although the effects of changes in these assumptions are known in general, the sensitivity analysis will show the exact consequence of changing assumptions on the results of the analysis. Further, sensitivity of the model results to the changing retrofit rates is examined.

3.1.2 Main modelling assumptions

The main modelling assumptions in the present research are energy prices, discount rate, technology learning and timing of the implementation of the mitigation measures.

The importance of these assumptions lies in the fact that they affect the final result (either the extent of the energy saving potential and/or the cost-effectiveness of the potential). First the assumptions most relevant to the dissertation models are described and then other factors determining the extent of the cost-effective potential are discussed.

Energy prices

If the energy prices increase, the cost-effectiveness of most of the abatement options improves due to increased energy cost savings (e.g. McKinsey 2007a, Fleiter *et al.* 2009). Future energy price development is linked to a high degree of uncertainty, especially in the time of risks to the security of supply and depleting supplies of natural resources including energy fossil sources.

In the proposed research the energy prices are gathered from the relevant agencies for district heat and natural gas and are assumed to increase by 1.5% per year (based on projections in Petersdorff *et al.* 2005, Novikova 2008). The energy price includes VAT and energy tax (for detail see Chapter 4).

Discount rates

Costs and benefits occurring in different times must be discounted (EC 2008a). Discount rate expresses the view (of either society or private decision-makers) on how future benefits and costs should be valued against present ones (EC 2008a). Discount rates attract extensive discussion across analytical tools in which they are used to put costs and benefits occurring in different points in time at comparable footing (e.g. Halsnaes *et al.* 1998).[34] There are differences between how the society as a whole and the private agents perceive the value of money in time. There are two approaches how to set discount rates: a. *societal perspective* (prescriptive, ethical approach) and b. *decision-maker perspective* (descriptive approach).

Discount rates from the societal perspective takes into account the *social rate of time preference* (Halsnaes *et al.* 1998). This approach suggests using discount rate which reflects the preferences of the society as a whole to investment in the long term. This implies society's preference of the investment into sustainability, despite the fact that the benefits of such investment will occur in the long-term. Therefore the social discount rate would be lower than the discount rate from the perspective of the individual market agents. This is also because the

[34] Halsnaes et al (1998): 'The arguments of either approach are unlikely to be resolved, given that they have been going on since well before climate change was an issue.'

society as a whole faces a lower risk than individual decision makers such as companies and households (Fleiter *et al.* 2009). The social discount rate lies below the cost of capital discount rate and far below the discount rate that considers also transaction costs (Fleiter *et al.* 2009).

The discount rates from the perspective of the individual decision-maker takes into account *market rate of return to investment* (IPCC 2001: 466). The financial discount rate "reflects the opportunity cost of capital, defined as the expected return forgone by bypassing other potential investment activities for a given capital" (EC 2008a). The private agents (such as households and private companies) usually give a higher value to an investment which they can recover in a relatively short time. Therefore the private discount rate is usually higher than the social discount rate, because the decision-maker's time frame is usually much shorter (McKinsey 2009b). Thus, the ethical approach leads to low rates of discount (approx. 3% in real terms) and the descriptive, private, approach, results in higher rates (around 20% and above) (Halsnaes *et al.* 1998).

IPCC recommends that in the analysis of the mitigation effects on the national level, the decision- makers should take into consideration at least partly discount rates that reflect the opportunity cost of capital (IPCC 2001: 466). For the developed countries discount rates of about 4% - 6% are used.[35] Rates of this level are used also for appraisal of public sector projects in the EU (IPCC 2001: 466).

The studies on potential in the building sector use a wide range of discount rates (Table 4). For instance, Petersdorff *et al.* (2005) and Novikova (2008) use a discount rate of 6%, while

[35] For comparison, discount rates of 10-20% are used for developing countries (IPCC 2001:466).

Szlávik *et al.* (1999) use discount rates of 3% and 5%. Joosen and Blok (2001) use 4% discount rate for the service sector. McKinsey studies also vary by country – from Switzerland (2.5%) to USA (7%) (McKinsey 2009b and 2007c, respectively). Note, that in the later studies (for Poland and the world) McKinsey uses societal rate of 4% (in line with interest rate of a typical long-term governmental bonds) for all sectors which makes it comparable across the sectors and countries (McKinsey 2009a, 2010a). The highest discount rate used in abatement cost curves assessment is used in UK study by DEFRA and Enviros (2006) – a rate of 15% for the non-domestic sector, which is based on the private perspective. Eichhammer *et al.* (2009) examines the potential from both societal and decision-maker perspectives, applying 6% and 8% to the service sector, respectively. The societal (6%) level is characterized as a level where the cost-effectiveness can be achieved at the country level and where the barriers are largely removed by the supporting policies (Eichhammer *et al.* 2009). On the other hand, the private (8%) level is the level where the cost-effectiveness is assumed from the view of the consumer under usual market conditions and lower policy involvement (Eichhammer *et al.* 2009).

Table 4 Use of discount rates in selected studies

Study	Sector to which the discount rate applies	Country	Discount rate	Perspective applied in the model
Petersdorff *et al.* (2005)	Building sector	EU-NMS	6%	Societal perspective
Novikova (2008)	Residential buildings	Hungary	6%	Mixed societal (6% p.a.) and private (taxes) perspective.
Szlávik *et al.* (1999)	Household and service sector	Hungary	3% and 5%	Societal perspective
Joosen and Blok (2001)	Service sector	EU-15	4%	Private perspective, discount rates vary by sector.
McKinsey (2010a)	All sectors, including building sector	Poland	Approx. 4%	Societal perspective
McKinsey (2007a)	Commercial buildings	Germany	9% real DR	Private perspective, discount rates vary by sector.
McKinsey (2009b)	All sectors, including building sector	Switzerland	2.5%	Discount rate based on societal interest rate equivalent to long-term governmental bonds.

Study	Sector to which the discount rate applies	Country	Discount rate	Perspective applied in the model
McKinsey (2007c)	All sectors, including building sector	USA	7% real DR	Costs are considered from societal perspective.
DEFRA and Enviros (2006)	Non-domestic sector	UK	15%	Private perspective
McKinsey (2007b)	5 major emitting sectors including building sector	UK	7% real DR	Societal perspective
McKinsey (2009a)	All sectors	World	4% IR	Societal perspective
Eichhammer *et al.* (2009)	Service sector	EU-27	6%	Societal perspective
			8%	Private perspective

The choice of the discount rate has significant implications for the costs of the measures, especially in the sectors which are influenced by consumer behaviour, such as transport and buildings (McKinsey 2009b). The higher the discount rate the lower the cost-effective abatement potential. A higher discount rate increases the slope of the curve and thus it has a relatively low effect on the left side and a stronger effect on the right side (Fleiter *et al.* 2009). In other words, higher discount rate shifts the negative part of the cost curve upwards. And vice versa, a lower discount rate results in larger cost-effective potential and thus shifts the cost curve downwards.

As the choice of discount rates may have a significant impact on the resulting extent of cost-effective potential, the cost-effective potential is often calculated for more than one discount rate (Halsnaes *et al.* 1998). This is to provide the policy maker with guidance on how sensitive are the results on the choice of the discount rate (Halsnaes *et al.* 1998).

In line with the recent studies on potential in building sector in the CEE region (Petersdorff *et al.* 2005 and Novikova 2008), the dissertation research uses the societal perspective for consideration of costs and benefits of energy savings measures; and applies a discount rate of 6%. Application of societal perspective also implies that no taxes (nor subsidies) are included in the considered monetary calculations. Nevertheless, sensitivity analysis shows the results also from the private perspective (by application of discount rate of 8% and relevant taxes to the model).

Timing of implementation of the mitigation measures

Timing of implementation of abatement options is crucial, as usually the costs of the initial units of abatement are fairly inexpensive (so-called low-hanging fruits), while the "additional units of abatement require more extensive changes and involve significantly higher costs" (IPCC 2001: 81). Most of the model-based studies thus show rising *marginal abatement costs* (MAC), i.e. the costs are rising with the timing of their implementation (IPCC 2001: 81). However, this does not have to be so, if the abatement measures are applied at once to the considered building to the lowest possible level, e.g. to the level of a passive house standard. Harvey (2009) shows on an comparison of 32 buildings in the USA that met different levels of LEED standard[36] that the costs of a higher level retrofit (around 50% energy savings) are lower than the costs of a lower level retrofit (30% energy savings). This points out advantages of early investment utilizing the holistic approach to retrofit, when several measures that are taken in the higher level of retrofit may have synergic effects, which may reduce the costs of such retrofit. On the other hand, technology learning can decrease the cost of new technologies over time and thus help decrease the cost of mitigation in the latter phase of the projected period.

Technology learning

Technology learning means the rate of decline in price while the production of a certain product doubles. This can be both due to the experience in that specific sector (e.g. through

[36] LEED – Leadership in Energy and Environmental Design

development of the production process) or scale of the market (more providers of such service/product). Although it is often observed that the unit cost of new technologies decreases with the experience and scale effects, assessments of cost degression of demand side energy technologies are rather rare (Fleiter *et al.* 2009). Fleiter *et al.* (2009) claims that considering learning- and scale-induced cost degression is important in the cost curve analysis especially for emerging energy efficient technologies that still have a low market share and thus, there is a high potential for learning and scale effects. Nevertheless, it is important to point out that this is not only important in case of cost curve analysis, but also in any cost-effectiveness analysis which includes emerging technologies. Neij (1998, cited in Fleiter *et al.* 2009) classifies three groups of technologies with an estimate of their learning rate, according to which the buildings components (insulation, boiler, windows etc) would fall under modular technologies which can be produced by mass production and which have a learning rate of 5-30%.[37] For instance, Novikova (2008) uses technology learning assumptions for high-performance windows, passive house technology for new construction and for pellets. In the present research, the technology learning is applied to the high-performance windows in the component-based model, and for the low energy and passive house technology for both new construction and retrofit of the existing public buildings.

Other factors determining the cost-effective potential

Besides above mentioned main modelling assumptions and the related discussion, there are also other factors that may have an impact on the final results, the total cost-effective potential, order of the abatement options and/or shape of the cost curve (both in the component- and performance-based models). These factors are:

- Determination of costs – considering full or additional costs

[37] If a technology has a learning rate of e.g. 15%, this means that the price of a product decreases by 15% when the production doubles.

- Inclusion of external costs and co-benefits
- Rebound effect
- Choice of the technologies considered in the analysis

- ***Determination of costs – considering full or additional costs***

When evaluating cost-effectiveness of an abatement investment it is important to distinguish between full and additional costs (often called marginal costs). Full costs concern the full investment in technology (e.g. insulation of an external wall which was not insulated before). On the other hand the additional costs relate only to the difference between the cost of the abatement technology and a standard technology (this occurs e.g. when an old boiler is replaced by a new one – either a new standard boiler or a new condensing boiler). Consideration of these costs depends on the underlying assumptions in the model. The concept of additional costs results in considerably lower costs (Fleiter *et al.* 2009). At the same time, it also places restrictions on the diffusion of energy-efficient technologies (Fleiter *et al.* 2009). If the energy efficiency investment is regarded as an alternative investment, it can only take place within the period of general investment cycles (Fleiter *et al.* 2009), which are in case of building renovations relatively long (on average about 30-40 years in the OECD countries, Laustsen 2008; 30-50 years in Hungary, Csoknyai 2009). This would imply that if one considers accelerated diffusion of abatement technologies, the full costs have to be taken into account (and not only additional) for those retrofits which occur beyond the typical renovation cycle.

Novikova (2008) assumes full cost for those technologies which are assumed to be done above the natural rate of retrofit (1% p.a.), and additional costs for those technologies which are renovated/replaced with a more efficient alternative as compared to the standard technology on the market within the natural rate of retrofit.

One of the factors which determines the cost-effectiveness of the technology is its lifetime. Fleiter *et al*. (2009) shows on an example from industry that accounting for a lifetime three times lower "would roughly triple the annual costs and the diffusion speed of new technology". This implies that technology lifetime may bias the results of cost calculations, however, its importance is often underestimated in the literature (Fleiter *et al.* 2009).

- ***External costs and co-benefits***

External costs are costs incurred by third parties not directly involved in economic activities and they usually relate to reduced pollution as a result of applying abatement options (Fleiter *et al.* 2009). These include transaction costs such as management time to implement energy efficiency measure, costs involved in raising awareness, the costs of overcoming high discount rates and other (McKinsey 2007b). Co-benefits refer to non-energy benefits of energy savings measures such as improved comfort of living, improved indoor air quality, noise protection (Jakob 2004). Consideration of these costs and benefits depends on the perspective. If a social perspective is taken, these costs and benefits can be incorporated. Worrell *et al.* (2003, cited in Fleiter *et al.* 2009) found out that the cost-effective conservation potential in the iron and steel industry doubled due to incorporation of co-benefits. Jakob (2004) reports that the co-benefits in the residential sector may amount to the same order of magnitude as the energy-related benefits. The co-benefits are difficult to quantify and that is the reason why these are usually not considered in cost curve assessment. The effect of exclusion of co-benefits is that such cost curves overestimate the costs of energy efficiency and thus result in lower cost-effective saving potential (Fleiter *et al.* 2009).

- ***Rebound effect***

Rebound effect describes the increase in energy consumption as a direct consequence of cost savings due to energy conservation (Fleiter *et al.* 2009). Although rebound effect might have a significant impact on the results of the cost curve (ignoring it leads to overestimating the savings potential), its incorporation into the cost curve is not straightforward – this is because it relates to higher energy consumption, and thus contradicts to the concept of constant utility that lies behind the cost curve (Fleiter *et al.* 2009).

- ***Consideration of technological options***

Last but not least, the choice and definition of distinct conservation options or grouping them might influence the results of the cost curve – especially when many options are combined into one large bundle, the cost curve might be completely different (Fleiter *et al.* 2009).

The current research focuses on energy efficiency measures without considering the co-benefits, transaction costs or rebound effect. However, it is recognized that these issues are important and should be thoroughly studied in further research.

3.2 Main data sources

Each stage of the present research requires different types of data. The number of buildings and their classification and aggregation to the different building types is based on the collection of documents of the Hungarian Statistical Office (KSH 2000, 2005). Floor area is collected based on previous projects (see Ürge-Vorsatz *et al.* 2000), and set of energy audits mentioned below. The space and water heating energy requirement per floor area for each building type is calculated as an average of heating requirements of buildings audited within three sets of audits distinguished according to the building types considered in the model (UNDP/GEF audits 2008), and energy audits provided by Nagy (2008) and Csoknyai

(2008a)). The calculated average heating energy requirements are based on processing of cca. 110 audits, which were selected out of about 150 reviewed audits. This covers 129 buildings which were used for calculating the averages per building type. The non-quality audits and unrealistic data were excluded.

Technical details and costs of the abatement options in the technology database in the component-based model are based on previous research - Novikova (2008), product catalogues, literature (such as Harvey 2006, McKinsey 2007-2010) and expert consultations (Tamás Csoknyai 2009, Zoltán Kiss 2009, István Kovacsics 2009, Lászlo Szekér 2009). The energy performance levels are based on demonstration projects (e.g. Solanova, see Csoknyai 2005), literature (Veronica 2004, 2008) and assumptions on the current trends and future development of these levels are based on consultations with Tamás Csoknyai (2009), Lászlo Szekér (2009), Roland Matzig (2009) and Günter Lang (2009).

3.3 Modelling equations for space heating

In the research the following groups of equations are used: i. Equations for calculation of specific heating energy requirement for space heating from the energy audits; ii. Equations used in component-based model; ii. Equations used in the performance-based model; iii. Equations common to both component-based and performance-based model.

Average heating energy requirements for space heating per building type are calculated based on the collection of energy audits of public buildings in Hungary (UNDP/GEF 2008, Nagy (2008) and Csoknyai (2008a)). The methodology of calculating average heating energy requirements are consulted with Tamas Csoknyai (2008b).

Final energy consumption in public sector is determined based on the heating energy requirement for space and water heating (kWh/(m^2.a)) per building type, heated area (m^2) and the efficiency of space heating system. For calculation of the energy savings due to application of abatement options in the component-based model equations for determining the reduction in heat loss are used. These equations are adopted from Novikova (2008) and developed based on consultation with Tamas Csoknyai (2008b). The basis of the equations used in performance-based approach are similar to those in the baseline, only that they are extended to cover variety of building performance levels and enable implementation of several different energy performance levels at the time, with different periods of implementation. The equations for calculation of the cost of CO_2 reductions are based on Novikova (2008), modified and extended in such a way as to allow for consideration of full and additional investment.

3.3.1 Equations used for processing of energy audits

Based on the energy audits specific energy requirement was calculated for space heating, water heating and electricity.

3.3.1.1 Calculation of specific space heating energy requirement

Due to different quality of the energy audits, a methodology to calculate specific energy requirement for space heating was developed in cooperation with Tamas Csoknyai (1.1):

$$q_{sh\,i} = \frac{\overline{FE}_{SH\,i}.\eta_{sh}}{A_{h\,i}} \qquad (1.1)$$

Where:

$\overline{FE}_{SH\,i}$ – average of annual final energy consumption for space heating per building *i* for the last three years corrected by weather factor for the location of building *i* [MWh]

$q_{sh\,i}$ – specific annual space heating requirement per unit of heated floor area of building *i* [kWh/(m^2.a)]

η_{sh} – efficiency of the space heating system [%]

$A_{h\,i}$ – heated floor area in building *i* [m^2]

Then, an average specific space heating requirement $\overline{q_{sh\ j}}$ (kWh/(m^2.a)) is calculated per each building type.

3.3.1.2 Final energy consumption for space heating

Energy demand and final energy consumption for space heating per building is calculated based on the following equations (1.2) and (1.3):

$$Q_{SH\ j} = \overline{q_{sh\ j}} \,.\, A_{h\ j} \tag{1.2}$$

$$FE_{SH\ j} = \frac{Q_{SH\ j}}{\eta_{sh}} \tag{1.3}$$

Where:
$Q_{SH\ j}$ – annual energy demand for space heating per building, building type *j* [MWh]
$FE_{SH\ j}$ – final annual energy consumption for space heating per building, building type *j* [MWh]
$\overline{q_{sh\ j}}$ – average specific space heating requirement per unit of heated floor area per building type *j* [kWh/(m^2.a)]
$A_{h\ j}$ – heated floor area per building type *j* [m^2]
η_{sh} – efficiency of the space heating system [%]

Then, the final energy for space heating at the country level is calculated (1.4):

$$FE_{country\ SH\ j} = Q_{SH\ j} \,.\, N_j \tag{1.4}$$

Where:
$FE_{country\ SH\ j}$ - final energy consumption for space heating at country level per building type *j* [MWh]
N_j – number of considered buildings per building type *j*

The annual final energy consumption for space heating in the whole public sector is calculated as a sum of the annual final energy consumption in all considered building types.

3.3.1.3 Calculation of specific water heating requirement

Most of the energy audits did not report separately the final energy consumption for water heating. Thus, this was calculated separately based on the total cold water demand of the audited building and this was then distracted from the overall final consumption for (space and water) heating. Hot water consumption typically accounts for 40% of the total cold water demand per building (Tamas Csoknyai, personal com., 2009). Energy demand for hot water is calculated through the following equations (based on personal com. with Tamas Csoknyai, 2009) (1.5) and (1.6):

$$Q_{WH\,i} = V_{CW\,i}.0.4.c.\rho.(T_{HW} - T_{CW}) \tag{1.5}$$

$$q_{wh\,i} = \frac{Q_{WH\,i}}{A_{h\,i}} \tag{1.6}$$

Where:

$Q_{WH\,i}$ - energy demand for water heating of the audited building *i* [MWh]

$V_{CW\,i}$ - consumption (volume) of cold water of the audited building *i* [m^3]

c - specific heat of water $(4200\,J/kg.K)$

ρ - water density *(1000 kg/m^3)*

T_{HW} - temperature of hot water (assumed $t_{HW} = 40\,°C$)

T_{CW} - temperature of cold water (assumed $t_{CW} = 10\,°C$)

$A_{h\,i}$ – heated floor area of the audited building *i* [m^2]

$q_{wh\,i}$ - specific water heating requirement of the audited building *i* per heated floor area [kWh/(m^2.a)]

Then, an average specific water heating requirement $\overline{q_{wh\,j}}$ is calculated per each building type *j* (kWh/(m^2.a)).

3.3.1.4 Final energy consumption for water heating

Energy demand and final energy consumption for water heating is calculated similarly as in the case of space heating by using the following equations (1.7) and (1.8):

$$Q_{WH\,j} = \overline{q_{wh\,j}}.A_{h\,j} \tag{1.7}$$

$$FE_{WH\,j} = \frac{Q_{WH\,j}}{\eta_{wh}} \tag{1.8}$$

Where:
$Q_{WH\ j}$ – energy demand for water heating per building, building type *j* [MWh]
$FE_{WH\ j}$ –final energy consumption for water heating per building, building type *j* [MWh]
$\overline{q_{wh\ j}}$ – average specific water heating requirement per unit of heated floor area per building type *j* [kWh/(m^2.a)]
$A_{h\ j}$ – heated area per building type *j* [m^2]
η_{wh} – efficiency of the water heating system (assumed the same as efficiency of space heating system) [%]

Then, final energy for water heating at the country level is calculated (1.9):

$$FE_{country\ WH\ j} = Q_{WH\ j} . N_j \tag{1.9}$$

Where:
N_j – number of considered buildings of building type *j*
$FE_{country\ WH\ j}$ - final energy consumption for water heating at country level per building type *j* [MWh]
Calculation is based on Novikova (2008).

3.3.2 Equations used in the component-based model

3.3.2.1 Calculation of reduced heat loss due to implementation of thermal options

Energy savings resulting from application of thermal options are based on calculation of the reduction of heat loss through lower heat transmission and reduction of heat loss through lower air infiltration which occur in the retrofitted buildings due to the improved thermal properties of the different building elements (e.g. through insulation of external walls, basement and roof and exchange of the windows). Calculations are based on Novikova (2008).[38]

- ***Reduction of heat loss through lower transmission***

$$\Delta Q_k = \Delta U_k \cdot A_k \cdot HDH \tag{1.10}$$

$$\Delta Q_a = \sum_k \Delta Q_k \tag{1.11}$$

[38] Note, that for the purpose of the study the calculation of reduction in heat loss is simplified. The solar gains, internal gains and impact of the thermal mass are neglected in the calculations.

Where:
ΔQ_a – reduction of heat loss through heat transmission [kWh]
ΔQ_k – reduction of heat loss through building element *k* [kWh]
A_k – surface area of the building element *k* [m^2]
ΔU_k – change in the average heat transfer coefficient of the building element *k* [$W/m^2.K$]
HDH – heating degree hours [K.h]

- ***Reduction of heat loss through lower air infiltration***

$$\Delta Q_v = cp \;.\; \rho \;.\; \Delta ACH \;.\; V_j \;.\; HDH \qquad (1.12)$$

Where:
ΔQ_v – heat loss through air infiltration [kWh]

c_p – specific heat capacity of air $(c_p = 1.0\, kJ/kg \cdot K \quad at \quad 20°C)$

ρ - density of air $(1.2\, kg/m^3 \quad at \quad 20°C)$
V_j – air volume inside the building type *j* [m^3]
ΔACH – change in air change rate per hour [h^{-1}]

Reduction of heat loss is calculated for each building type. Based on this the reduction in the heating energy demand ΔQ_{SH} is calculated according to the following equation (1.13):

$$\Delta Q_{SH} = \Delta Q_a + \Delta Q_v \qquad (1.13)$$

Subsequently, the final energy savings are calculated based on equation (1.14):

$$\Delta FE_{SH} = \frac{\Delta Q_{SH}}{\eta_{sh}} \qquad (1.14)$$

3.3.3 Equations used in the performance-based model

In the performance-based model, annual energy savings potential is calculated as difference between final energy consumption in the BAU and in the mitigation scenario. Final energy consumption in each scenario is based on the final energy consumption per building multiplied by the stock of buildings. This is calculated separately for new and existing buildings and for each building type according to the following equations (1.15 – 1.21).

- **New construction:**

<u>Calculation of annual final energy consumption in BAU scenario:</u>

$$FE_{BAU,NC} = FE_{2006} \, . \, BS_{NC,total} \tag{1.15}$$

Where:
$FE_{BAU,\, NC}$ – final energy consumption in BAU scenario of new construction
FE_{2006} - final energy consumption of 2006 standard
$BS_{NC,total}$ – total building stock of new construction built per building type.

<u>Calculation of annual final energy consumption in mitigation scenario:</u>

$$FE_{mit,NC} = FE_{2006} \, . \, BS_{NC,2006} + FE_{2011} \, . \, BS_{NC,2011} + FE_{low} \, . \, BS_{NC,low} + FE_{NC,passive} \, . \, BS_{NC,passive}$$
$$+ FE_{2006} \, . \, (BS_{NC,total} - BS_{NC,2011} - BS_{NC,low} - BS_{NC,passive}) \tag{1.16}$$

Where:
$FE_{mit,NC}$ – final energy consumption in the mitigation scenario for new construction.
FE_{2011}, FE_{low}– final energy consumption of the 2011 standard, low-energy standard, respectively
$FE_{NC,passive}$ - final energy consumption of the passive house standard for new construction
FE_{2006} - final energy consumption of the 2006 standard (beyond BAU scenario, i.e. only in 2011 and 2012)
$BS_{NC,total}$ – total building stock of new construction built per building type.
$BS_{NC,2011}$, $BS_{NC,low}$, $BS_{NC,passive}$ – building stock of new construction built at the level of 2011, low-energy and passive house standard, retrospectively
BS_{2006} – building stock of new construction built at the level of the 2006 standard (beyond BAU scenario, i.e. only in 2011 and 2012)

<u>Calculation of annual final energy savings potential:</u>

$$FE_{pot,NC} = FE_{BAU,NC} - FE_{mit,NC} \tag{1.17}$$

Where:
$FE_{pot,\, NC}$ – final energy savings potential for new construction

❖ Existing buildings:

<u>Calculation of annual final energy consumption in BAU scenario:</u>

$$FE_{BAU,EX} = FE_{partial} \, . \, BS_{retro,partial} + FE_{2006} \, . \, BS_{retro,2006} + FE_{non-retro} \, . \, (BS_{retro,total} -$$
$$- BS_{retro,partial} - BS_{retro,2006}) \tag{1.18}$$

Where:
$FE_{BAU,EX}$ – final energy consumption in BAU scenario for existing buildings (built before 1990)
FE_{2006}, $FE_{partial}$ – final energy consumption of 2006 standard and partial retrofit, retrospectively
$BS_{retro,total}$ - total building stock of annually retrofitted buildings

$BS_{retro,2006}$, $BS_{retro,partial}$ – building stock of annually retrofitted buildings to the level of 2006 standard and partial retrofit, respectively

Calculation of annual final energy consumption in mitigation scenario:

$$FE_{mit,EX} = FE_{2011} \,.\, BS_{retro,2011} + FE_{low} \,.\, BSr_{retro,low} + FE_{retro,passive} \,.\, BS_{retro,passive} + \\ + \overline{FE}_{2006} \,.\, (BS_{retro,total} - BS_{retro,2011} - BS_{retro,low} - BS_{retro,passive}) \qquad (1.19)$$

Calculation of annual final energy savings potential:

$$FE_{pot,EX} = FE_{BAU,EX} - FE_{mit,EX} \qquad (1.20)$$

Where:

$FE_{pot,\,EX}$ – final energy savings potential for existing buildings built before 1990

Total energy savings potential for public buildings in Hungary

The total final energy savings potential is calculated as a sum of potentials for new construction and existing buildings (1.21):

$$FE_{pot,total} = FE_{pot,NC} + FE_{pot,EX} \qquad (1.21)$$

3.3.4 Common equations – energy savings and mitigation potential, mitigation cost

Energy savings potential is a result of implementation of energy savings measure and it is calculated as difference between final energy consumption before and after implementation of the energy savings measure (1.22):

$$\Delta FE = FE_{BAU} - FE_{MIT} \qquad (1.22)$$

The CO_2 mitigation potential of individual abatement options can be a result of implementation of energy saving technology or change of the emission factor (for district heating) due to different energy mix. This can be expressed by equation (1.23):

$$\Delta CO_{2,m,i} = \Delta EF_i \,.\, \Delta FE_{m,i} \qquad (1.23)$$

Where:

$\Delta CO_{2,m,i}$ - CO_2 savings resulting from implementation of abatement option *m* in year *i* (t CO_2);

ΔEF_i - difference between emission factor in the BAU and mitigation scenario in year *i (g CO_2/kWh)*;
$\Delta FE_{m,i}$ - final energy savings resulting from implementation of abatement technology option *m* in year *i (kWh)*;

The cost of conserved energy (CCE) is calculated based on present value of the annualized investment over the lifetime of the measure, which is divided by energy savings generated by implementation of the measure *m*. CCE considers only those annuities of the initial investment which occur in the modelling period (and the same principle is applied to the energy savings) (1.24). The equation is based on Novikova (2008), Fleiter *et al*. (2009) and Hermelink (2009).

$$CCE_{m,i} = \frac{\Delta AIC_{m,i}}{\Delta FE_{m,i}} \quad (1.24)$$

Where:
$\Delta AIC_{m,i}$ – annualized additional investment costs of technology option *m* in year *i* (Euro)

The cost of conserved CO_2 is calculated based on a difference between the present value of the annualized additional investments of technology option *m* in year *i* (compared to BAU) and present value of the energy cost savings resulting from implementation of this option, which is divided by the CO_2 savings achieved by implementing the option *m* in the same year (1.25). The equations are based on Novikova (2008) and Hermelink (2009).

$$CCO_{2,m,i} = \frac{\Delta AIC_{m,i} - \Delta EC_{m,i}}{\Delta CO_{2,m,i}} \quad (1.25)$$

Where:
$CCO_{2,m,i}$ – cost of conserved CO_2 (Euro/t CO_2)
$\Delta AIC_{m,i}$ – annualized additional investment costs of technology option *m* in year *i* (Euro)
$\Delta EC_{m,i}$ – energy costs savings resulting from implementation of option *m* in year *i* (Euro)
$\Delta CO_{2,m,i}$ - CO_2 savings resulting from implementation of option *m* in year *i* (t CO_2)

Annualized additional investment costs are calculated as a difference between the cost of the abatement technology option *m* and the cost of reference technology annualized over the lifetime of the option (1.26). They include both capital and installation costs.

$$\Delta AIC_{m,i} = a_m . AIC_{m,i} - a_{ref} . AIC_{ref,i} \quad (1.26)$$

Where:

a_m, a_{rec} – annuity factor for options *m* and reference technology calculated based on equation (1.27):

$$a_j = \frac{(1+DR)^n \ . DR}{(1+DR)^n - 1} \quad (1.27)$$

Where:

DR – discount rate

n – lifetime of the technology option

The energy cost savings are calculated as savings of final energy (kWh) achieved by implementation of the option *m* multiplied by the price of energy in year *i* (Euro/kWh) (1.28):

$$\Delta EC_{m,i} = \Delta FE_{m,i} . Price_{energy,i} \quad (1.28)$$

Where:

$\Delta FE_{m,i}$ – savings of final energy achieved by technology *m* in year *i* (kWh)

$Price_{energy,i}$ – price of energy in year *i* (Euro/kWh)

3.4 Limitations of the research

There are different types of limitations of the dissertation research – limitations related to the models in general, limitations related to bottom-up models, limitations related to component-based modelling approach, limitations related to the scope and time frame of the PhD research and limitations related to the data collection.

- *Limitations related to the models in general*

Simulation of the future is always linked to uncertainty. The model cannot simulate unexpected situations (e.g. natural catastrophes which can change the demand for energy, wars etc). This uncertainty is difficult to assess and impossible to quantify.

- *Limitations related to bottom-up models*

As mentioned above (Section 2.2.3.1) the bottom-up models do not include interaction with the rest of the economy and they rely on the behaviour of the market agents based on the cost-effectiveness. However, for the agents may be more interested in welfare or profit maximization rather than cost-effectiveness.

- *Limitations related to component-based modelling approach*

The cost assessment in the component-based approach does not consider resizing of the space heating system due to the previous demand-side efficiency measures. This is the reason why space heating systems (i.e. condensing boilers) are much less cost-effective than other efficiency measures. However, including this into the cost analysis is very time demanding due to the iterative process in the spreadsheet application and would require a programmable model. Nevertheless, this problem is avoided in the performance-based approach due to the fact that the cost analysis of the performance level already includes the resized heating system.

- *Limitations related to the scope of the research*

One of the limitations of the dissertation research is that the model does not include water heating, for which large energy efficiency potential may exist especially in hospitals and social buildings (such as homes for elderly). Nevertheless, inclusion of water heating in the model would necessitate further research as well as extension of the current modelling framework.

- *Limitations related to the data collection*

Uncertainty of the results depends by large of the quality of the input data, especially in the data-intensive bottom-up models.

The issue of data uncertainty occurs in several parts in the model:

- Although there is much more statistical detail on public buildings than commercial buildings in Hungary, the classification of the buildings into different building subcategories is often non-transparent, imprecise and contradictory. Unlike residential buildings, long-term series on number of public buildings and their average floor area is not available (floor area is based on the energy audits discussed below).

- Building stock projections depend on the projection indicators (4.1.3), which are based on extrapolation of the past trend in the demographic features to the future Hungarian population (e.g. number of kindergartners per thousand inhabitants, number of students per thousand inhabitants, number of beds in operation per ten thousand inhabitants). This extrapolation is based on the past trends in the last decade, and thus the uncertainty associated with the building stock projections is the uncertainty linked to the trends in this period.
- Some uncertainty is associated also to the processing of the energy audits (Section 4.2). Due to the differences in the quality of the audits and differences in the methodology used in the audits, as well as lack of information on certain parameters (heating degree hours, efficiency of the heating system, hot and/or water demand etc), several assumptions were made which may increase the uncertainty of the results.
- As the international as well as national energy statistics do not report energy use data separately for the public sector, and the share of the public and commercial sector on the tertiary energy use varies widely across countries, the calibration is based on the share of the public and commercial known floor area. Therefore, calibration is linked to a certain degree of uncertainty.
- Component-based studies necessitate detailed technical data on performance and cost of the technology, and there is a risk that by the time of finalization of the study, the collected data become outdated. This limitation is partly addressed by assumptions on technology learning of the premature options.
- The performance-based approach is also demanding on the costs of the considered measures. As the passive construction and retrofit are not mature technologies on the

market yet, the costs of these vary largely. The only currently available costed passive retrofit (SOLANOVA project) is about 2.3 times higher than the cost of the conventional retrofit. As it is obvious that this cost will decrease in the next decade significantly, and this issue is also addressed by a significant learning effect, based on expert estimates, it is linked to a certain degree of uncertainty.

Summary

The modelling framework of the dissertation consists of a common modelling framework, a component-based model, a performance-based model, scenario analysis and sensitivity analysis.

The common modelling framework includes typology of the public building stock, building stock projections until 2030 for the eight public building types and baseline energy projections in the same time horizon. The business-as-usual (BAU) scenario is used in the current research as a baseline. This means that the current policies (policies in place in 2009) are considered in the baseline. Any policies adopted after 2009 are not part of the baseline. The baseline energy use is constructed based on the heating requirements for the eight building types which were calculated on the basis of the energy audits of three sources – UNDP/GEF project (2008), Display campaign (Nagy 2008) and energy audits provided by Csoknyai (2008a). Mitigation scenarios are constructed separately for component- and performance-based models. The difference between the baseline energy use and energy use in the mitigation scenario is the energy saving potential achieved by application of various abatement measures. The component-based model includes individual technology options, and the total energy saving potential is calculated through cost curve method. The technologies are ordered by cost-effectiveness in the cost curve graph. The performance-based model is based on application of the different energy performance levels for the new construction and retrofit of the public buildings.

Based on the performance-based model several scenarios are constructed. The aim of the scenarios is to show the best alternative in terms of achievable cost-effective potential. This analysis aims to show which factors play an important role in achieving significant potential in reducing energy use in public buildings. And last, the sensitivity analysis will be conducted to show the importance of changes in several key assumptions on the final results.

This chapter presented the main data sources for the analysis and the equations for both modelling approaches and for calculation of the cost of CO_2 reductions, which is used as an indicator of cost-effectiveness in both approaches. The chapter concludes with summarizing the limitations of the current research, which does not aim to cover renewable energy solutions, but only measures which reduce the energy consumption for the main end-use in public buildings – the space heating.

CHAPTER 4. COMMON MODELLING FRAMEWORK

This chapter presents the main elements of the common modelling framework, i.e. the framework which is common for both modelling approaches used to determine the energy efficiency potential (component- and performance-based approach). These elements are: building typology and building stock projections, calculation of specific heating energy requirements per building type based on the energy audits and main common modelling assumptions. Further, the chapter shows the results of the construction of the frozen efficiency scenario, which is the common base scenario for both modelling approaches. The second type of baseline scenario, which is separately constructed in both approaches, is presented in the relevant chapters (Chapter 5 for component-based approach and Chapter 6 for the performance-based approach).

4.1 Building stock projections

Modelling of the building stock involves classification of the building stock, development of building stock typology and construction of the building stock projections.

4.1.1 Aggregation and categorization of the public building stock

Public building stock is very diverse. The data on the number of different public buildings was collected from different KSH sources. For the modelling purposes, this large variety of data is categorized into several subcategories based on their function (Table 5). A residual group "Other" is created from buildings which are too heterogenic and cannot be assigned to any subcategory or there is no data on these buildings and thus cannot be considered in the model. Table 5 shows the result of the aggregation process of the selected public buildings and the main categories of the building stock for year 2005.

Table 5 Aggregation of the public buildings into the main categories (2005)

Statistical classification	Number of buildings	Aggregated subcategories	Number of buildings according to aggregation
Educational buildings	13 409		
Kindergartens	4 450	Kindergartens and nurseries	4 963
Nurseries	513		
Primary schools	6 072	Primary and secondary schools	8 160
Vocational schools	523		
Secondary schools	1 001		
Buildings of basic artistic schools	164		
Special schools	250		
Special buildings of educational institutions	150		
Universities	286	Universities	286
Health care buildings	5005		
Buildings for confined to bed	841	Hospitals and buildings for confined to bed	881
Sanatoriums, hospitals and homes for terminally ill people	40		
Doctors' offices	2723	Doctor's offices and ambulance stations	2988
Ambulance stations	265		
Medical centres	1136	Medical centres	1136
Public administration buildings	5 403		
Major's and district notary offices	2 987	Small public administration buildings	4 408
Administration buildings	1 665		
Trade buildings	751	Large public administration buildings	995
Social buildings	2 735		
Multifunctional buildings providing services for old people	1 725	Social buildings	2 735
Temporary housing for old people	400		
Temporary homeless shelter	105		
Orphanages	460		
Other social buildings	45		
Cultural buildings	5 021		
Cultural centres	2 977	Cultural buildings	5 021
Libraries and stack rooms	753		
Museums	683		
Cinemas	171		
Multifunctional culture & sport establishments	211		
Other cultural buildings	226		
Other buildings	23 692		**23 692**
Learning workshops, central workshops (Educational)	285	Workhops & auxilliary office rooms	1 240
Mounting workshops (Auxiliary)	378		
Office/dressing room (Auxiliary)	577		
Repository storage (Auxiliary)	8 699	Storages, garages & other buildings	21 491
Other (Auxiliary)	6 888		
Garages (Auxiliary)	3 364		
Garage (Public administration buildings)	95		
Other buildings (Public administration buildings)	2 445		
Fire stations (Public administration buildings)	961	Fire stations	961
TOTAL PUBLIC BUILDINGS (excl. Other buildings)			**31 573**
TOTAL PUBLIC BUILDINGS (incl. Other buildings)			**55 264**

Source: KSH (2005)

The 'Other' buildings are not considered in the model. Majority of these buildings can be considered as buildings not requiring space heating, except for fire stations. Fire stations are not considered in the model due to limited data on average floor area and average specific heating energy requirement. (For fire stations only raw estimates exist, which were used for calibration of base year.)

The public buildings are classified into eight categories according to their function and/or typical size. In the educational and health care sector the buildings are divided into their categories based on the average size and function of the buildings. The public administration buildings are divided into categories based on the size of the municipality in which they are located. While small public administration buildings are assumed to be those located in the villages, large buildings are assumed to be located in the cities. The threshold for a city is municipality size of over 100,000 inhabitants (email com. with Zsuzsanna Szalay, 2008). Social and cultural buildings are considered as single categories without further division into small and large buildings based on the available data.[39] As a result of this classification, eight public building categories are considered in the public model for space heating (Table 6).

Table 6 Categories and subcategories considered in the model

#	Categories considered in the model	Subcategories considered in the model
1	Small educational buildings	Kindergartens and nurseries
2	Large educational buildings	Primary, secondary and tertiary educational buildings
3	Small health care buildings	Doctors' offices and ambulance stations
4	Large health care buildings	Hospitals, buildings for confined to bed and medical centres
5	Small public administration buildings	Administration buildings in villages
6	Large public administration buildings	Administration buildings in towns
7	Social care buildings	Social care buildings
8	Cultural buildings	Cultural buildings

[39] This is due to lack of detailed data on the size of the social and cultural buildings. To overcome this challenge, following steps for the consideration of the floor area in these buildings were undertaken. The floor area of social buildings is based on the results of the collection of energy audits where representation of large and small buildings is balanced. The floor area of the cultural buildings is a weighted average of small and large cultural buildings, where the floor area of the small buildings are based on the energy audits analysis (most of the cultural audits were of small size and located in small municipalities), while the floor area of the large buildings was based on own estimate of a size of a museum. This approach allows to take into consideration also the large areas of museums which are usually located in municipalities above 100,000 but are not represented in the energy audits.

Due to lack of data either on building stock or energy usage in some types of buildings, the following buildings are not considered in the model: military buildings and prisons; churches, public sport facilities (such as gyms, swimming pools and other, unless they are part of the educational buildings); and canteens (unless they are part of other buildings considered in the model).

Data on number of public buildings were collected from different KSH sources (publications and their online Stadat database). Table 7 provides an overview of these sources. Note that the data had to be aggregated, disaggregated and/or adjusted due to sometimes contradictory figures from different statistical sources.

Table 7 Sources for building stock data collection

Sector	Type of information	Sources
Educational buildings (incl. nurseries)	Number of buildings in 2005.	KSH. 2005. Real property of municipalities 2005.
Educational buildings (excl. nurseries)	Number of individual institutions 1990-2008.	KSH 2010e. Stadat online tables 2.6.3 (Kindergartens), 2.6.4, 2.6.5, 2.6.6, 2.6.7 (Primary and secondary schools), 2.6.9 (Universities).
Educational buildings (total)	Total number of educational buildings 2000-2008.	KSH 2010b. Stadat table online: Table 2.3.6. Real estates owned by the municipalities (2000-).
Educational buildings	Number of buildings per institution (for kindergartens, primary secondary and tertiary education)	Ürge-Vorsatz *et al*. 2000. Lighting municipally financed buildings in Hungary.
Health care buildings	Number of buildings in 2005.	KSH 2005. Real property of municipalities 2005.
	Buildings accommodating health and social services 1999-2008.	KSH 2010b. Stadat table online: Table 2.3.6 Real estates owned by municipalities (2000-).
Public administration buildings	Number of buildings in 2005.	KSH 2005. Real property of municipalities 2005.
	Buildings accommodating Trade, service, administration and hostel buildings 1999-2008.	KSH 2010b. Stadat table online: Table 2.3.6 Real estates owned by the municipalities (2000-).
Social care buildings	Number of buildings in 2005.	KSH 2005. Real property of municipalities 2005.
	Number of social buildings 2001-2008.	Disaggregated from health care and social buildings based on KSH 2010b. Stadat table online: Table 2.3.6 Real estates owned by the

Sector	Type of information	Sources
		municipalities (2000-).
Cultural buildings	Number of cultural buildings 2001-2008.	KSH 2010b. Stadat table online: Table 2.3.6 Real estates owned by the municipalities (2000-).
Other public buildings	Number of buildings in 2005.	KSH 2005. Real property of municipalities 2005.

4.1.2 Building typology of the Hungarian public building stock

The design of the buildings of public sector varies significantly and it is difficult to group them according to common building characteristics (com. with Zsuzsana Szolay, April 2008). Nevertheless, the most representative building types of the public building sector were selected for modelling purposes. The typology is based on the year of construction and architectonic style prevailing in that period. The dimensions of the building types is based on the images of the buildings from the UNDP/Energy centre (2008) audits and the average floor area which is based either on previous projects (Ürge-Vorsatz *et al*. 2000) and/or the audits of UNDP/Energy (2008), Nagy (2008), Csoknyai (2008a). These building types serve as a basis to calculate the area of glazing, roof, external wall and basement, as well as volume of the typical buildings. The graphical and tabular presentation of the typology is adopted from Novikova (2008). The difference between the typology of Novikova (2008) and the public building stock typology is that the heating energy requirement is not theoretically calculated based on the technical features of the building type, but the specific heating requirement is based on the results of the above mentioned set of energy audits to which the building type is adjusted. As a result, the following building types are considered for modelling thermal energy:

- Existing buildings built until 1990 (small and large)
- Modern buildings built between 1991 – 2005 (small and large)
- New construction – buildings built after 2005 (small and large)

Graphical representation of the building types together with details of their building structures can be found in Annex I.

Existing large buildings (built until 1990) within educational and health care sectors are further divided into the following categories representing different construction features:

- Large old traditional buildings built before 1900 and between 1901-1945
- Large panel and other industrialized buildings built between 1946-1990

4.1.3 Projections of the public building stock by building type

Several reviewed studies focusing on tertiary sector project the energy use based on the GDP growth rate and its energy intensity (e.g. Joosen and Blok 2001, Szlávik *et al*. 1999). The more recent studies use elasticity of floor area to GDP for projections of the building stock (e.g. McKinsey 2009a, described in Bressand *et al.* 2007). This is adequate for the commercial buildings which are largely influenced by GDP, but not for the public sector. Projections based on GDP forecast may bring uncertainty to the assessment if the actual GDP develops differently than expected.[40]

On the other hand, public sector must have a rather stable building stock to meet the requirements of provision of public services to the inhabitants. The building stock is thus more dependent on number of inhabitants and the extent of the services provided. As it can be seen from the statistics (KSH 2000, 2005-2010b-h), even the public building stock can experience rather deep changes in the period of transition. However, in the current research it is assumed that the transition period of the Hungarian public sector is over and that no further large single decreases in governmental property will occur (such as those which occurred in

[40] McKinsey (2010b) reports for China, that one percent increase in GDP growth rate per year would raise the emissions by 14% and one percent decline in GDP annual growth rate would decrease emissions by 11%.

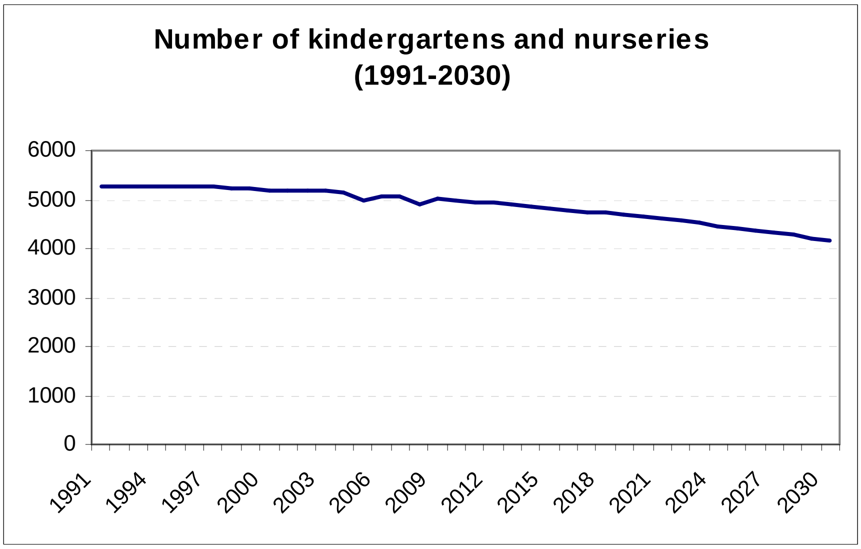
the early 2000s). Thus, assuming that the building stock is rather independent from the GDP growth, other indicators than GDP growth rate are used for public buildings projections. These vary by subsector, but are mainly based on demographic features of the subsector and include factors such as number of children in kindergarten, students in primary, secondary and tertiary education, number of beds in hospitals (see Table 8). This approach eliminates the uncertainty linked to GDP forecasting and by using different indicators for different subsectors diversifies the uncertainty of the whole public stock projections.

The indicators are collected from the online database of the Central statistical office (KSH). Most of the indicators are adjusted by population (KSH 2010g). The total public building stock slightly increases over the projected period from 31,573 buildings in 2005 to 33,410 buildings in 2030 (Figure 19 and Figure 20). This is a result of different trends within the various subsectors (described below). For example, kindergartens, primary and secondary schools are directly influenced by the negative trend in population growth and consequently declining number of enrolled pupils. On the other hand, the number of universities depends on the number of enrolled students, which has been increasing in the recent period. Trends in the different building categories are described below.

- ***Educational buildings***

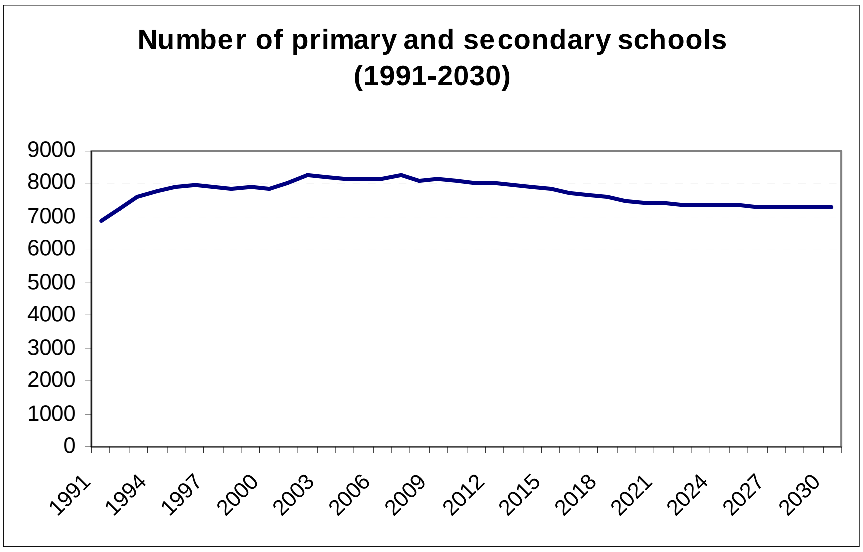
With the decreasing number of newborns, the number of children attending the kindergartens is decreasing as well. As a result of that there is lower demand for placement in the kindergartens and thus the number of kindergartens shows a decreasing trend in the past decade (by 7% since 1991, KSH 2010e). The decrease in number of kindergartens is slower than the decrease in number of kindergartners (KSH 2010e). One of the factors contributing to this decrease is thus believed to be a decrease in the number of pupils per classroom (other being economic restrictions). The decreasing trend in the number of kindergartens is expected also in the future. The number of the kindergartens is projected based on the number of kindergartners per 1000 inhabitants and floor area per kindergartner. As a result the number of kindergartens and nurseries is likely to decrease in the future (Figure 10).

Figure 10 Trend and projection of kindergartens and nurseries



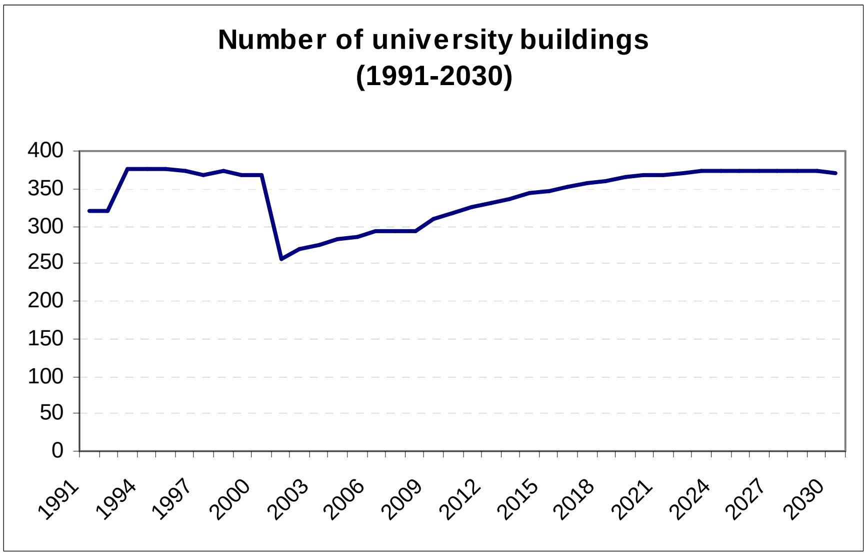
The situation in primary and secondary schools is a bit different. Although the number of students in primary and secondary education decreased (by 16% between 1991 and 2008), the number of primary and secondary institutions actually increased by 18% in the same period (KSH 2010e). This can be explained by changes in the statistical method, and split of the school entities, or change in the average number of buildings per institution (e.g. split of one institution into two separate units – primary school and secondary school) and also smaller number of students in the classroom. However, despite this gap, such increase in the number of buildings is unlikely to continue and it is assumed that the number of buildings will react to the decline in the number of students. Thus, the projections are based on number of students in the primary and secondary schools per 1000 inhabitants and floor area per student per 1000 inhabitants. Based on quadratic regression, the number of students per 1000 inhabitants will further decrease, but this decrease is slowed down by increase in floor area per student. The resulting projected building stock is thus projected to decrease only slightly (Figure 11).

Figure 11 Trend and projection of primary and secondary schools



Although the number of universities has decreased by 8% in 1991-2008 (KSH 2010e), the number of the full-time students at university has increased more than three times in the same period. Based on the quadratic regression, the number of students at universities will increase further in the future. The higher number of students will necessitate new buildings, and thus building stock of the universities is expected to increase (Figure 12).

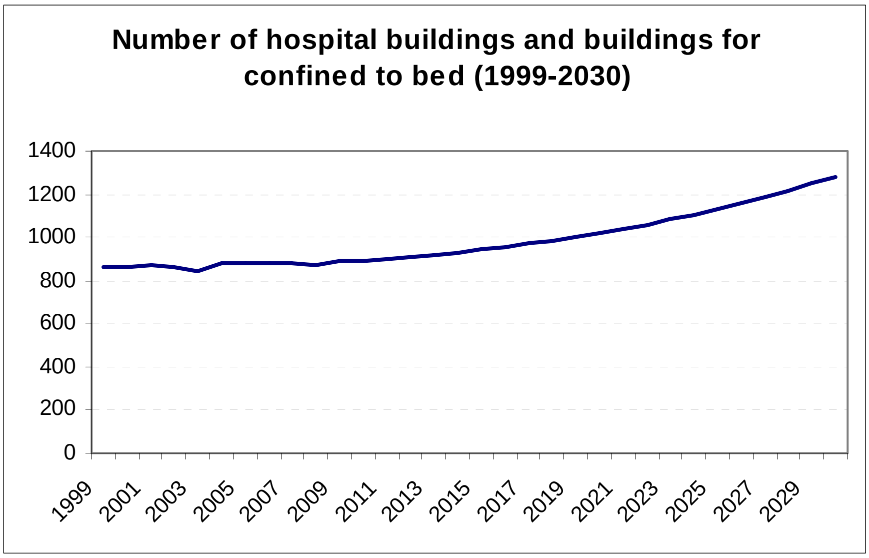
Figure 12 Trend and projections for university buildings



- ***Health care buildings***

Number of hospitals and buildings for bed-ridden patients are projected based on number of active beds per ten thousand inhabitants. The number of beds has been decreasing since 1999. However, this trend is likely to be a part of the restructuring process of the health care system when several regional hospitals have been closed down as well as when the stay of the patients in the hospitals is shortened. Based on quadratic regression, this trend will continue until it will stabilize and then start increasing again (see Figure 13).

Figure 13 Trend and projections for hospital buildings



The number of medical centres and doctors‘ offices is projected on the trend of number of the active practitioners per ten thousand inhabitants and trend of number of general practitioners (GPs) and family paediatricians per ten thousand inhabitants, respectively (Figure 14 and Figure 15). As both of these indicators show increasing tendency in the period 1999-2008, a similar trend is assumed to occur in the future.

Figure 14 Trend and projections for doctor's offices and ambulant stations

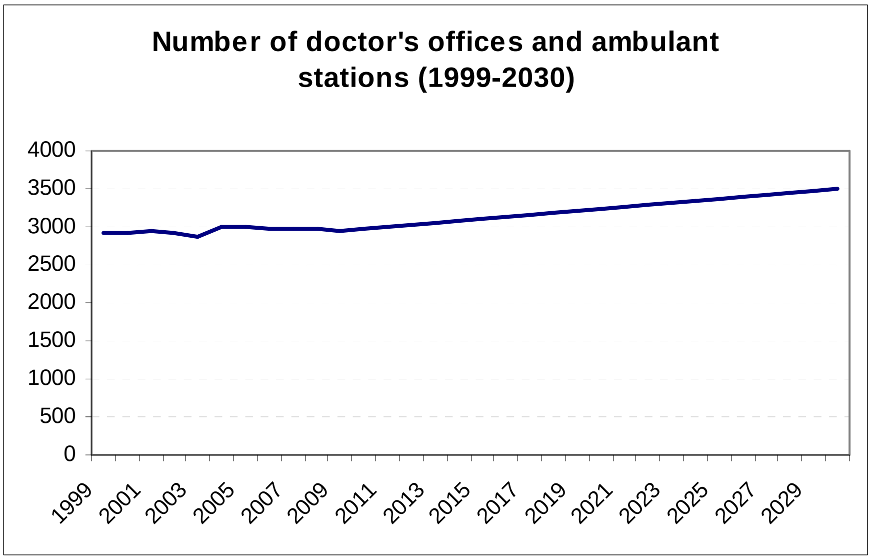
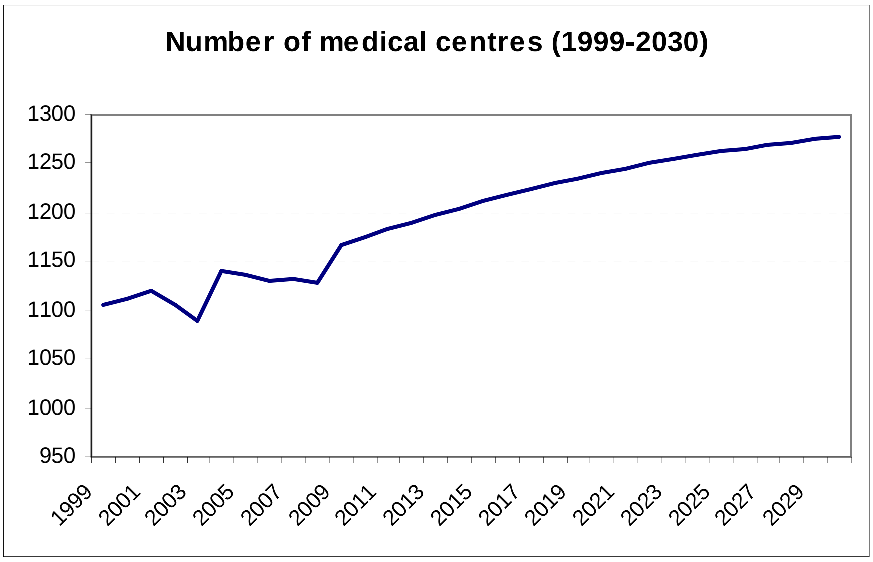


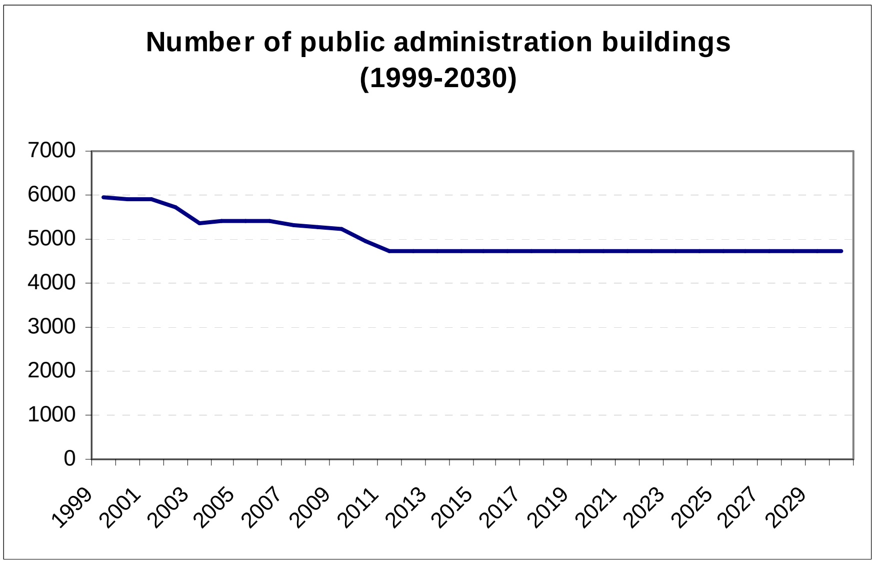
Figure 15 Trend and projections for medical centres



- ***Public administration buildings***

The number of buildings in public administration has been decreasing since 1999, with the largest decreases in 2002 and 2003. This is likely a result of restructuring when the national and local governments sell unnecessary buildings. At the same time, number of employees in the public administration sector has slightly increased. Due to the economic crisis and since the government will be forced to take measures that lead to significant cuts in public expenditures, it is assumed that the building stock of public administration will be further radically decreased in the next two years (together by 10%) and then will stabilize (Figure 16).

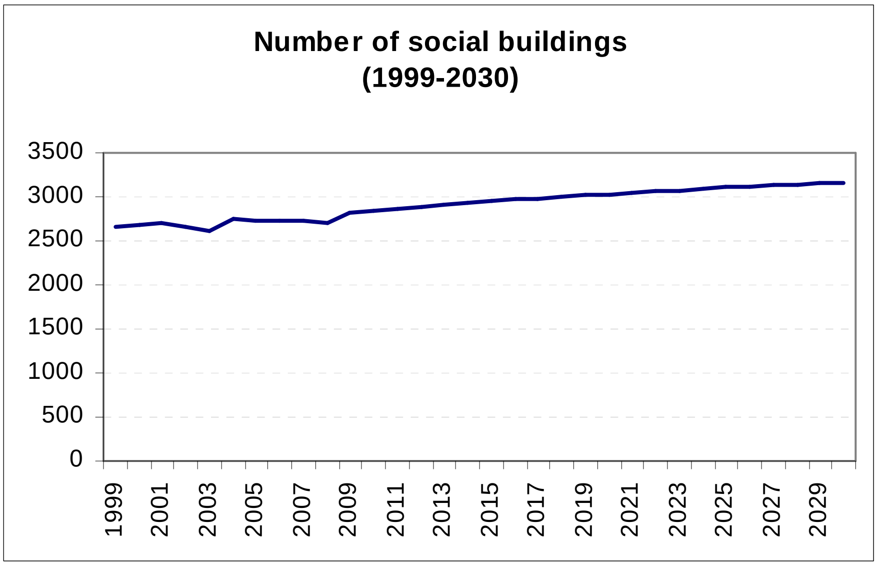
Figure 16 Trend and projections for public administration buildings



- ***Social buildings***

Social care buildings consist mainly of buildings accommodating homes for elderly and disabled people. Number of the elderly has increased by about one fifth since 1990 (Eurostat 2010a). The number of buildings has increased in the same period although at a slower pace. Due to the expected high increase in number of the elderly, it is assumed that the number of buildings will increase as well in the future as to meet the increasing demand for placement in these institutions (Figure 17). The number of social buildings is projected based on the trend in the number of elderly people in period 1990-2008.

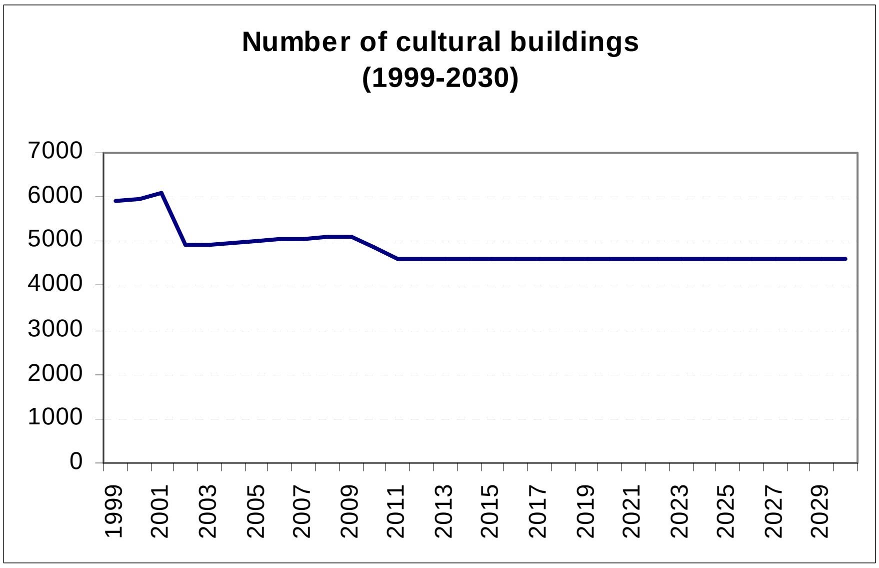
Figure 17 Trend and projections for social care buildings



- ***Cultural buildings***

Cultural buildings encountered a large decrease in 2002 when the building stock decreased by almost 20% (KSH 2010b). Similarly to the public administration building stock, cultural buildings are also assumed to encounter large decrease in the building stock in the upcoming period (by 5% p.a. in the following two years) due to recession and governmental effort to decrease the public debt. After this decrease, the cultural building stock will be stabilized for the rest of the projection period (Figure 18).

Figure 18 Trend and projections for cultural buildings



Indicators used for different subsectors are summarized in Table 8.

Table 8 Summary of indicators for public building stock projections

Building category	Projection indicator	Type of forecast	Source
Kindergartens and nurseries	Number of kindergartners per thousand inhabitants (1990-2007)	Linear regression based on trend in 1990-2008.	KSH (2010f) Stadat online table 2.6.1. Pupils and students in full-time and part-time education (1990–).*
	Floor area per kindergartner per thousand inhabitants (1990-2007)	Linear regression in years (1997-2007).	
Primary and secondary schools	Number of students in the primary and secondary schools per thousand inhabitants (1990-2007)	Quadratic regression based on trend in 1990-2008.	KSH (2010f) Stadat online table 2.6.1. Pupils and students in full-time and part-time education (1990–).*
	Floor area per student in primary and secondary schools per thousand inhabitants (1990-2007)	Quadratic regression based on 1991-2008, assuming that it will not decrease below the average of the last ten years.	
Universities	Number of full-time enrolled students per thousand inhabitants	Quadratic regression based on trend in 1990-2008.	KSH (2010f) Stadat online table 2.6.1. Pupils and students in full-time and part-time education (1990–).*
	Floor area per student in universities per thousand inhabitants (1990-2007)	Average value in the past decade (1999-2008).	
Hospitals and buildings for bed-ridden patients	Number of beds in operation per ten thousand inhabitants	Quadratic regression based on trend in 1999-2008.	KSH (2010d). Stadat online table 2.5.1. Physicians', general practitioners (GP), hospital services, pharmacies, dental care (1990–).*
	Number of buildings per bed per ten thousand inhabitants	Average in the period 1999-2008.	
Doctor's offices	Number of GPs and family paediatricians per ten thousand inhabitants	Average growth rate in the period 1990-2008.	KSH (2010d). Stadat online table 2.5.1. Physicians', general practitioners (GP), hospital services, pharmacies, dental care (1990–).*
	Number of buildings per GP and family paediatrician per ten thousand inhabitants	Average in the period 1999-2008.	
Medical centres	Number of active physicians per ten thousand inhabitants	Quadratic regression based on trend in 1960-2008.	KSH (2010c). Stadat online tables. 2.4. Public health (1960-).*
	Number of buildings per active physician per ten thousand inhabitants	Average value in the period 1999-2008.	
	Number of buildings per employee in public administration per thousand inhabitants	Average value in the period 1999-2008.	
Social buildings	Number of elderly per thousand inhabitants	Quadratic regression based on trend in period 1990-2008.	Eurostat (2010a) Proportion of population aged 65 and over.*
	Number of buildings per elderly per thousand inhabitants	Average based on period 1999-2008.	

* Population in 1959-2008 is based on KSH (2010b-h)

As a result of the projections for the different building subsectors in the public sector, the total building stock is slightly decreasing. Figure 19 provides an overview of the tendencies in different subsectors and Figure 20 shows the total building stock of the public sector.

Figure 19 Trends and projections of the different public subsectors in 2005-2030

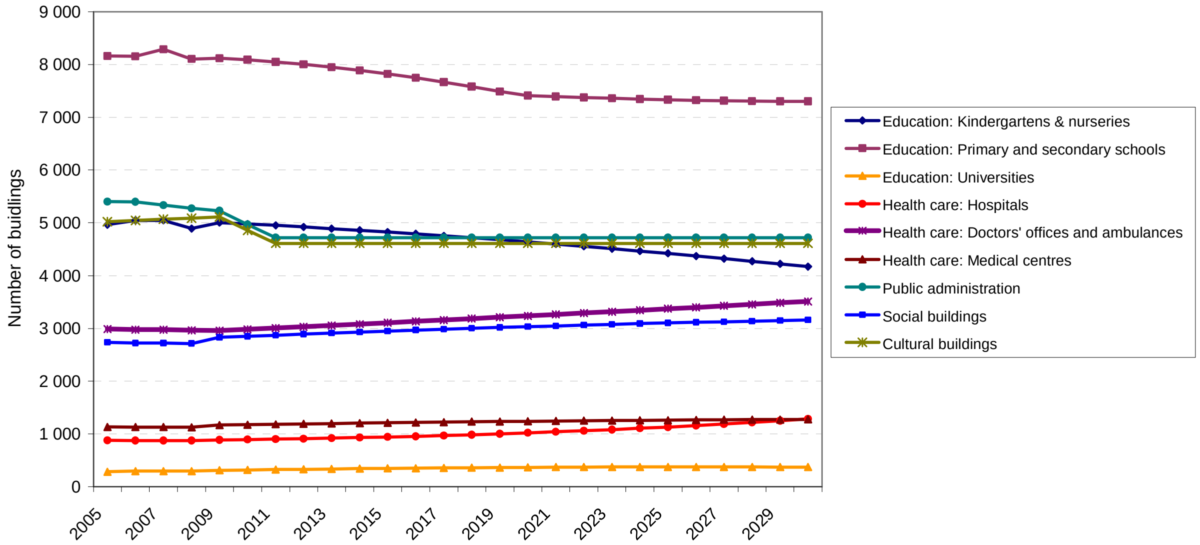
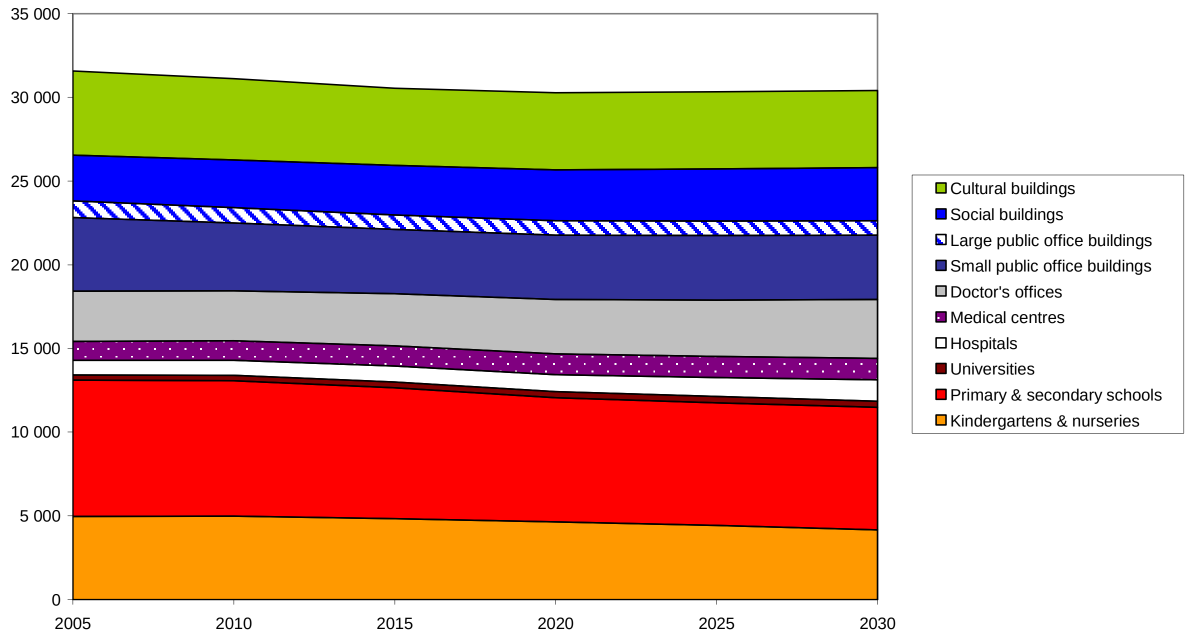


Figure 20 Trends and projections of the total building stock in 2005-2030



4.2 Processing energy audits - calculation of specific heating energy requirement

Heating energy requirement for the eight different building categories is based on the results of an analysis of a sample of energy audits of public building in Hungary. These audits come from three sources: most of the audits stem from UNDP/GEF collection of audits (further 'UNDP/Energy centre (2008)), and the rest are audits provided by Nagy (2008, audits used within project 'Display campaign') and Csoknyai (2008a). The UNDP/Energy centre (2008) audits were conducted by several Hungarian auditor companies within the programme "UNDP/GEF Public Sector Energy Efficiency Programme (2002–2008)"[41] and they are managed by the Energy Centre, Budapest. The programme has been extended several times in the period 2002-2008 and over 1000 energy audits of public buildings were collected. Access to the audits was provided by the project authorities and facilitated by the Energy Centre, Budapest.

Energy audits which were considered for calculation of the average specific heating energy requirements were selected in such a way that all public building categories as well as municipalities of different sizes are represented in the selection. This was challenging due to limited detail on the content of the archived audits. As most of the randomly selected audits were audits of small municipality buildings, in the later stage the selection was oriented towards the audits in larger municipalities, which were expected to include more audits of large buildings.

Some audits were excluded due to lack of basic data necessary for calculations (such as gross floor area, heated volume or annual final energy consumption for space heating). The quality

[41] For details see http://europeandcis.undp.org/environment/eu/show/3D25CD0A-F203-1EE9-B1532D1DAF8FF524

of the audits varied depending on the auditor. Due to the differences in quality and the different techniques for calculation of heating requirement used, an independent common methodology for processing of all selected audits was developed together with Csoknyai (personal com., 2008b). In this process, specific energy requirement was calculated for space heating, water heating and electricity.

The process of calculation of the heating energy requirements included following steps:

1. Calculation of the annual space heating energy consumption corrected by climatic conditions (kWh p.a.). Since the heating degree hours (HDH) are not reported for each municipality which was audited, the municipalities with similar geographical coordinates were grouped and a common HDH was allocated to this group.
2. Calculation of the average of the annual final energy consumption for space heating in the recent years (depending on availability of the data, this ranges from 1-4 years). This result was compared to the result in the audit and adjusted if necessary (e.g. excluding the year with extremely high or low consumption which cannot be explained by weather changes).
3. Calculation of the specific heating energy requirement (kWh/(m^2.a)) based on the average annual final energy consumption and the heated area of the particular building and assumed space heating efficiency.[42]
4. Calculation of the specific energy requirement for water heating is based on the total cold water demand as no hot water data is available. Underlining assumption is that in general hot water demand makes up 40% of the total cold water demand (Csoknyai, personal com., 2008b) unless stated otherwise in the audit. The resulting specific

[42] Due to the fact that the energy audits did not report the efficiency of the heating systems, a common average efficiency of the heating systems (DH, central building heating and individual heating) was assumed – 74% for both space and water heating.

energy requirement for water heating is subtracted from the specific heating energy requirement (considered on case-by-case basis).

5. Calculation of the specific energy requirement for electricity based on the given data of annual electricity consumption per building and the heated floor area per building.
6. Consequently, the sum of the specific energy requirements for space heating, water heating and electricity results into the total specific energy requirement, which was compared to the data in audits, if available.

Energy audits, which resulted in unrealistically low energy requirements and could have not been explained by the outstanding design or performance of the building, were excluded from the consideration (e.g. space heating requirement for doctor's office of 90 kWh/(m^2.a)).

The sample used for calculation of specific energy requirements consists of over 100 UNDP/Energy centre (2008) audits, many of which included more than one institution. More than 200 institutions were checked, out of which 114 buildings were used for calculation of the average specific energy requirements. Additional 50 buildings were added from the audits provided by Nagy (2008) and Csoknyai (2008a), out of which 16 were considered in the calculation of the averages. In total, 130 buildings were used in the calculation.

The complexes of the buildings, such as large hospital complexes were split into different buildings according to their function and size. Final energy of these complexes was distributed based on the heated volume and then the specific heating energy requirement was calculated based on the heated floor area.

The averages are categorized in the following way:

- Small educational buildings – kindergartens. This category includes all available audits of kindergartens. No audits of nurseries were available. Selection based on function.
- Large educational buildings – primary and secondary buildings. Selection based on function. Schools of all available sizes were considered. No audits of university building were available.
- Small health care buildings – doctor's offices. This category includes mainly doctor's offices and small medical centres, as well as a psychiatric and rehabilitation institute of a small size. Selection based on size.
- Large health care buildings – this category includes large hospital complexes, large psychiatric institute as well as large health/medical centres. Selection based on size.
- Large public administration buildings – this category includes large town halls and other large buildings of public administration. Selection based on size of the building.
- Small public administration buildings – includes small town halls – of usually small municipalities. Selection based on size of the building.
- Social care buildings – includes buildings such as homes for elderly, homes for children, home for the blind, club for elderly etc. Selection based on function.
- Cultural buildings – includes buildings such as community centers, cultural centres, an archive and a library. Selection based on function.

The resulting energy requirements for space heating, water heating and electricity are presented in Table 9 and Figure 21.

Table 9 Specific energy requirements for eight public building categories based on processing of energy audits

Building type	Space heating	Water heating	Electricity	Total
	kWh/(m^2.a)	kWh/(m^2.a)	kWh/(m^2.a)	kWh/(m^2.a)

Building type	Space heating	Water heating	Electricity	Total
	kWh/(m^2.a)	kWh/(m^2.a)	kWh/(m^2.a)	kWh/(m^2.a)
Kindergartens	206	15	22	243
Primary and secondary educational buildings	164	10	20	193
Doctor's offices	219	3	31	253
Hospitals and medical centres	204	27	73	304
Small public administration buildings	162	4	42	208
Large public administration buildings	122	4	35	161
Social buildings	273	26	34	334
Cultural buildings	151	3	18	172

Source: based on UNDP/Energy centre (2008), Nagy (2008), Csoknyai (2008a)

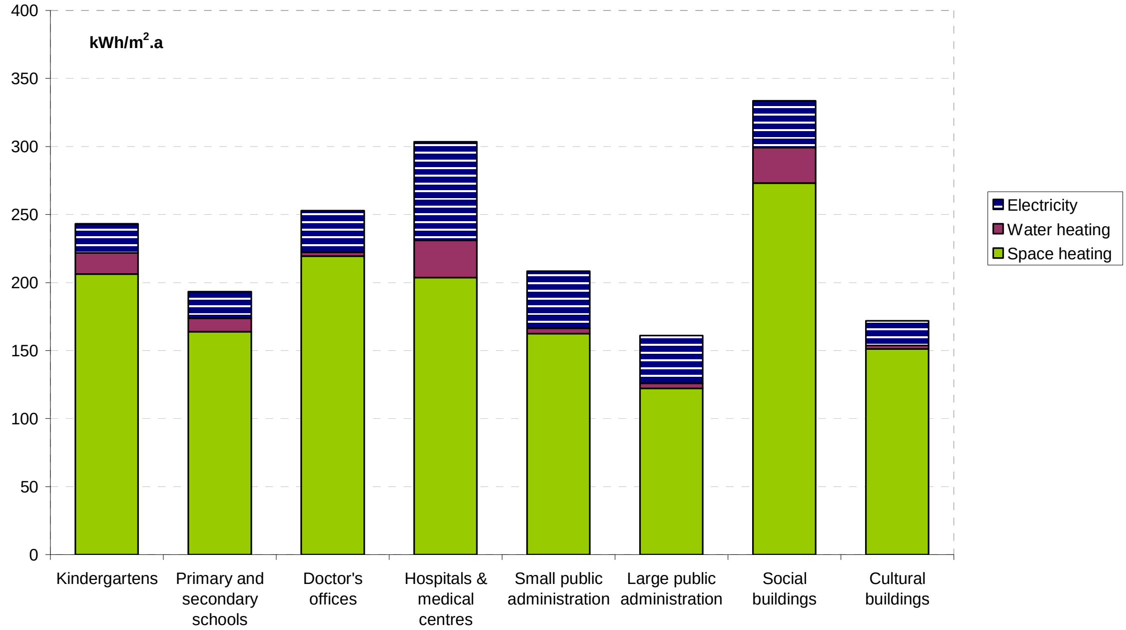
The results show that the small (mainly one-storey buildings) have a larger specific heating energy requirement than the large, multi-storey buildings. This is due to the fact that the small buildings have a larger cooling down surface relative to their volume (represented by so-called A/V, area/volume ratio). This implies that more compact buildings perform better in terms of space heating.

This premise, however, does not hold for small and large health care buildings. Although the small buildings include doctor's offices which could be presumably more energy efficient in terms of space heating than hospitals due to shorter work hours and lower average daily temperatures, their specific heating energy requirement is very high due to their unsuitable A/V ratio. On the other hand, although the large health care buildings could have better performance thanks to their A/V ratio, due to the day-long occupancy, higher average daily heating temperatures as well as high demand of fresh air[43], these buildings have also shown a high specific heating energy requirement.

[43] Csoknyai, personal com. (2010)

The most efficient in terms of space heating are large public administration buildings followed by cultural and large educational buildings. This can be mainly ascribed to the compactness of the building as well as shorter working hours of institutions residing in these types of buildings. Large educational buildings are less efficient than the public administration buildings mainly due to longer working hours (some schools have also afternoon classes, while the public administration buildings operate usually only on one shift).

Figure 21 Specific energy requirements of the Hungarian public buildings (kWh/(m^2.a))



Source: UNDP/Energy centre (2008), Nagy (2008), Csoknyai (2008a)

Note: 'Electricity' does not include electricity for space heating.

4.3 Common modelling assumptions for the baseline scenario

This section describes the main common modelling assumptions for the two modelling approaches – component- and performance-based approach. Based on these assumptions the frozen efficiency scenario is constructed.

Final energy for space heating depends on heated floor area, heating energy requirement and heating system efficiency. The floor area is assumed constant during the projection period (see Table 10).

Table 10 Floor area in public buildings (m^2)

	Gross average floor area (m^2)	Source	Comments
Educational buildings			
Small educational buildings	501	Ürge-Vorsatz *et al.* (2000)	
Large educational buildigns	1544	Weighted average for primary, secondary schools and universities based on the Ürge-Vorsatz *et al.* (2000).	
Health care buildings			
Small health care buildings	659	UNDP/Energy centre (2008), Nagy (2008) and Csoknyai (2008a)	
Large health care buildings	4799	Ürge-Vorsatz *et al.* (2000)	Based on the size of hospitals (Ürge-Vorsatz *et al.* 2000). Medical centres are assumed to be of the same size as hospitals.
Public administration buildings			
Small public administration buildings	507	UNDP/Energy centre (2008), Nagy (2008) and Csoknyai (2008a)	
Large public administration buildings	2794	UNDP/Energy centre (2008), Nagy (2008) and Csoknyai (2008a)	
Social care and cultural buildings			
Social care buildings	1329	UNDP/Energy centre (2008), Nagy (2008) and Csoknyai (2008a)	
Cultural buildings	642	UNDP/Energy centre (2008), Nagy (2008) and Csoknyai (2008a) for small cultural and own assumption for large cultural buildings.	Weighted average based on KSH (2005)

All buildings are not heated in the same way. Table 11 provides assumptions on the heated area as a share of the total floor area of the building.

Table 11 Assumption on heated area as a share of the total floor area (%)

Building category	Heated area (share of the floor area) %
Educational buildings	95%
Health care buildings	95%
Public administration buildings	95%
Social care buildings	95%
Cultural buildings	85%
Fire stations	80%

Source: Based on Kovacsic, email com. (2008) for educational, health care and public administration buildings and adjusted estimates for other building types.

In the frozen efficiency scenario all buildings built from 2006 are assumed to be built according to the 2006 Hungarian Building code (Ministerial order No.7/2006 published in Magyar közlöny 2006), which corresponds to approx. 50% of the average heating energy requirement of the existing buildings built before 1990 (Csoknyai, personal com., 2009). No retrofit is assumed for the existing buildings. The heating energy requirement for the modern buildings is assumed to be 20-40% lower than the heating energy requirement of the existing buildings built before 1990 (for small and large buildings, respectively) (Csoknyai, personal com., 2009), for summary see Table 12.

Table 12 Main assumptions in the frozen efficiency scenario (common baseline scenario)

Frozen efficiency scenario (common baseline scenario)	
Existing buildings (built before 1990)	• No retrofit assumed • Specific heating energy requirement based on energy audits (UNDP/Energy 2008, Nagy 2008, Csoknyai 2008a)
Modern buildings (built between 1990-2005)	• Small buildings: HER 20% lower than existing buildings • Large buildings: HER 40% lower than existing buildings
New construction (built after 2005)	• All new buildings built according to 2006 Building code

Another important parameter for modelling space heating energy consumption is the type and efficiency of the heating systems. Three different space heating modes are distinguished in the public buildings: district heating, central building heating (this can be a building boiler or a central block heating – more than one building is heated with the same boiler) and individual heating - these are usually so-called "gas convectors" (Kovacsics, personal com., 2008)[44]. Distribution of these three heating modes among the public subsectros is based on KSH (2005), see Table 13.

Table 13 Distribution of the public buildings according to heating modes

Space and water heating mode	Educational buildings	Health care buildings	Public administration buildings	Social buildings	Cultural buildings
District heating	11%	12%	6%	11%	3%
Central heating	67%	57%	41%	66%	39%
Individual heating	22%	32%	53%	23%	58%

Source: KSH (2005).

The efficiency of the heating systems is based on the assumption of heat production efficiency and distribution and control losses (based on Csoknyai, personal com., 2009), see Table 14. The efficiency of heat production in district heating installations is increasing from 77% to about 87% in 2025 and then is constant (based on Novikova 2008).

[44] Non-gas heating systems in the public building sector are negligible and thus not considered in the model.

Table 14 Efficiency of the heating system for existing and new buildings in the frozen efficiency baseline scenario

Heating system	Heat production efficiency	Distribution losses	Control losses	Total efficiency
Existing buildings (built before 1990)				
District heating	100%*	6%	10%	86%
Central building heating	83%	6%	10%	71%
Individual heating	75%	6%	10%	64%
New buildings (built after 2005)				
District heating	100%*	3%	3%	94%
Central building heating	90%	3%	3%	85%
Individual heating	85%	3%	3%	80%

Source: Csoknyai, personal com. (2009)

Note: * Heat production of district heating is approximately 100%. This represents theoretical efficiency of the heating system within the system boundaries, i.e. efficiency of the heat exchangers within the building.

The energy prices used in the model (for all scenarios) are based on data collected from the relevant agencies for district heat and natural gas (see Table 15) and are assumed to increase by 1.5% per year (based on projections in Novikova 2008, Petersdorff *et al.* 2005). Energy prices do not include VAT.

Table 15 Assumed energy prices

Fuels	Energy price, EUR/kWh (EUR_{2005})					Source
	2005	2006	2007	2008	2009	
Natural gas	0.020	0.024	0.024	0.030	0.031	Hungarian Energy Office (2005-2009)
District heat	0.017	0.021	0.022	0.022	0.026	FŐTÁV online (2009)

Note: The presented energy prices are based only on the flexible component of the energy costs, as the fixed amount is not reduced even if energy saving measures are implemented.

The exchange rate of 300 HUF/EUR is assumed for the whole period 2005-2030.

4.4 Frozen efficiency scenario - energy use and CO_2 emissions

This section presents the result of construction of the baseline scenario, which is common for the two modelling approaches (component-based and performance-based) – the frozen efficiency scenario.

The frozen efficiency baseline scenario is constructed based on the building stock projections, heating energy requirements, heating system efficiency, heated floor area and other factors and assumptions. The resulting energy consumption shows a slightly declining trend which can be explained both by decline of the number of buildings in building categories as well as improvement of efficiency of the district heating system (Figure 22).

Figure 22 Total final energy consumption in frozen efficiency baseline scenario (GWh)

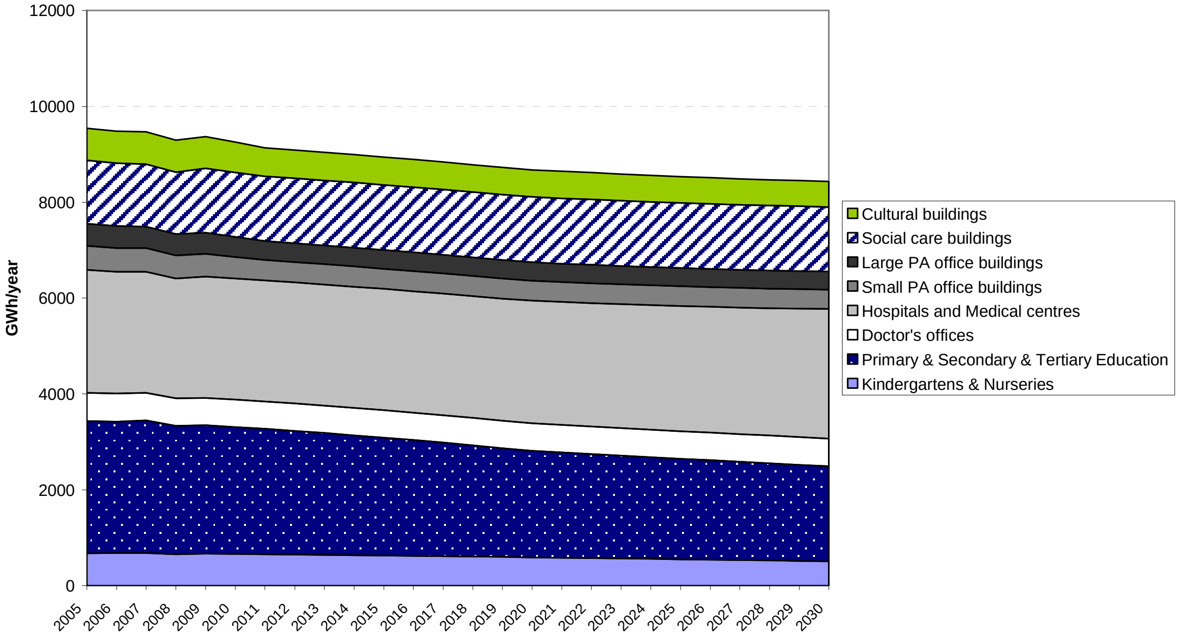
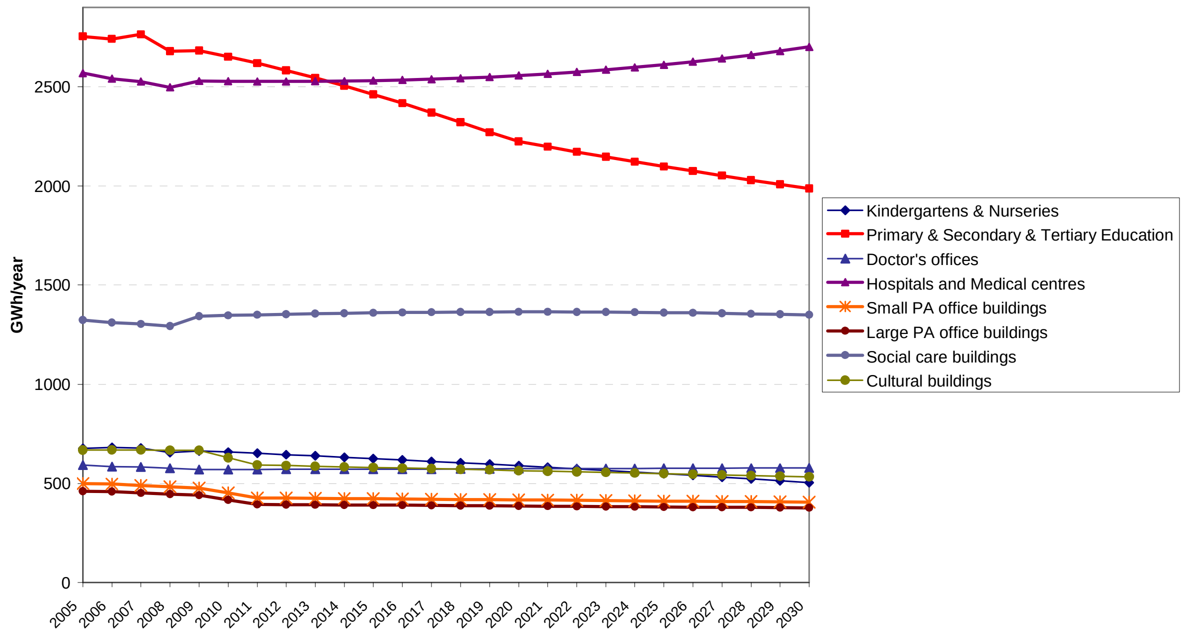


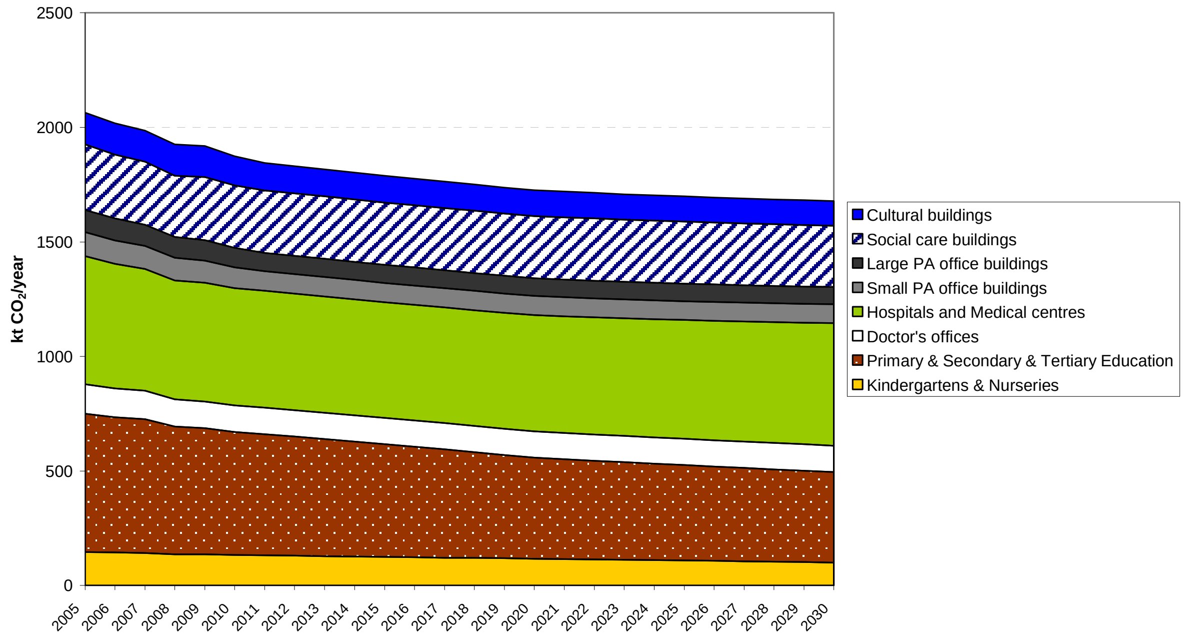
Figure 23 shows that the decline in the total final energy consumption in the frozen efficiency scenario is caused mainly by the decline in the number of Primary and secondary educational buildings.

Figure 23 Final energy use in frozen efficiency baseline scenario by subsector (GWh)



The resulting CO_2 emissions baseline shows even more pronounced declining trend which is given by the gradually improving emission factor for district heating (Figure 24).

Figure 24 CO_2 emissions in frozen efficiency baseline scenario (kt CO_2)



4.5 Calibration of the base year energy consumption in the public sector

This section sets the energy use in the base year (2005) into the perspective of the total national energy consumption in that year.

The statistical data for energy use exist only for the common sector “Commercial and public services” without distinguishing further the energy use by either commercial or public sector. This makes it difficult to calibrate the total energy use for space heating in the current model, and therefore several approximations have to be used.

Total final energy use in the Hungarian commercial and public service sector was 40 TWh in 2005 (IEA 2008a). Out of this the use of natural gas and district heat accounted for 29.2 TWh (IEA 2008a). Due to lack of data on the split of final energy use into public and commercial sectors, an approximation based on the floor area is used. Assuming only heated premises, the share of the public floor area on the total tertiary floor area is approximately 43% (Table 16).[45] Information on military buildings and prisons is incorporated in the public sector in order to provide a wider perspective of the sector’s floor area.[46]

Table 16 Number of buildings and floor area (m^2) in the public and commercial sectors in Hungary in 2005

2005	Number of buildings	Floor area per building (m^2)	Total floor area (thousand m^2)	Share on total FA of the tertiary sector (%)
PUBLIC BUILDINGS	**31 573**		**39 210**	**32%**
Educational buildings	**13 409**		**15 194**	
Kindergartens & nurseries	4 963	501	2 485	
Primary and secondary schools	8 160	1 365	11 137	
Universities	286	5 500	1 573	

[45] Commercial buildings account for a large part of the non-residential sector and may range from 45-97% of the total building stock (Itard *et al.* 2008).

[46] In Hungary there are 29 institutions which host prisons with a total heated building-related floor area of 335 075 m^2 (est.) (Tünde Gere, email com., May 2010). Since data on number of military buildings in Hungary was not available at time of writing, it is assumed that in Hungary there are twice as many military buildings as in Slovakia (around 30 buildings, SRO 2010), an assumption based on the population ratio in the two countries.

2005	Number of buildings	Floor area per building (m^2)	Total floor area (thousand m^2)	Share on total FA of the tertiary sector (%)
Health care buildings	**5 005**		**11 713**	
Hospitals & Buildings for confined to bed	881	4 799	4 228	
Doctor's offices & ambulance stations	2 988	680	2 032	
Medical centres	1 136	4 799	5 452	
Public Administration office buildings	**5 403**		**5 016**	
Small public office buildings	4 407	507	2 233	
Large public office buildings	996	2 794	2 783	
Social care buildings	**2 735**	1 371	**3 749**	
Cultural buildings	**5 021**	705	**3 538**	
COMMERCIAL BUILDINGS	**231 679**		**72 630**	**60%**
Commercial office buildings	**259**		**2 164**	
Small commercial office buildings	79	1 706	135	
Large commercial office buildings	180	11 273	2 029	
Trade buildings	**178 417**		**42 004**	
Shopping centres	57	18 160	1 035	
Hypermarkets	91	6 693	609	
Retail shops	166 738	104	17 298	
Wholesale warehouses	11 531	2 000	23 062	
Of which heated warehouses (est. 30%)	*3 459*	*2 000*	*6 919*	
Hotels & Restaurants	**53 003**		**28 462**	
Hotels	836	3 000	2 508	
Pensions & Hostels	2 361	1 500	3 542	
Restaurants	49 806	450	22 413	
OTHER PUBLIC BUILDINGS	**23 692**		**9 173**	**8%**
Workhops & dressing rooms	1 240	300	372	0.3%
Storage, garages, other buildings (excl. fire stations)	21 491	300	6 447	5.3%
Fire station (Public administration)	961	2 450	2 354	1.9%
Other buildings not considered in the model	**89**		**515**	
Military buildings	60	3 000	180	0.1%
Prisons (number of institutions)	29		335	0.3%
TOTAL	**287 033**		**121 529**	**100%**
Heated buildings				
Public buildings incl. fire stations & prisons			42 451	42.9%
Commercial buildings without warehouses			49 568	
Only heated warehouses			6 919	
Total commercial			56 487	57.1%
Total			**98 938**	**100%**

Using this share to roughly estimate the energy use of the public sector on the total tertiary final energy use, the resulting total final energy used in Hungarian public buildings based on IEA (2008a) is approximately 12.5 TWh. Space heating accounts for 79% of the thermal energy use (EC 2001), which translates into 9.87 TWh. The final energy used in public sector calculated in the model for 2005 is 9.5 TWh, which increases to 9.86 TWh if the final energy for space heating of fire stations is included (see Table 17). This is in line with the estimate based on the IEA (2008a).

Table 17 Calibration of the base year final energy use in the Hungarian public sector

Calibration of base year final energy use in the public sector	GWh	Source
Statistical data		
Natural gas, Commercial and institutional sector, Hungary, 2005	26 516	IEA 2008a. Energy Balances of OECD countries.
Heat use, Commercial and institutional sector, Hungary, 2005	2 675	IEA 2008a. Energy Balances of OECD countries.
Public sector		
Estimated share of public sector on total tertiary sector (based on floor area)	43%	Based on floor area (KSH 2000-2010b-h) and energy audits
Estimate of natural gas use in public sector	11 377	
Estimate of heat us in public sector	1 148	
Total estimated thermal energy use in public sector	12 524	
Space heating in public sector		
Share of space heating on total thermal energy in public sector	79%	EU (2001)
Total estimated energy use for space heating in public sector	9 868	Based on IEA (2008a). Energy Balances of OECD countries.
Model: Space heating		
Total final energy for space heating in public sector	9 535	
Final energy of fire stations (estimate)	326	
Total final energy for space heating in public sector	**9 861**	
Space and water heating in public sector		
Share of space and water heating on total thermal energy in public sector	92%	EU (2001)
Total estimated final energy for space and water heating in public sector from (statistics)	11 576	Based on IEA (2008a). Energy Balances of OECD countries.
Model: water heating		
Final energy for DHW in public sector (exc. fire stations)	725	
Final energy DHW for fire stations (est.)	86	
Total final energy for DHW in public sector	**811**	
Model: space and water heating		
Total final energy for space heating in public sector	**9 861**	
Total final energy for DHW in public sector	**811**	
Total final energy for space and water heating in public sector (incl. fire stations)	**10 672**	

Accounting for both space and water heating (92% of the total thermal final energy of the commercial sector, EC 2001), the final energy for these two end-uses based on IEA (2008a) accounts for 11.6 TWh. The final energy for space and water heating calculated in the model accounts for 10.7 TWh (Table 17). The remaining part includes energy uses (e.g. cooking) and building types not covered by the model (e.g. prisons, military buildings).

Summary

The frozen baseline was constructed based on building stock projections, specific heating energy requirement for each building category, heated floor area, type and efficiency of heating system and other assumptions. The base year is 2005 and the projection period 2005-2030. The building stock is constructed based on the statistical data (mainly Hungarian Statistical Office, KSH) and aggregated into eight building categories (small and large educational buildings, small and large health care buildings, small and large administration buildings, social care and cultural buildings). These are further divided into several building types depending on the year of construction and architectural features. The future buildings stock is projected based on the projection indicators specific for each building category, such as number of children attending kindergartens, number of students attending primary, secondary and tertiary education, number of active beds in hospitals, number of general practitioners in medical centres etc. The resulting future building stock shows a slight increase over the projection period. Specific heating energy requirement is based on the sample of energy audits in the Hungarian public buildings collected from UNDP/Energy centre (2008), Nagy (2008) and Csoknyai (2008a). Due to different quality and calculation procedures separate methodology for processing energy audit data was developed together with Csoknyai (2008b). The resulting specific energy requirements for space heating, water heating and electricity fill in the information gap of this type of information for public buildings and can also be used in other countries of the CEE region. The results show that more compact buildings have better energy performance due to a more suitable area/volume (A/V) ratio. This premise is however not valid for small and large health care buildings – while in hospitals the suitable A/V ratio is offset by longer operation hours in the hospitals, the lesser need for high temperatures in the doctor’s offices is compensated by unsuitable area/volume ratio. The most efficient in terms of space heating are large public administration buildings followed by cultural and large educational buildings. Social care buildings and small health care buildings rank among the least energy efficient public buildings. The chapter presents overview of the assumptions behind the baseline frozen efficiency scenario, the resulting energy use and related CO_2 emissions. Finally, the building stock, baseline energy consumption and CO_2 emissions in the base year are calibrated based on the available statistical sources.

CHAPTER 5. RESULTS: COMPONENT-BASED APPROACH - IMPROVING BUILDING ELEMENTS ACCORDING TO COST-EFFECTIVENESS

In the past decade the cost-effectiveness approach of determining the mitigation potential has gained in importance. An increasing number of studies have been conducted (see Chapter 2); however, most of these studies focus either solely on residential buildings, investigate only a few types of tertiary/public buildings, or treat the building sector as a whole without paying special attention to tertiary/public buildings. However, public buildings play an important function as an example for the wide public as well as business community. Therefore, it is important to establish the energy saving potential in these buildings as well. Due to large variability of the public building stock and limited statistical data the potential in the tertiary sector is determined based on its value added. However, the value added of the public sector is difficult to establish due to its relatively small share on the GDP (and the projections of economic activities in general). We believe that treating public sector on the basis of building stock that is predicted based on sector-specific indicators is more precise for determination of energy saving potential. This chapter describes the main assumptions, technical options, results and analysis of such potential determination based on the building stock projections.

5.1 Assumptions for component-based approach

The component-based approach consists of a model for existing buildings (built until 1990), modern buildings (built between 1991-2005) and new construction (buildings built after 2005). The main assumptions for the component-based model are summarized below:

- Base year is 2005
- Projection period is 2005-2030
- Mitigation action starts in 2011

- In the period 2005-2010 the mitigation scenario is assumed to follow the same trajectory as the BAU scenario (referred to also as BAU_{comp})
- In the mitigation scenario: all existing buildings (built until 1990) are gradually retrofitted by 2030
- In the mitigation scenario: all new buildings are gradually built to the level of passive house standard from 2019

The methodology for the component-based determination of the energy saving potential involves construction of Business-as-usual (BAU_{comp}) scenario and a mitigation scenario (for research framework see Chapter 3).

❖ Business as usual scenario (BAU_{comp})

The BAU_{comp} scenario assumes that energy saving options are installed at the natural rate of retrofit (1% of existing building stock). The abatement options in the BAU_{comp} scenarios include both thermal envelope insulation (insulation of external wall, basement and roof, window replacement, for details of these see subsection 'Mitigation scenario') as well as improvement of the heating systems (standard building boiler). The BAU_{comp} does not include temperature management. All new buildings are assumed to be built according to the 2006 Building code (Ministerial order No.7/2006 published in Magyar közlöny, 2006, further 2006 Building code). The Hungarian 2006 Building code represents approximately 50% energy savings compared to the existing buildings built until 1990 (Csoknyai, email com., 2009). In the BAU_{comp} for new construction no further energy efficiency improvements are assumed over the projection period due to typically low level of compliance to building codes in the absence of additional policies.[47] Energy consumption of the non-retrofitted buildings is based

[47] The compliance of building codes is a major problem in many countries (Laustsen 2008). According to Warren (2008) and Hjorn (2008) only 50-65% of new homes do not comply with basic energy standards (in Lechtenböhmer and Schüring *Forthcoming*).

on the energy audits from the following sources: UNDP/Energy centre (2008), Csoknyai (2008a), Nagy (2008). For overview see Table 18.

❖ Mitigation scenario

Mitigation scenario assumes that energy efficiency options are installed in such a way that all existing buildings built before 1990 are renovated by 2030. This implies an accelerated rate of retrofit compared to the natural rate of retrofit and renders an average annual retrofit of 4% of the existing building stock (built until 1990) p.a. The abatement options include improvement of building envelope, improvement of heating system efficiency and temperature management (see Section 6.2).

For new construction it is assumed that all new buildings are gradually built according to the passive house (PH) standard by year 2019. This is based on Article 9 of the recast of the EPBD, which obliges all new buildings occupied and owned by public authorities be built as nearly zero energy buildings (EC 2010).[48] In the period 2005-2011 the 2011 Building code and low-energy standard play an important role as transition standards towards the passive house standard. The 2011 Building code phases-out in 2015 and the low-energy standard in 2019, when the only allowed standard for new buildings is passive house standard (see Table 18).

Table 18 Main assumptions in the component-based model

Component-based model		
BAU_{comp}	Existing buildings	• Rate of retrofit: 1% of the existing buildings built until 1990 • Retrofitted: incremental application of energy efficient technologies • Non-retrofitted: average energy consumption based on energy audits[49]
	New buildings	• All new buildings are built to the level of 2006 Building code

[48] Based on the recast of the Energy Performance of Buildings Directive (2002/91/EU). The new directive (2010/31/EU) is not a part of the BAU scenario, because it was not in force in 2009, condition for including the policy into the BAU scenario. The recast was adopted on 19 May 2010.
[49] Survey includes energy audits of UNDP/Energy centre (2008), Csoknyai (2008), Nagy (2008). Further referred to only as UNDP/GEF audits.

Component-based model		
	Existing buildings	• All existing buildings (built until 1990) are retrofitted by individual measures (insulation, windows exchange and efficient building boilers) by 2030 • Accelerated rate of retrofit of approximately 4% of the existing buildings built until 1990 (depending on building type)
$\text{Mitigation}_{\text{comp}}$	New buildings	• All new buildings are PH from 2019 • The rest is assumed 2011 (phase-out in 2015) and low-energy (phase-out in 2019) • Phase-out of 2006 Building code: 2011

The main assumptions imply that the component-based model is in fact a mixed model using component-based approach for the existing buildings and performance-based approach for the new construction. This is given by the nature of the current building codes where the requirements for the new construction are increasingly quantified as performance-based indicators depending on the A/V ratio and other factors (see e.g. Hungarian 2006 Building code).[50]

5.2 Abatement technologies

The building envelope serves as a barrier to the transfer of heat between the inside and outside of the building (Harvey 2009). At the same time, the outside air may enter the building through leaks in the building elements (and thus leads to infiltration losses). Thus, it is important that both the transmission and infiltration losses are avoided. This can be done through proper insulation of external wall, roof and basement and installation of high-performance windows and doors. Using these elements lowers heat losses and thus lowers peak load of heating system (Smeds and Wall 2007). Moreover, throughout the process of building retrofit it is essential that thermal bridges are avoided (Smeds and Wall 2007).

[50] In the current study for the new construction the same model is used for component-based (current Chapter 5) and performance-based model (Chapter 6), as well as scenarios (Chapter 7), and it is also referred to as Passive accelerated scenario.

In the component-based model the following abatement technologies are explored in terms of energy saving potential:

- insulation of external walls,
- insulation of roof,
- insulation of basement,
- exchange of windows,
- temperature management
- installation of condensing building boiler,
- passive house standard for new construction.

It is assumed that all components are applied to the building at once. This section presents technological characteristics and the costs of the applied options. The abatement options are applied to all existing public buildings built before 1990 in Hungary except for buildings not applicable to certain types of measures (e.g. external wall insulation is not applied to the buildings with thick walls – the old traditional buildings built before 1945).

As the technical parameters of the thermal insulation and window exchange in public sector are similar to the residential sector in terms of technical parameters and investment cost, these are adopted from Novikova (2008), see below. Nevertheless, as the public buildings are on average of a larger floor area than residential buildings, and there are differences in the heating systems between the two building sectors, these options were investigated in more detail.

The public space heating model does not include fuel switch as most of the public buildings are supplied either by natural gas or district heating. Renewable energy sources (such as heat pump, pellets, solar thermal) are not examined in the model as the main focus of the current study is on energy efficiency and energy saving potential (and the related CO_2 mitigation potential).

In the text below the individual abatement options (components) are described and their technical parameters are reported.

❖ External wall insulation

The energy savings of external wall insulation depend on the building type and area of external wall surface. Due to the fact that the buildings built until 1946 have thick walls and since it is often impossible to alter the façade of the historical buildings (Novikova, 2008), external wall insulation was not applied to the old traditional buildings, but only to the industrialized ones.[51] The importance of the external wall insulation in the industrialized buildings is that it not only lowers the heat transfer between the building and the environment but it also reduces the thermal bridge losses (Csoknyai 2005). Table 19 provides overview of the technical characteristics for external wall insulation considered in the model.

Table 19 Technical parameters of external wall insulation

Building type	U-value before retrofit ($W/m^2.K$)	U-value after retrofit ($W/m^2.K$)
Small buildings (constructed until 1990)	1.25	0.35
Industrialized large buidlings	2.00	0.35

Source: Novikova (2008)

[51] The industrialized technology covers both the so-called “panel buildings” as well as buildings “built by other type of industrialized technology (e.g. block-, cast-, tunnel-shuttered-, ferro-concrete skeleton houses)” (Csoknyai 2005).

❖ Roof insulation

Roof insulation is assumed to be installed on the top of the building in case of the industrialized buildings and to the attic floor in case of the traditional and existing small buildings (Novikova 2008).

Table 20 Technical parameters of roof insulation

Building type	U-value before retrofit ($W/m^2.K$)	U-value after retrofit ($W/m^2.K$)
Small buildings (constructed until 1990)	0.89	0.225
Traditional large buildings	0.89	0.225
Industrialized large buildings	0.77	0.23

Source: Novikova (2008)

❖ Basement insulation

The basement insulation can be installed on the floor of the cellar in case the building has one, or on the top of the ground floor in case building has no cellar (Novikova 2008).

Table 21 Technical parameters of basement insulation

Building type	U-value before retrofit ($W/m^2.K$)	U-value after retrofit ($W/m^2.K$)
Small buildings (constructed until 1990)	0.66	0.23
Traditional large buildings	0.66	0.23
Industrialized large buildings	0.50	0.23

Source: Novikova (2008)

❖ Replacement of windows

All existing buildings are retrofitted with high-performance windows (Novikova 2008), which lower the heat loss through transmission (double-glazing) and air infiltration (better sealing of the window). The improved sealing between the window panel and the frame lowers the air change rate (times of exchange of the air per hour) and related heat loss.

Table 22 Technical parameters of window replacement

Building type	U-value		Air change rate	
	Before retrofit ($W/m^2.K$)	After retrofit ($W/m^2.K$)	Before retrofit (times/hour)	After retrofit (times/hour)
Small buildings (constructed until 1990)	2.50	0.95	0.8	0.5
Traditional large buildings	2.50	0.95	0.9	0.5
Industrialized large buidlings	2.50	0.95	1.0	0.5

Source: Novikova (2008)

❖ Temperature management

Based on the opinion of the experts at the workshop "Mitigation potential in Hungarian buildings" 2008) about 80% of all existing public buildings (built before 1990) are currently overheated. In these buildings average daily temperature can be lowered by at least 2ºC ("Mitigation potential in Hungarian buildings" 2008). This means that for instance, buildings which are heated during the heating season at the average daily temperature of 23ºC can lower their average daily temperature to 21ºC. This can be done either by better thermal regulation during the working hours, dividing the building into several heating zones with different temperature needs or switching off the heating during the nights and weekends, and in times when the building is not occupied. To do this, one can either install thermostatic radiator valves (TRVs), which allow the temperature to be regulated manually or Programmable thermostats, with which the users can program the temperature according to usual working hours and it will regulate the temperature in the building automatically.[52]

By decreasing the temperature by 1ºC it is possible to save 5-6% of energy in Hungary ("Mitigation potential in Hungarian buildings", 2008). Thus, with 2ºC average temperature

[52] It is also possible to lower the daily average temperature by means of a computerized Building energy management system (BEMS). BEMS is however not studied in this study. Another, much less costly solution is to appoint the portiere of the building with the task of regulating the temperature when all users of the building leave. This is a solution for buildings with irregular time schedule such as special schools, in which temperature management is difficult to be programmed automatically (Varga 2008). This option is also not studied here due to lack of energy savings cost information.

drop, energy savings of 11% is assumed. It is difficult to calculate exactly the cost of this measure as this depends on the complexity of the heating system in each individual building. The cost of this measure does not include only the purchase of the TRVs or programmable thermostats, but also other equipment that regulates the temperature of the cycle for space heating and hot water. It can range from 75,000 HUF per building (small buildings) up to 800,000 HUF per building (large buildings) (Kiss, personal com., 2009). The installation costs for temperature management equipment are assumed to be 100% of the cost of the equipment (based on Novikova 2008).

- **Condensing boilers**

In the mitigation scenario it is assumed that existing building boilers (with a heating efficiency of 71%) are replaced by condensing boilers with the total heating efficiency of 93% (Csoknyai, personal com., 2009). The total heating efficiency is a result of heat production efficiency and the distribution and control losses (see Table 23).

In order to find the suitable condensing boiler for each building type a heat demand was calculated (kW per building per year) for each building type. The heat demand specifies the peak needs for heating of the building to comfortable temperature. This figure was increased by 30% in order to secure sufficient supply of heat (Kovacsics, personal com., 2009). Based on this, the most cost-efficient alternatives of condensing boilers were selected from product catalogues (Junkers, Vaillant, Termomax, Viessmann) and the average cost of these was calculated. Besides the higher cost of the condensing boiler, larger radiators are needed due to the fact that the condensing boiler the system has lower circulation temperature and thus requires radiators with bigger surface (Kiss, personal com., 2009, Novikova 2008). Therefore, the total additional cost of the condensing boiler (including radiators) is much higher than those of the standard boiler. The cost of radiators depends on the heated volume of the building and was calculated based on Novikova (2008) and Csoknyai (email com., 2008). The cost of installation of both the boiler and the radiators is 50% of the cost of the equipment.

The condensing boiler replaces also the new standard boiler which would have been otherwise bought under the BAU scenario. The total efficiency of the heating systems for the new standard boilers is 85% (Csoknyai, personal com., 2009). Similarly as for the condensing boilers, the cost of the standard building boiler is determined based on the heat demand in each type of building based on the product catalogues (mentioned above). The cost of accessories for the new standard boiler (such as chimney, tubes and pipes) is assumed to be 100% of the cost (Kiss, personal com., 2009).

Table 23 Heating efficiency for existing and new buildings

Heating system	Heat production efficiency	Distribution losses	Control losses	Total efficiency
Current state (existing buildings in 2005-2010)				
District heating	100%	6%	10%	86%
Central building heating	83%	6%	10%	71%
Individual heating	75%	6%	10%	64%
BAU scenario (existing in 2011-2030 and new buildings in 2005-2030)				
District heating	100%	3%	3%	94%
Central building heating	90%	3%	3%	85%
Individual heating	85%	3%	3%	80%
Mitigation scenario (existing in 2011-2030 and new buildings in 2011-2030)				
District heating	100%	1%	3%	96%
Central building heating	97%	1%	3%	93%
Individual heating	92%	1%	3%	88%

Source: based on Csoknyai, personal com. (2009).

❖ Application of passive house standard to new construction

In the mitigation scenario it is assumed that all new buildings are built according to the passive standard technology from 2019, while during the transition towards the passive future new buildings are built according to the level of the so-called "2011 Building code"[53] and low-energy standard.

The requirements of the passive house standard (PHS) for new construction include the following (PHI 2003):

- the heating requirement in the building shall be not more than 15 kWh/(m^2.a)
- the air-tightness of the building should be at least 0,6/h n_{50}-value.

A high-performance thermal envelope can reduce heat losses to the point where a large portion of the "remaining heat loss can be offset by internal heat gain (from people, lighting, appliances) and passive solar heat gain, with the heating system required only for the residual" (Harvey 2009). Complying with the heating requirement of 15 kWh/(m^2.a) of the PHI (2003) is usually achieved by lowering the heat loss to about 45 kWh/(m^2.a), where one third of the heat loss is offset by internal heat gains, one third by passive solar heat gains and the rest by the heating system (Harvey 2009).

The 2011 Building code assumes energy consumption of 60 kWh/(m^2.a) and the low-energy standard energy consumption of 30 kWh/(m^2.a) (Csoknyai, personal com., 2009).

The current additional costs for the new passive house are assumed 20% higher than the cost of a building built today (Szekér, personal com., 2009).[54] The currently high costs of tertiary buildings built with PHS technology in Hungary are determined by the costs of the imported technology and lack of experience. However, with the development of the passive

[53] '2011 Building code' is named in such a way as to indicate when such a requirement should be implemented in order to provide a transition towards passive house technology.

[54] The additional costs of passive tertiary buildings may range between 20-50% above the construction costs of the standard building (Kistelegdi, personal com., 2009), but it is very important to consider what kind of conventional building is used as a reference, as the costs vary widely. Note, that this estimate refers to both new construction and retrofit to the passive standard level.

construction market in Hungary the additional costs of the passive standard are assumed to decrease gradually to the level of 8% by 2020 (based on Veronica 2008; and in line with estimates by Matzig, personal com., 2009 and Csoknyai, personal com., 2009).[55] This assumes a strong development of the Hungarian passive house components market as well as mass training of the architects, planners and construction workers over the projected period.

The costs of low-energy buildings are assumed 10% higher than the cost of new standard buildings (based on Csoknyai, personal com., 2009). The costs of the 2011 Building code are assumed 3% higher than the average costs of the standard building (Csoknyai, personal com., 2009). The costs of standard new buildings are based on ETK (2006-2009).

5.3 Results of the component-based model: energy saving potential in terms of cost

In this section the results of determination of the energy saving potential are presented. First, the potential is calculated for the individual abatement options and then, the combined potential is established through the use of the supply curve method based on the order of cost-effectiveness of the options. This method ensures that double-counting of the potential of the overlapping abatement options is avoided. Table 24 shows the energy saving potential and the costs of realization of this potential when the measures are are assessed individually.

Table 24 CO_2 mitigation and energy saving potential of individual options for space heating and their costs in the mitigation scenario in 2030

Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030
	$ktCO_2$/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh
Educational small buildings (built until 1990)	**42**		**213**	

[55] The current level of additional costs of new passive house construction in Austria and Germany is 6-10% (Ronald Matzig, personal com., 2009).

Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030
	$ktCO_2$/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh
Temperature management 2C in small education buildings (only DH & CBH)	5	-37	26	0.001
Exchange of windows in small educational buildings	7	-2	33	0.008
Condensing building boiler in small educational buildings	10	-2	48	0.008
Insulation of external wall in small educational buildings	6	0	29	0.008
Insulation of roof in small educational buildings	9	6	46	0.009
Insulation of basement in small educational buildings	6	8	29	0.010
Educational large buildings (built until 1990)	**131**		**658**	
Temperature management 2C in large educational buildings (only DH & CBH)	11	-17	55	0.005
Insulation of external wall in industralized large educational buildings	29	-11	147	0.006
Exchange of windows in large educational buildings	45	-7	226	0.007
Condensing building boiler in large educational buildings	31	5	153	0.009
Insulation of roof in large educational buildings	10	19	49	0.012
Insulation of basement in large educational buildings	5	56	27	0.011
Health care small buildings (built until 1990)	**42**		**209**	
Temperature management 2C in health care small buildings (only DH & CBH)	5	-39	25	0.0008
Exchange of windows in small health care buildings	7	-9	33	0.0066
Condensing building boiler in small health care buildings	9	-7	45	0.0067
Insulation of external wall in small small health care buildings	5	-3	26	0.0079
Insulation of roof in small health care buildings	10	3	49	0.0090
Insulation of basement in small health care buildings	6	6	31	0.0095
Health care large buildings (built until 1990)	**175**		**878**	
Temperature management 2C in large health care buildings (only DH & CBH)	24	-36	124	0.001
Exchange of windows in large educational buildings	57	-20	287	0.004
Insulation of external wall in industralized large educational buildings	30	-14	154	0.006
Condensing building boiler in large educational buildings	45	-8	225	0.007
Insulation of basement in large educational buildings	6	10	31	0.010
Insulation of roof in large educational buildings	11	16	57	0.012
Public administration small buildings (built until 1990)	**37**		**184**	
Temperature management 2C in PA small buildings (only DH & CBH)	3	-31	14	0.002
Insulation of external wall in small PA buildings	10	-3	49	0.008
Exchange of windows in small PA buildings	9	1	47	0.009
Insulation of roof in small PA buildings	6	2	29	0.009
Insulation of basement in small PA buildings	4	4	19	0.009
Condensing building boiler in small PA buildings	5	5	26	0.009
Public administration large buildings (built until 1990)	**38**		**192**	
Insulation of external wall in industralized large PA buildings	8	-13	38	0.006
Temperature management 2C in large PA buildings (only DH & CBH)	3	-13	13	0.006
Exchange of windows in large PA buildings	18	-3	92	0.008
Condensing building boiler in large PA buildings	5	8	24	0.010
Insulation of basement in large PA buildings	2	9	9	0.010
Insulation of roof in large PA buildings	3	14	16	0.011
Social buildings (built until 1990)	**85**		**-14**	
Exchange of windows in social buildings	17	-29	87	0.003
Temperature management 2C in social buildings (only DH & CBH)	15	-28	77	0.003
Condensing building boiler in social buildings	29	-14	144	0.005

Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030
	ktCO₂/yr.	EUR/tCO₂	GWh/yr.	EUR/kWh
Insulation of basement in social buildings	7	3	34	0.009
Insulation of external wall in small social buildings	6	8	28	0.010
Insulation of roof in social buildings	11	13	53	0.011
Cultural buildings (built until 1990)	**51**		**255**	
Temperature management 2C in cultural buildings (only DH & CBH)	3	-30	14	0.002
Exchange of windows in cultural buildings	11	-12	56	0.006
Insulation of external wall in cultural buildings	8	-1	39	0.008
Insulation of roof in cultural buildings	15	4	72	0.009
Insulation of basement in cultural buildings	9	7	46	0.010
Condensing building boiler in cultural buildings	6	18	28	0.012
New public buildings (built after 2010)	**166**		**835**	
Passive energy standard in educational small buildings built after 2010	6	-8	29	0.007
Passive energy standard in educational large buildings built after 2010	51	3	258	0.013
Passive energy standard in health care small buildings built after 2010	14	-3	69	0.008
Passive energy standard in health care large buildings built after 2010	61	14	307	0.011
Passive energy standard in public administration small buildings built after 2010	3	26	14	0.013
Passive energy standard in public administration large buildings built after 2010	2	63	9	0.021
Passive energy standard in social buildings built after 2010	22	-12	110	0.006
Passive energy standard in cultural buildings built after 2010	8	18	39	0.012
Total	**766**		**3408**	

Note: Assumed exchange rate 300 HUF/EUR

Table 25 shows the results of the combination of the abatement technologies using the cost curve method. The measures are ordered by sectors. The total energy savings potential is approx. 3.2 TWh in year 2030 which translates into 645 kt CO_2.

Table 25 Energy saving and CO_2 mitigation potential of combined options for space heating and their costs in the mitigation scenario in 2030

Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Investments 2011-2030	Saved energy costs 2011-2030
	kt CO₂/yr.	EUR/tCO₂	GWh/yr.	EUR/kWh	million EUR	million EUR
Educational small buildings (built until 1991)	**38**		**188**		**93**	**77**
Temperature management 2C in small education buildings (only DH & CBH)	5	-37	26	0.001	1	10
Exchange of windows in small educational buildings	10	-14	48	0.005	16	18
Condensing building boiler in small educational buildings	9	2	45	0.008	19	18
Insulation of external wall in small educational buildings	4	13	22	0.011	14	9
Insulation of basement in small educational buildings	4	29	21	0.014	17	9
Insulation of roof in small educational buildings	5	42	26	0.017	26	14
Educational large buildings (built until 1991)	**102**		**511**		**305**	**211**
Temperature management 2C in large educational	11	-17	55	0.01	14	21

Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Investments 2011-2030	Saved energy costs 2011-2030
	kt CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	million EUR	million EUR
buildings (only DH & CBH)						
Insulation of external wall in industralized educational buildings	27	-8	134	0.01	54	48
Exchange of windows in large educational buildings	36	1	184	0.01	93	72
Insulation of basement in large educational buildings	3	46	17	0.02	18	8
Condensing building boiler in large educational buildings	19	56	94	0.02	90	49
Insulation of roof in large educational buildings	5	70	27	0.02	35	13
Health care small buildings (built until 1991)	**32**		**162**		**84**	**63**
Temperature management 2C in health care small buildings (only DH & CBH)	5	-39	25	0.001	1	9
Exchange of windows in small health care buildings	6	-7	31	0.007	13	11
Condensing building boiler in small health care buildings	7	1	36	0.008	15	15
Insulation of external wall in small health care buildings	4	10	20	0.010	12	8
Insulation of roof in small health care buildings	7	22	34	0.013	26	14
Insulation of basement in small health care buildings	3	48	16	0.018	17	7
Health care large buildings (built until 1991)	**140**		**704**		**284**	**268**
Temperature management 2C in large health care buildings (only DH & CBH)	24	-36	124	0.001	8	45
Exchange of windows in large health care buildings	53	-18	267	0.005	75	93
Insulation of external wall in industralized large health care buildings	21	0	104	0.008	51	42
Condensing building boiler in large educational buildings	31	20	153	0.012	91	65
Insulation of basement in large educational buildings	4	41	20	0.016	19	8
Insulation of roof in large health care buildings	7	51	36	0.018	39	15
Public administration small buildings (built until 1991)	**29**		**143**		**87**	**54**
Temperature management 2C in PA small buildings (only DH & CBH)	3	-31	14	0.002	2	5
Insulation of external wall in small PA buildings	9	-2	47	0.008	24	17
Exchange of windows in small PA buildings	7	13	37	0.011	24	14
Insulation of roof in small PA buildings	4	23	20	0.013	15	8
Insulation of basement in small PA buildings	2	33	11	0.015	10	3
Condensing building boiler in small PA buildings	3	77	14	0.027	14	7
Public administration large buildings (built until 1991)	**30**		**149**		**87**	**57**
Insulation of external wall in industralized PA buildings	8	-13	38	0.01	13	13
Temperature management 2C in large PA buildings (only DH & CBH)	2	-8	11	0.01	4	4
Exchange of windows in large PA buildings	15	5	75	0.01	41	28
Insulation of basement in large PA buildings	1	51	5	0.02	5	2
Insulation of roof in large PA buildings	2	63	8	0.02	10	4
Condensing building boiler in large PA buildings	2	83	12	0.00	14	6
Social buildings (built until 1991)	**71**		**355**		**132**	**134**
Exchange of windows in social buildings	17	-29	87	0.00	13	31
Temperature management 2C in social buildings (only DH & CBH)	14	-26	70	0.00	11	26
Condensing building boiler in social buildings	23	-7	116	0.01	39	46
Insulation of basement in social buildings	5	20	25	0.01	18	10
Insulation of external wall in social buildings	4	29	20	0.01	17	8
Insulation of roof in social buildings	7	38	37	0.02	35	15
Cultural buildings (built until 1991)	**38**		**190**		**120**	**77**
Temperature management 2C in cultural buildings (only DH & CBH)	3	-30	14	0.002	2	5
Exchange of windows in cultural buildings	11	-11	54	0.006	19	19

Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Investments 2011-2030	Saved energy costs 2011-2030
	kt CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	million EUR	million EUR
Insulation of external wall in cultural buildings	6	9	31	0.010	18	12
Insulation of roof in cultural buildings	10	23	52	0.013	39	21
Insulation of basement in cultural buildings	5	41	27	0.017	26	12
Condensing building boiler in cultural buildings	3	81	13	0.025	16	7
New public buildings (built after 2010)	**166**		**835**		**530**	**270**
Passive energy standard in small educational buildings - new construction	6	-8	29	0.01	13	9
Passive energy standard in large educational buildings - new construction	51	3	258	0.01	155	85
Passive energy standard in small health care buildings - new construction	14	-3	69	0.01	35	22
Passive energy standard in large health care buildings - new construction	61	14	307	0.01	228	98
Passive energy standard in small public administration - new construction	3	26	14	0.01	12	4
Passive energy standard in large public administration buildings - new construction	2	63	9	0.02	13	3
Passive energy standard in social buildings - new construction	22	-12	110	0.01	44	36
Passive energy standard in cultural buildings - new construction	8	18	39	0.01	30	12
Total	**645**		**3238**		**1 723**	**1 211**

Note: Assumed exchange rate 300 HUF/EUR

The table above shows that the largest potential (reduction of 166 kt CO_2 emissions) can be achieved by gradually applying passive house standard to new construction. However, retrofit of the large health care (140 kt CO_2) and large educational buildings (102 kt CO_2) offer also a large potential. In total, retrofitting of all existing buildings built before 1990 offers larger potential than high-performance new construction. The supply cost curves for each building type are presented in Annex IV. Table 26 lists the measures in order of cost-efficiency.

Table 26 Energy saving and CO_2 mitigation potential of combined options and their costs in the mitigation scenario in 2030 for space heating ordered by cost-effectiveness

#	Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Investments 2011-2030	Saved energy costs 2011-2030
		kt CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	mil. EUR	mil. EUR
1	Temperature management 2C in health care small buildings (only DH & CBH)	5	-38.7	25	0.001	1.0	9.0
2	Temperature management 2C in small education buildings (only DH & CBH)	5	-37.0	26	0.001	1.4	9.8
3	Temperature management 2C in large health care buildings (only DH & CBH)	24	-36.3	124	0.001	8.1	44.8
4	Temperature management 2C in PA small buildings (only DH & CBH)	3	-31.1	14	0.002	1.5	5.0
5	Temperature management 2C in cultural buildings (only DH & CBH)	3	-30.1	14	0.002	1.6	5.1
6	Exchange of windows in social buildings	17	-28.9	87	0.003	13.4	30.5

#	Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Investments 2011-2030	Saved energy costs 2011-2030
		kt CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	mil. EUR	mil. EUR
7	Temperature management 2C in social buildings (only DH & CBH)	14	-26.3	70	0.003	11.1	25.8
8	Exchange of windows in large health care buildings	53	-18.1	267	0.005	74.9	93.3
9	Temperature management 2C in large educational buildings (only DH & CBH)	11	-17.2	55	0.005	13.8	21.1
10	Exchange of windows in small educational buildings	10	-14.5	48	0.005	15.5	17.6
11	Insulation of external wall in industralized PA buildings	8	-13.4	38	0.006	12.6	13.3
12	Passive energy standard in social buildings - new construction	22	-12.1	110	0.006	43.6	36.1
13	Exchange of windows in cultural buildings	11	-10.8	54	0.006	19.4	19.3
14	Passive energy standard in small educational buildings - new construction	6	-7.9	29	0.007	12.6	9.4
15	Insulation of external wall in industralized educational buildings	27	-7.8	134	0.007	54.2	48.5
16	Temperature management 2C in large PA buildings (only DH & CBH)	2	-7.7	11	0.007	3.8	4.3
17	Condensing building boiler in social buildings	23	-7.2	116	0.007	38.5	45.9
18	Exchange of windows in small health care buildings	6	-6.5	31	0.007	12.9	11.1
19	Passive energy standard in small health care buildings - new construction	14	-2.7	69	0.008	35.2	21.8
20	Insulation of external wall in small PA buildings	9	-1.6	47	0.008	23.6	16.6
21	Insulation of external wall in industralized large health care buildings	21	-0.1	104	0.008	51.4	42.0
22	Condensing building boiler in small health care buildings	7	0.6	36	0.008	14.7	14.7
23	Exchange of windows in large educational buildings	36	1.0	184	0.009	93.2	72.5
24	Condensing building boiler in small educational buildings	9	1.5	45	0.008	18.7	18.2
25	Passive energy standard in large educational buildings - new construction	51	3.4	258	0.013	155.5	85.1
26	Exchange of windows in large PA buildings	15	4.9	75	0.009	41.0	28.0
27	Insulation of external wall in cultural buildings	6	8.8	31	0.010	18.1	11.9
28	Insulation of external wall in small health care buildings	4	10.3	20	0.010	12.1	7.7
29	Exchange of windows in small PA buildings	7	12.5	37	0.011	23.6	14.1
30	Insulation of external wall in small educational buildings	4	13.3	22	0.011	14.4	9.0
31	Passive energy standard in large health care buildings - new construction	61	14.0	307	0.011	227.6	97.7
32	Passive energy standard in cultural buildings - new construction	8	18.2	39	0.012	30.5	12.2
33	Condensing building boiler in large educational buildings	31	19.5	153	0.012	91.2	64.9
34	Insulation of basement in social buildings	5	19.7	25	0.012	18.0	9.6
35	Insulation of roof in cultural buildings	10	22.6	52	0.013	38.9	21.0
36	Insulation of roof in small health care buildings	7	22.4	34	0.013	26.0	13.9
37	Insulation of roof in small PA buildings	4	22.8	20	0.013	15.0	8.0
38	Passive energy standard in small public administration - new construction	3	25.9	14	0.013	12.3	4.4
39	Insulation of external wall in social buildings	4	28.8	20	0.014	16.7	7.9
40	Insulation of basement in small educational buildings	4	29.5	21	0.014	17.3	8.7
41	Insulation of basement in small PA buildings	2	32.5	11	0.015	10.0	3.3
42	Insulation of roof in social buildings	7	38.2	37	0.016	34.6	14.6
43	Insulation of basement in large educational buildings	4	40.6	20	0.016	19.2	8.0
44	Insulation of basement in cultural buildings	5	41.1	27	0.017	25.9	11.9

#	Measure	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Investments 2011-2030	Saved energy costs 2011-2030
		kt CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	mil. EUR	mil. EUR
45	Insulation of roof in small educational buildings	5	42.5	26	0.017	26.0	14.0
46	Insulation of basement in large educational buildings	3	46.1	17	0.018	17.9	7.6
47	Insulation of basement in small health care buildings	3	47.5	16	0.018	17.3	6.8
48	Insulation of roof in large health care buildings	7	50.6	36	0.018	38.8	14.6
49	Insulation of basement in large PA buildings	1	51.0	5	0.018	5.2	2.1
50	Condensing building boiler in large educational buildings	19	56.3	94	0.020	90.2	49.1
51	Insulation of roof in large PA buildings	2	62.7	8	0.021	10.3	3.7
52	Passive energy standard in large public administration buildings - new construction	2	63.4	9	0.021	12.8	2.9
53	Insulation of roof in large educational buildings	5	70.3	27	0.022	35.3	12.6
54	Condensing building boiler in small PA buildings	3	77.1	14	0.027	13.9	6.9
55	Condensing building boiler in cultural buildings	3	80.8	13	0.025	16.2	7.3
56	Condensing building boiler in large PA buildings	2	82.8	12	0.001	14.2	6.0
	Total	**645**		**3 238**		**1 723**	**1 211**

Note: Assumed exchange rate 300 HUF/EUR

The most cost-effective set of options is the temperature management with the aim to lower the average daily temperature by 2ºC followed by window replacement and insulation of external wall (see Table 27). Temperature management is the most cost-effective measure in majority of building types (except for Large public administration and Social buildings). While windows replacement is more important for the small buildings, wall insulation is important for large buildings. Installation of condensing boiler is important for highly energy intensive buildings, such as small educational buildings, small health care and social buildings. The development towards passive standard for new construction presents a whole range of costs of CO_2 mitigation. While the passive house standard applied to the social buildings is competing with such low-cost measure as temperature management, the application of passive house standard to public administration and cultural buildings occurs at the other end of the list.

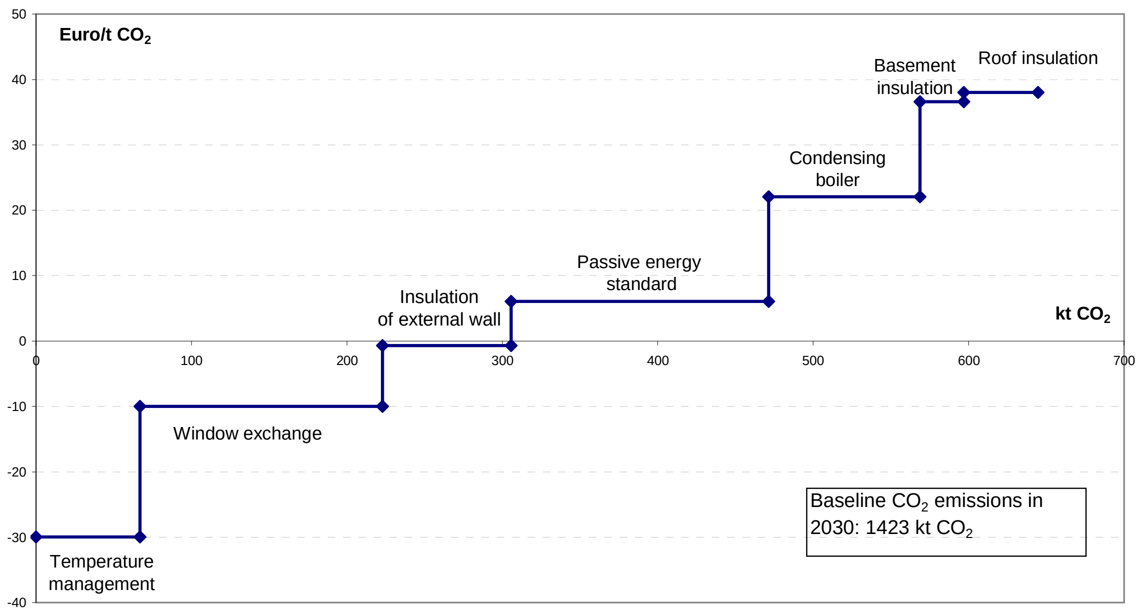
Table 27 Mitigation and energy saving potential, costs of mitigated CO_2 and cost of energy conserved for space heating

Abatement option	CO_2 savings in 2030	CO_2 savings (2011-2030)	Cost of mitigated CO_2 in 2030	Energy savings in 2030	Energy savings (2011-2030)	CCE in 2030	Investments 2011-2030	Saved energy costs 2011-2030
	kt CO_2	kt CO_2	EUR/tCO_2	GWh/yr.	GWh/yr.	EUR/kWh	mil. EUR	mil. EUR
Temperature management 2ºC	67	67	-30	339	339	0.003	42	125
Exchange of windows	156	223	-10	783	1123	0.01	294	286
Insulation of external wall	83	306	-1	416	1539	0.01	203	157
Passive building standard	166	471	6	835	2374	0.01	530	270
Condensing boiler	97	569	22	483	2857	0.01	298	213
Insulation of basement	28	597	37	142	2998	0.02	131	58
Insulation of roof	48	645	38	239	3238	0.02	225	102
TOTAL	**645**			**3238**			**1723**	**1211**

Note: Assumed exchange rate 300 HUF/EUR

Table 27 shows that by mitigation action in the period 2011-2030, energy savings of 3.2 TWh can be realized, which translates into a reduction of 645 kt CO_2. To utilize this potential it is necessary to invest 1.7 billion EUR in 2011-2030; however, application of the abatement measures will result in energy cost savings of 1.2 billion EUR in the same period. On average, the most cost-effective measures are temperature management, exchange of windows and insulation of external wall (Figure 25).

Figure 25 Average supply cost curve for the Hungarian public buildings for space heating



The total potential of all energy efficiency measures considered in the component-based model is 45% of the 2030 BAU final energy consumption. The cost-effective potential accounts for 21% of the 2030 BAU final energy consumption (Table 28), which means that the total energy cost savings achieved by these energy efficiency measures over the projection period outweigh the initial investment needed for implementation of these measures.

Table 28 Energy saving and mitigation potential in cost groups[56]

	CO_2 savings		Energy savings		Investment vs. energy cost savings	
	Cumulative CO_2 savings in 2030	Share of baseline CO_2 emissions in 2030	Cumulative energy savings in 2030	Share of baseline final energy in 2030	Cumulative investments 2011-2030	Cumulative energy cost savings 2011-2030
Cost group	kt CO_2	%	GWh	%	bil. EUR	bil. EUR
<0	293	21%	1475	21%	0.45	0.53
<20	538	38%	2705	38%	1.21	0.98
<100	645	45%	3238	45%	1.72	1.21

Although some measures are more expensive than others, only thorough retrofit will bring the related benefits. Therefore, not only the most cost-effective measures should be implemented, but also the more expensive ones. Only then can the maximum potential be achieved.

Summary

This chapter presented the results of the determination of energy savings potential based on the component-based modelling approach. It shows how important are the temperature management and insulation of all building envelope components. The most cost-effective energy savings measures are temperature management, window exchange, external wall insulation and application of passive energy standard to new construction in several types of buildings.

[56] Note: While the calculation of cost-effectiveness of the measures is based on the present value (discounted) of the investment costs and energy cost savings, the cumulated investments and energy cost savings shown in the tables are undiscounted. This is to show the future value of the required investment and what are the related energy cost savings. In both cases investment costs and energy cost savings are expressed in EUR_{2005}.

Lowering average daily temperature in buildings by 2ºC during the heating season is the most cost-effective option and it is applicable to all types of buildings. According to experts, over 80% of all public buildings are overheated and can lower their average temperature by 2ºC (workshop "Mitigation potential in the Hungarian buildings" 2008). Temperature management should be utilized especially in buildings with half-day occupancy, where space heating is not required during night (schools, administration offices) or longer periods of the day as well as during holidays and the schedule for heating can be programmed. A wide range of advanced thermal regulation equipment, which ensures comfortable working and living conditions and saves energy costss is available on the market.

The passive house standard offers the largest potential from a single measure, but at different cost levels depending on the building type. The most cost-effective application of passive house standard is for the social care buildings (e.g. homes for elderly), small health care buildings (e.g. doctor's offices) and small educational buildings (e.g. kindergartens). On average, the additional cost of passive house technology in Hungary is much higher than in countries with a longer tradition of passive construction (Germany, Austria). Thus, developing suitable conditions for domestic businesses which are involved in manufacturing the necessary passive house components may bring the costs down to the level of 8% within the projected period (Matzig, personal com. 2009).

Window replacement offers high energy savings, particularly in large health care buildings, which can be attributed to the high energy requirement per unit of floor area and to the size of the building. Roof and basement insulation and in several cases condensing boiler are higher on the cost curve which means that they require higher investment (depending on building type). Nevertheless, the cost of CO_2 mitigation for condensing boiler is on average still below 100 Euro/t CO_2. It is important to stress that once the building is retrofitted, application of the high performance options should be assured even at higher additional costs, as this investment pays back in savings on energy costs.

This chapter showed ranking of the abatement options in terms of cost-effectiveness. This may lead to the conclusion that the most cost-effective measures should be prioritized for investment (or even state support) without investing in the least cost-effective ones. However, it is important to note that a holistic approach, rather than a selective focus on the application of separate cost-effective measures, has to be applied when designing support programmes for building retrofit at national level. Thus, it is important that along with the support for passive house standard for new construction, this standard is also applied to retrofits of the existing buildings. The cost effectiveness of passive house standard in the new construction shows the advantages of the holistic approach. The first public building in Hungary retrofitted to the level of passive house standard is a proof that this is feasible in the country and should be further supported.[57]

Only this way can the full extent of the energy savings potential be achieved and energy be conserved for several decades. This applies mainly to the measures which are related to the building envelope and space heating. Different studies show that "only complex retrofit measures, including the simultaneous insulation of walls, exchange of windows and renovation of heating systems provide better thermal performance and less risk of fabric damages" (Zöld and Csoknyai 2007). Further, "missing one or two items from these will not result in energy saving, moreover the risk of fabric damages may become higher" (Zöld and

[57] Presentation of I. Kistelegdi, Passive house conference, Budapest, 5 February, 2009.

Csoknyai 2007). McKinsey (2007) also stresses that "complete renovation of old, inefficient buildings yields greater improvement than just applying standards to individual parts of buildings". In addition, application of certain thermal measures that improve air-tightness of the building necessitates further changes such as installation of ventilation systems with heat recovery to eliminate the risk of moulds and fabric damage and thus to secure healthy and comfortable living and working conditions. Therefore, all retrofits should be planned and performed by the professionals certified by a central body. In new construction it is inevitable that architects and engineers coordinate their work throughout the process. Moreover, it has to be mentioned that even the advanced buildings do not always perform as expected (Harvey 2006). This can be eliminated by commissioning and subsequent periodical monitoring and maintenance. Commissioning typically reduces total energy consumption by 5-20% (Harvey 2006) and should become an obligatory part of any renovation and new construction in the public sector.[58] This applies especially to large buildings with complex heating, ventilation and air-conditioning systems. A holistic approach to the retrofit is analysed in the following chapter.

[58] Commissioning is a process of systematically checking that all of the componets of heating, ventilation and air-conditioning system are present and functioning properly, and involves adjusting system controls so that it can achieve its best possible performance (Harvey 2006). Commissioning costs about 1-3% of the heating, ventilation and air-conditioning construction costs (Harvey 2006).

CHAPTER 6. RESULTS: PERFORMANCE-BASED MODEL AND ANALYSIS – TOWARDS AN INTEGRATED DESIGN

Currently, the trend in policy design in the building sector is to move towards performance-based regulation and standards (such as the recast of the EPBD, Hungarian GIS). Although this trend in policy is not new, determination of the energy savings potential and the resulting CO_2 reduction has relied mainly on component-based approaches so far (see Chapter 2 for overview of the studies using a component-based approach). However, the need for a more radical transformation towards a low-carbon economy, as well as the need for an integrated design and holistic approach to building energy efficiency makes it inevitable that energy savings potentials are determined on the basis of performance.

This chapter starts with an overview of performance-based approaches in policy making in the building sector and first developments of performance-based modelling approaches to determine energy savings potential in this sector. This is followed by description of assumptions behind the performance-based model for determination of energy saving potential in Hungarian public sector, the resulting energy saving and CO_2 reduction potential, and finally these results are compared to the potential determined via the component-based approach.

6.1 Development of performance-based approaches used in policy making and in modelling mitigation potential in the building sector

While the component-based approaches prescribe technical requirements for each building component for retrofit of an existing building, the performance-based regulations rather prescribe the maximum level of the total energy consumption per building in absolute terms.

Thus, while in the first case, the architects are limited to the use of components, it is not ensured that all the components work together in such a way as to decrease the total energy consumption of the building to a significantly lower level. Component-based codes prescribe the U- or R-values and efficiency of the installations (Laustsen 2008). According to Hui (2002) "prescriptive codes are not able to consider the interactions between the building systems and measures that would optimise the combined performance". However, if the energy consumption of the whole building is regulated, this has two effects: i. decrease in the total energy consumption of the building is ensured and ii. the architects and constructors can choose different building components to fulfil the total energy requirement and thus use their experience and innovation to reach the requirement in an integrated manner and at lower costs. The performance approach leaves a greater space for innovation and new techniques in energy efficiency design (Hui 2002). At the same time this approach requires using computer-based models and a deeper understanding of the building principles (Laustsen 2008).

Most countries use prescriptive requirements for individual components in their building regulations (Laustsen 2008). However, over time, more flexibility has been allowed in the building codes, such as enabling trade-offs allowing adjustments of the individual values (Laustsen 2008).[59] Recently increasing number of countries have building codes based on a performance approach for regulating energy use in buildings. These include New Zealand, USA, Canada, and even some developing countries, such as Singapore, are revising their building codes using this approach (Hui 2002), as well as the European Union with its Energy Performance Building Directive (EPBD). Within Europe, Sweden and Denmark have performance-based building codes which are supported with prescriptive U-values for some

[59] Laustsen (2008) classifies the building codes into six categories: prescriptive, trade-off, model building, energy frame, energy performance and hybrid of these approaches. All these approaches can be classified as either U-value based building codes (which corresponds to the component-based approach used in current study) and performance-based building codes (Laustsen 2008). The current study distinguishes only the two basic categories – component-based and performance-based approaches.

components (Laustsen 2008). Also the currently valid Hungarian building code (Magyar közlöny 2006) is of a mixed nature – the minimum requirements for the new buildings are given by three levels of criteria, where the first level prescribes maximum U-values, while the second and the third levels are performance-based (maximum requirement for specific heating requirement and specific primary energy requirements are set for selected building types and they depend on A/V ratio of the building). The building must meet the primary energy performance requirement. Fulfilment of the component-based requirements does not automatically guarantee the fulfilment of the performance-based requirement (Zöld 2007).

As shown above several countries use a mix of component-based and performance-based building regulations (Hui 2002, Laustsen 2008). This is to provide a choice to the designers – either use an approach which is simple to calculate or to use a more complicated approach which offers more freedom and flexibility (Laustsen 2008). Another reason why in some countries both performance and prescriptive values are set is that the prescriptive values are tighter than the value for the overall building performance which ensures that buildings constructed according to the prescriptive, component-based, approach automatically fulfil the energy performance requirements (Laustsen 2008). The use of the approaches varies also depending on the building type - it has been observed that while the building codes for residential buildings are often more prescriptive on the building components, the requirements for non-residential buildings tend to be more performance-oriented (Hui 2002).

At the same time, the recent commitment for a more radical mitigation action lead to development of national targets on very low energy buildings (VLEB) in several European countries. These targets are expressed in terms of building energy performance indicators (either as absolute level of energy consumption per unit of floor area and year or as a relative decrease in building energy performance). For instance, the UK plans to have zero-carbon requirements for heating, lighting, DHW and appliances by 2016, Norway aims to achieve Passive house level by 2020 and France, Germany and the Netherlands plan to have all new buildings either energy neutral or energy producing (Jensen *et al.* 2009, Dyrbøl *et al.* 2009), see Table 29. In addition, several countries have set improved requirements for the renovation of existing buildings (Jensen *et al.* 2009, Dyrbøl *et al.* 2009). Moreover, the recast of the EPBD will further fuel this process as it will be obligatory for the MSs to set their definitions of VLEB and to ensure that all new buildings are build as zero energy buildings starting from 2019 for public buildings and from 2020 for other buildings (EC 2008b, EC 2010).

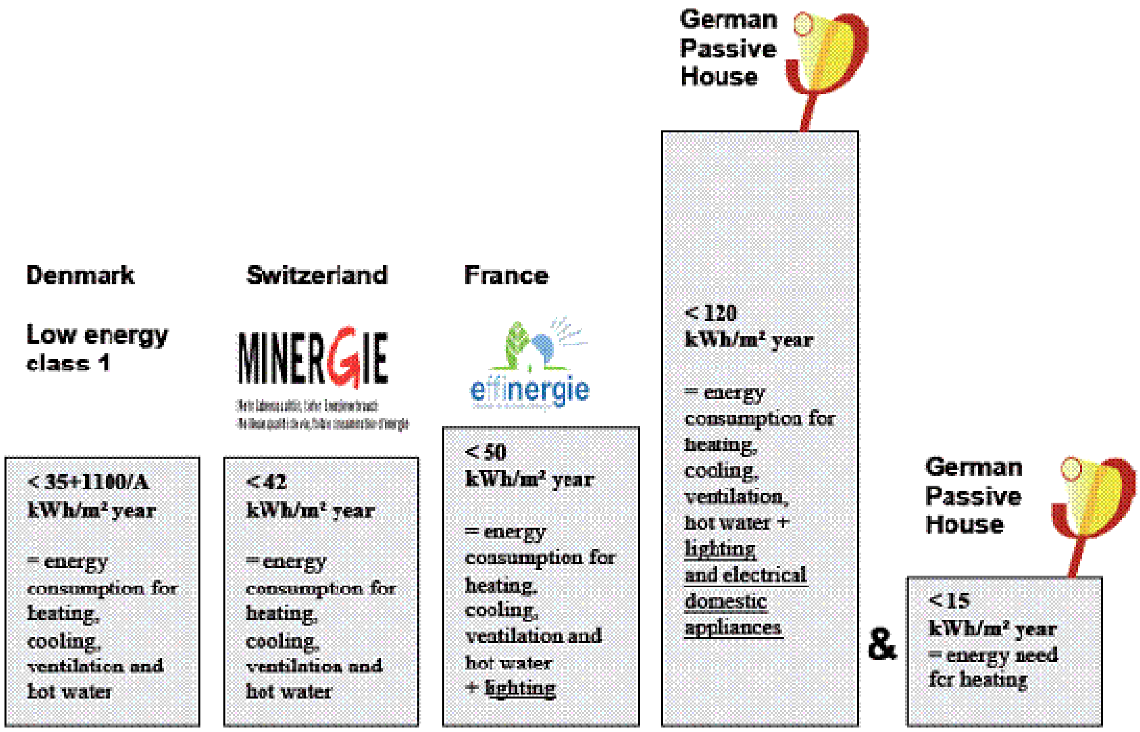
Table 29 Examples of the main national targets for energy building performance for new buildings in several European countries

Country/year	2012	2013	2015	2016	2020
Denmark					-75% compared to 2006 requirements
Germany					Non-fossil fuel buildings
Finland			Low energy buildings (equivalent to Passive house)		
France	Low energy buildings				Energy plus buildings
Ireland		Net zero energy buildings*			
Netherlands			Passive house		Energy neutral buildings
Norway					Low energy buildings (equivalent to Passive house)
United Kingdom		Passive house		Net zero energy buildings	

Source: based on Thomsen *et al.* (2008), Jensen *et al.* (2009); Dyrbøl *et al.* (2009), Dyrbøl (2009)

Figure 26 shows the currently established performance-based standards for energy demand of a building. The standards vary not only by level of ambition but also by the coverage of different energy end-uses.

Figure 26 Performance-based standards in selected countries



Source: Thomsen *et al.* (2008)

The trends in building codes, development in performance-based standards by independent research bodies (e.g. Passive house standard developed by Passivhausinstitut Darmstadt) as well as the recent development in more ambitious targets for new buildings have triggered a need for performance-based modelling approaches of determination of energy saving and CO_2 reduction potential. Novikova (2008) is among the first ones among the reviewed studies that used a simple performance-based framework for calculation of the mitigation potential in new construction which is a part of a component-based residential model for Hungary. Harvey (2009) constructed a generic scenario for future energy use and energy intensity for a given region based on performance-based approach. The study from Jensen *et al.* (2009) is based on a simple performance-based approach, where two scenarios are constructed for new buildings in five countries. The current study is the third known study to use the performance-based approach for determining energy saving and CO_2 reduction potential. At the same time, independent research is being conducted within the framework of the Global Energy

Assessment (GEA), which aims to calculate energy savings potential at a global level with the help of performance-based approach (Ürge-Vorsatz 2010). The current dissertation research is the first known study where the component- and performance-based approaches are compared. The next sections describe the performance-based model in detail.

6.2 Main assumptions in the performance-based approach

The basic assumptions behind the performance-based model are aligned to the component-based model and vice versa, so that the results of the two scenarios can be compared. Similarly to the component-based model, the performance-based model consists of Business-as-usual (BAU) scenario and mitigation scenario (called Passive accelerated scenario). The common basic assumptions include the following:

- Base year is 2005
- Projection period is 2005-2030
- Mitigation action starts in 2011
- In the period 2005-2010 the mitigation scenario is assumed to follow the same trajectory as the BAU scenario
- In the mitigation scenario: all existing buildings (built before 1990) are gradually retrofitted by 2030
- In the mitigation scenario: all new buildings are gradually built to the level of passive house standard by 2019

In addition, the building projections, floor area and other building characteristics as well as heating energy requirements are the same for the respective scenarios in both models.

❖ Business-as-usual scenario (BAU_{perf}) scenario

All new buildings are assumed to be built also according to 2006 Building code (Ministerial order No.7/2006 published in Magyar közlöny, 2006, further 2006 Building code). The Hungarian 2006 Building code represents approximately 50% energy savings compared to the existing buildings built before 1990 (Csoknyai, email com., 2009). In this scenario no further energy efficiency improvements are assumed due to low level of compliance to building codes in the absence of additional policies.[60] Energy consumption of the non-retrofitted buildings is based on the energy audits from the following sources: UNDP/Energy centre (2008), Csoknyai (2008a), Display campaign (2008). Table 30 provides an overview.

This scenario assumes that existing buildings built before 1990 are retrofitted at the natural rate of retrofit (1% p.a., based on Novikova, 2008 and Petersdorff *et al*. 2005) [61] either to level of partial retrofit or to the level of the 2006 Building code. From 2011 the partial retrofit is assumed to account for 33% of all retrofitted buildings and the rest of the existing buildings is retrofitted to the level of 2006 Building code.

Partial retrofit is assumed to result in energy savings of 28% per building, average energy savings reached under Panel program in 66 residential buildings in Székesféhervár (Pájer 2009). This assumption is based on a renovation programme for residential buildings due to the fact that evaluation of energy savings under renovation programme focusing on municipality buildings is not available yet. There are indications that the KEOP programme resulted in very low energy savings in the initial phase (5-10% energy savings, Bencsik 2009),

---

[60] According to Warren (2008) and Hjorn (2008) between 50-65% of new homes do not comply with basic energy standards (in Lechtenböhmer and Schüring *Forthcoming*).

[61] This is also in a line with the assumptions in Lechtenböhmer and Schüring (*Forthcoming*), where the rate of retrofit is 1.2% for North-Western Europe, 0.9% for Southern Europe and 0.7% for Member States which joined EU in 2005 (including Hungary) in 2004. This is assumed to increase to just above 1% in 2010 for the Member States of 2005 accession (Lechtenböhmer and Schüring *Forthcoming*).

and there are plans for larger energy savings under the same programme (53% energy savings to be achieved in 7 municipality buildings under KEOP in Nyíregyháza, Nagy 2009). Nevertheless, as the real realization of this program is uncertain average energy savings in residential buildings is used as a basis for the assumption of partial retrofit.

The energy savings reached under the 2006 Building code are assumed to reach the same level as the one required for the new buildings by the Ministerial order 7/2006 (Magyar közlöny 2006).

Table 30 Assumptions behind BAU scenario

BAU_{perf} scenario	
Existing buildings	• Rate of retrofit: 1% p.a. of the existing buildings built until 1990 • The retrofitted buildings are renovated either to the level of the currently prevailing partial retrofit (28% energy savings relative to building built before 1990) or to the level of 2006 Building code (50% energy reduction compared to buildings built before 1990). • Non-retrofitted: average energy use based on survey of energy audits[62]
New buildings	• All new buildings are built to the level of 2006 Building code

While the costs in the BAU_{comp} scenario depend on the costs of individual components, the costs in BAU_{perf} are based on costs of achieving the performance level. The costs of the new construction built to the level of 2006 Building code are based on ETK in years 2006-2009 (ETK 2006-2009). The cost of the BAU retrofit is a weighted average of partial retrofit and retrofit to the level of 2006 Building code based on the ratio fo the two performance levels on the retrofitted building stock each year. The cost of the partial retrofit is a weighted average based on application of Csider's (2009) costs to the energy retrofit levels reported by Pájer (2009) for Székesféhervár and translated into 2005 price level. The cost of retrofit to the level of 2006 Building code is based also on Csider (2009) for “Complex retrofit” in 2005 price level (although this “Complex retrofit” results on average into 40-45% energy savings, it is

[62] Survey includes energy audits of UNDP/Energy centre (2008), Csoknyai (2008), Display campaign (2008), further referred to only as energy audits.

the best available estimate for the retrofit corresponding to 50% energy savings). The costs of the partial retrofit, 2006 Building new construction and retrofit to the same level are assumed to be constant over time as these technologies are assumed to be already mature and the cost of these technologies is unlikely to decrease over time.

- **Mitigation scenario (Passive accelerated scenario)**

The mitigation scenario (also called Passive accelerated scenario) assumes that all existing buildings built before 1990 are retrofitted by 2030. This assumption implies an accelerated rate of retrofit. The rate of retrofit is on average 4% p.a. of the existing building stock (built before 1990).

The retrofit rate in this scenario is higher than usually assumed in similar studies on potential in the building sector. For instance, Lechtenböhmer *et al.* (2009) assumes an increased rate of retrofit of 2.5% of the existing buildings in their EU-wide scenario assessing mitigation potential by 2020. However, the assumption of Lechtenböhmer *et al.* (2009) applies both to the residential and tertiary buildings and both to Western and Eastern European Member States. The rate of retrofit assumed in the dissertation is higher due to two reasons: first, since the public sector should play an exemplary role in mitigation efforts (Article 5 of the Energy service Directive (ESD) - EC 2006b),[63] we maintain that the public buildings must be retrofitted at much higher speed than residential and other buildings. As a recognition of the exemplary role of the public sector, some countries, such as France, have already started to plan accelerated retrofit in publicly owned buildings (Rockwool 2009).

Second, retrofit of the Central and Eastern European (CEE) existing buildings in the last decades has been lagging behind the total EU-27 average, and thus, it is expected that

[63] Article 5: "Member States shall ensure that energy efficiency improvement measures are taken by the public sector, focussing on cost-effective measures which generate the largest energy savings in the shortest span of time." (EC 2006b)

majority of the public buildings in this region need renovation of some of its building elements or heating systems in the upcoming decades in order to maintain the basic functioning of these buildings.

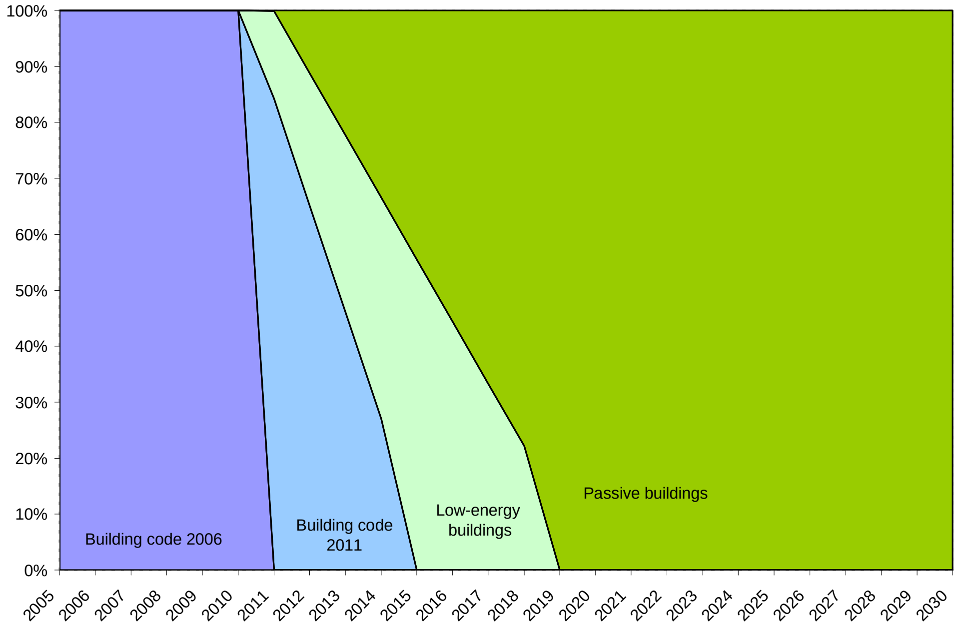
The Passive accelerated scenario assumes that the majority (85%) of the existing buildings (built before 1990) are gradually retrofitted to the level of passive house by 2020. According to Szekér (personal com., 2009) passive retrofit entails more technical difficulties than passive new construction; nevertheless, mass retrofit of the existing public buildings to passive house level is possible with proper training of professionals during the transition period. This implies that in order to achieve the share of 85% passive retrofit on all retrofitted existing buildings the architects, designers and engineers have to be trained intensively on integrated design and passive house techniques, as well as these subjects have to be included in the curricula at the technical universities. The transition towards the passive retrofit includes retrofit to the level of low-energy and so-called 2011 Building code. No partial retrofit is allowed after 2011 (see Table 31).

Table 31 Assumptions behind Passive accelerated scenario

Passive accelerated scenario	
Existing buildings	• All existing buildings (built until 1990) are retrofitted by 2030 • Accelerated rate of retrofit of 3-5% of the existing buildings built until 1990 depending on building type • Out of the retrofitted buildings these performance levels are achieved by 2020: • 5% 2011 Building code • 10% Low energy • 85% PH • Phase-out of partial retrofit: 2011 • Phase-out of 2006 Building code: 2013 • Non-retrofitted: average energy use based on energy audits
New buildings	• All new buildings are PH from 2019 • The rest is assumed 2011 Building code (phase-out in 2015) and low-energy (phase-out in 2019) • Phase-out of 2006 Building code: 2011

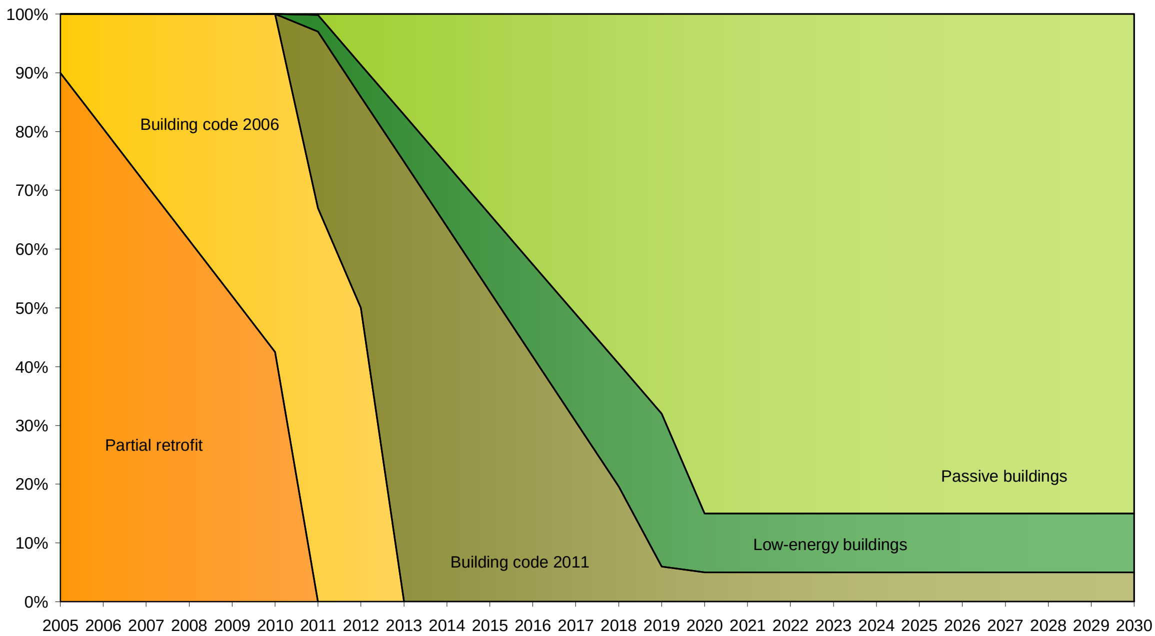
For new construction it is assumed that the 2006 Building code phases-out in 2011. The 2011 Building code will phase-out in 2015 and the low-energy standard in 2019 and thus give way to the full implementation of passive house standard (Figure 27). These assumptions are identical to those in component-based model for new construction as to allow for comparison.

Figure 27 Annual shares of various standards on the new construction stock in Passive accelerated scenario



The existing buildings (built before 1990) are assumed to be retrofitted to the level of 2006 Building code until 2013, when this standard will be banned. From 2011 the buildings can be retrofitted to the level of 2011 Building code, low-energy and passive house level. Building code 2011 is a hypothetical name based on an assumption that the next building code in Hungary should be issued in 2011. This assumption is based on the requirements of the EPBD which prescribes that building standards should be regularly reviewed in periods which should not be longer than five years (EC 2006b). Nevertheless, in time of modelling, there were no plans for this 2011 Building code to be issued yet and thus, it is not included into the baseline. Passive house standard is gradually increasing its share on the stock of annually retrofitted buildings to 85% by 2020. It is assumed that in 2020 buildings which cannot be retrofitted to the level of passive house, will be retrofitted to either 2011 Building code (5% of the retrofitted building stock) or low-energy standard (10% of retrofitted building stock) (see Figure 28).

Figure 28 Annual shares of the performance levels on the retrofitted building stock in Passive accelerated scenario



The heating energy requirement for the passive house standard for new construction is 15 kWh/(m^2.a) (PHI 2003). Although there are several outstanding examples of retrofitting an existing building to the level of 15 kWh/(m^2.a), not all existing buildings can be renovated to such a low level. Therefore the criteria for retrofit to the passive house level issued by Passive House Institute (PHI) are lower than for the new construction - 25 kWh/(m^2.a) PHI (2010). Specific energy requirements (or energy savings as compared to the relevant reference) for the different performance levels are shown in Table 32.

Table 32 Specific energy requirement (kWh/(m^2.a)) or energy savings (%) for different performance levels

Performance level	Type of operation	Specific heating energy requirement (kWh/(m^2.a)), Energy savings (%)	Source
Partial retrofit	Retrofit	28% energy savings compared to BAU retrofit	Weighted average based on Székesfehérvár Panel program (Pájer 2009)

Performance level	Type of operation	Specific heating energy requirement (kWh/(m^2.a)), Energy savings (%)	Source
2006 Building code	New and retrofit	50% energy savings compared to energy use of an existing building	Csoknyai (personal com. 2009)
2011 Building code	New	60 kWh/(m^2.a)	Csoknyai (personal com. 2009)
	Retrofit	60 kWh/(m^2.a)	Csoknyai (personal com. 2009)
Low energy level	New	30 kWh/(m^2.a)	Csoknyai (personal com. 2009)
	Retrofit	45 kWh/(m^2.a)	Average of low energy retrofits (Hegger *et al.* 2009, Richarz *et al.* 2008)
Passive house level	New	15 kWh/(m^2.a)	PHI (2003)
	Retrofit	25 kWh/(m^2.a)	PHI (2010)

The current additional costs for the new passive house are assumed 20% higher than the cost of a building under BAU scenario (Szekér, personal com., 2009). The cost of the passive retrofit is based on the Hungarian experience of passive retrofit of a panel residential building in Dunajváros which is about 2.3 times higher than the conventional retrofit assumed in the model. The cost of the passive standard for new construction is decreasing gradually to the level of 8% additional costs by 2020 (based on Veronica, 2008; Matzig, personal com., 2009 and Csoknyai, personal com., 2009). The cost of passive retrofit is assumed to decrease to 16% by 2020, which is based on an assumption that the additional costs of retrofit will be twice as high as of passive new construction. The cost assumptions of the rest of the performance levels are set in relation to the 2006 BC and passive house level (of their relative reference – new construction or retrofit) (Table 33).

Table 33 Sources and assumptions for cost of achieving different performance levels

Performance level	Type of operation	Investment	Source
Partial retrofit	Retrofit	53 EUR_{2005}/m^2	Weighted average based on application of the costs of Csider (2009) to the retrofits of Pájer (2009).
2006 Building code	New	Depends on building type, (see Table 34)	ETK (2006-2009)
	Retrofit	76 EUR/m^2	Based on cost of "complex retrofit" in Csider (2009).
2011 Building code	New	3% additional to 2006 BC	Csoknyai (personal com. 2009)
	Retrofit	3% additional to 2006 BC	Csoknyai (personal com. 2009)
Low energy level	New	10% additional to 2006 BC	Csoknyai (personal com. 2009)

Performance level	Type of operation	Investment	Source
	Retrofit	20% additional to 2006 BC	Csoknyai (personal com. 2009)
Passive house level	New	20% additional to 2006 BC	Szekér (personal com. 2009)
	Retrofit	211 EUR_{2005}/m^2	Based on SOLANOVA (Hermelink 2007)

Note: prices are shown in Euro2005 exclusive of VAT.

Table 34 shows the costs of new buildings built according to the 2006 Building code by building type. These costs are at 2005 level and exclusive of VAT. After 2008 they are constant, as it is assumed that no more technology learning is possible after that year.

Table 34 Costs of new buildings built according to 2006 Building code, 2005 price level

Type of buildings	Total constr. cost of building, EUR_{2005}/m^2, excl. VAT			
	2005	2006	2007	2008
Educational small buildings	690	714	645	634
Educational large buildings	690	714	645	634
Health care small	867	913	813	796
Health care large	1127	1187	1057	1035
Public administration small buildings	1044	1113	982	958
Public administration large buildings	1044	1113	982	958
Social buildings	867	913	813	796
Cultural buildings	867	913	813	796

Source: ETK (2006-2009)

The cost assumptions for passive and low-energy standard is in line with with fact that the cost of achieving a given energy performance is lower in new buildings than in existing buildings, and the achievable energy performance is much better for new buildings (Harvey 2009). This is due to the fact that some energy efficiency measures can be made only in the design phase of the building construction. For example, the orientation is one of the crucial factors for passive standard design; however, the orientation of an existing building is already given and thus other measures have to be implemented in order to achieve passive energy standard.

Therefore, it is very important that high level of energy performance standards are required in the building codes for the new buildings because the failure to do so represents a significant lost opportunity (Harvey 2009) of further energy savings. Nevertheless, as the existing buildings account for the majority of the current and future building stock and thus represent the majority of the achievable energy saving potential, it is equally important that building standards include provisions for renovation of buildings at the level of requirement of the new buildings.

6.3 Determination of potential via performance-based model

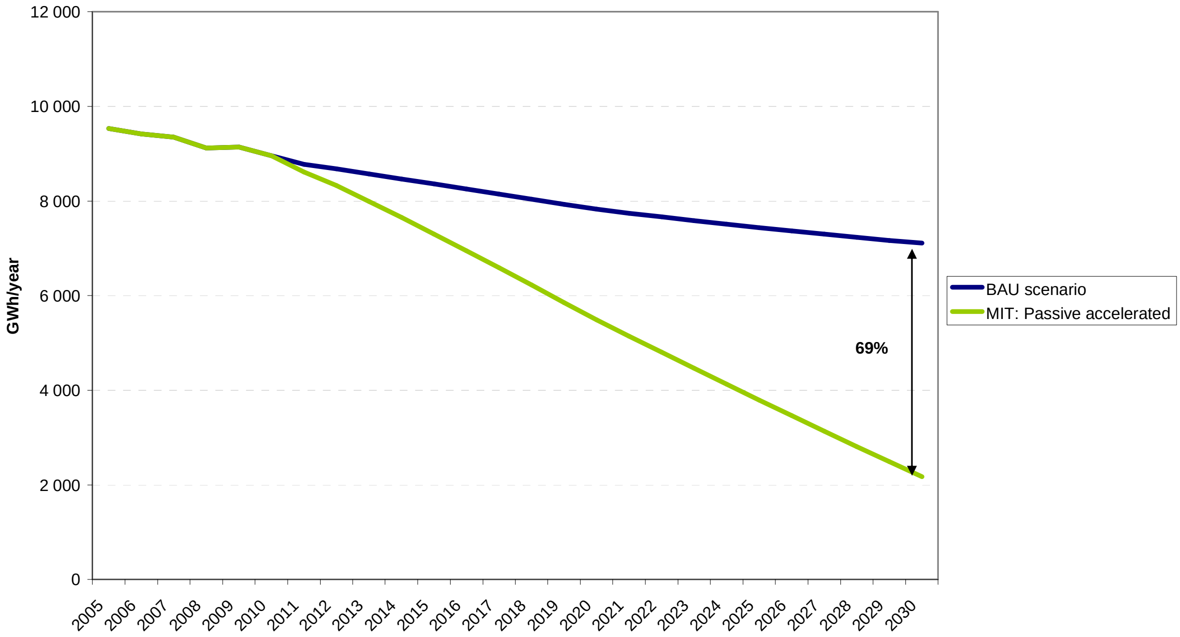
The steps in calculating energy savings and CO_2 reduction potential in the performance-based model are similar to those in the component-based model. However, the most significant difference is that instead of the incremental accounting for the potentials of the individual measures, the performance-based model counts the potential of the renovation of a building as a whole to a certain level of energy performance (2011 Building code, low-energy or passive house standard). Total potential is the difference between the final energy consumption before the mitigation action (BAU scenario) and after the mitigation action (mitigation scenario) (see Figure 8, Chapter 3). Investment costs are calculated based on the additional investment for the mitigation action (e.g. low-energy retrofit, passive retrofit, retrofit at the level of 2011 Building code) and number of buildings undergoing such mitigation action in the particular year (see Chapter 3). The investment of the particular mitigation scenario represents additional cost of such scenario compared to the BAU scenario. This includes both:

- additional costs to the buildings which would have been retrofitted under BAU scenario anyway, and,
- full costs for buildings which are retrofitted in the mitigation scenario above the natural rate of retrofit.

The cost-effectiveness is measured in terms of cost of CO_2 reduced, the calculation of which is based on the same principle as in the component-based model taking into account the cumulative annualized investment, energy cost savings and the reduced CO_2 emissions (see Section 3.3.4, Chapter 3).

The total energy savings in the performance-based model (represented by Passive accelerated scenario) reach approximately 5 TWh in 2030 and this leads to reduction of 981 kt CO_2 emissions. This decrease corresponds to energy savings of 70% compared to the BAU scenario (Figure 29).

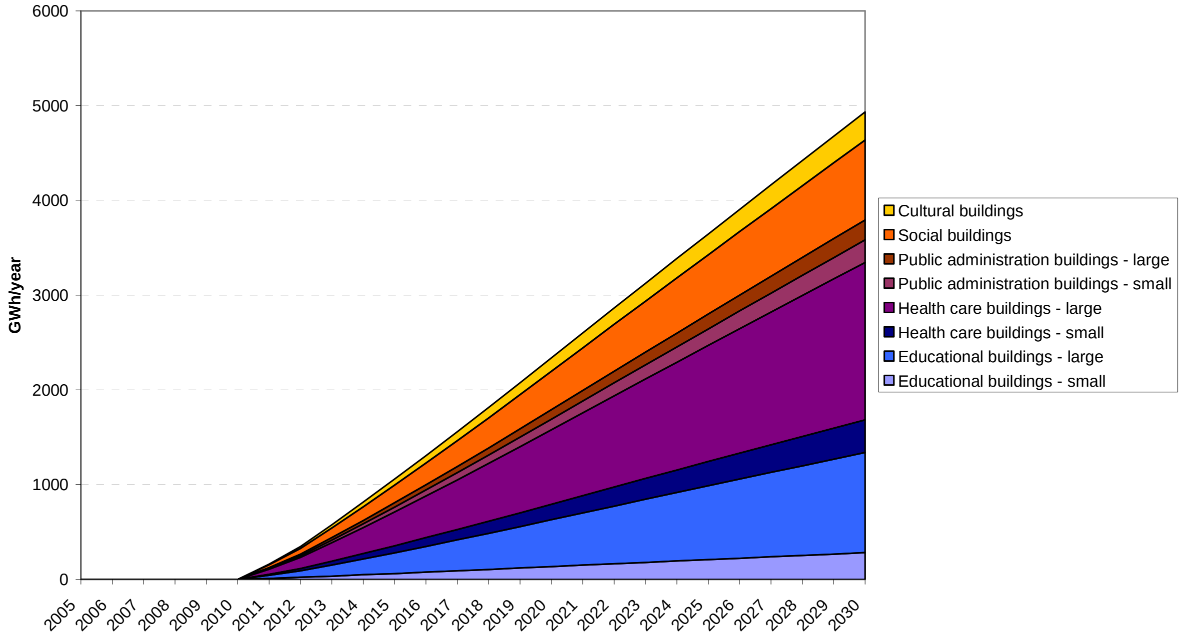
Figure 29 Comparison of mitigation and BAU_{perf} scenario in the performance-based model



6.3.1 Potential by building types

The largest potential is represented by large educational (primary, secondary and tertiary education), large health care (hospitals and medical centers) and social buildings (Figure 30).

Figure 30 Energy savings potential in Passive accelerated scenario by building type (GWh)



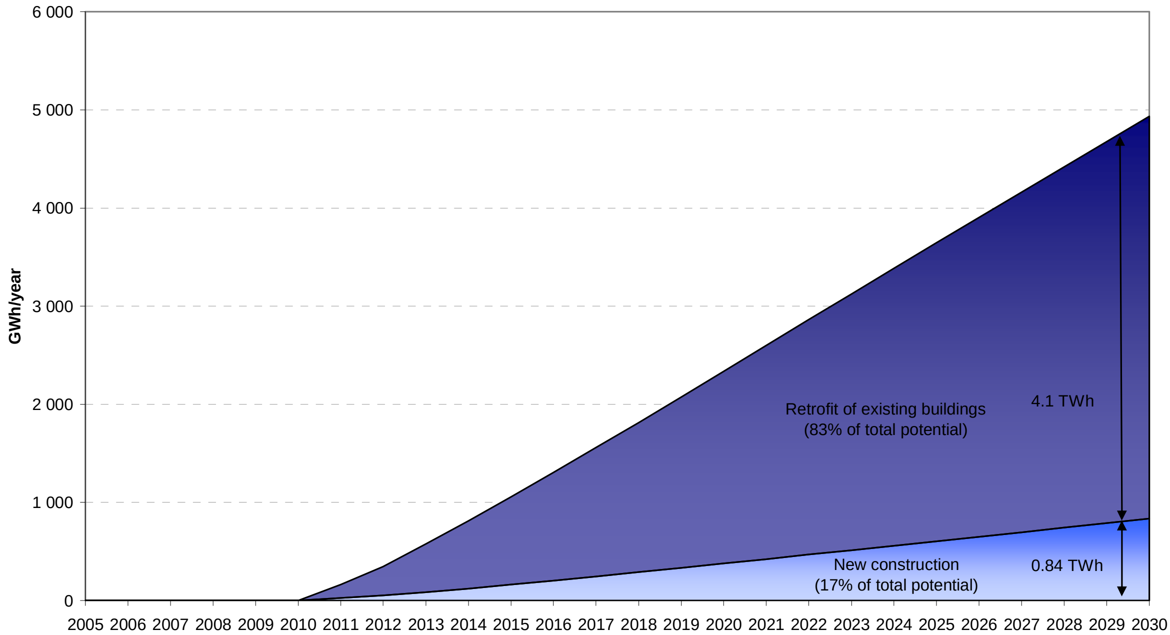
The extent to which a particular building type contributes to the overall potential depends on the specific heating requirement, number and size of the building. Since hospitals and social buildings are relatively low in number, and social buildings are not particularly large, their relatively large contribution to the total potential can be explained by their high specific heating energy requirement. On the other hand, in the case of large education buildings it is the number and the size of the buildings rather than their specific heating requirement that determine their relatively large energy savings potential.

6.3.2 Potential – contribution of new construction and existing buildings

The gradual phase-in of the passive energy retrofit to the whole building stock (Passive accelerated scenario) results in savings of almost 4.1 TWh in 2030. The resulting CO_2 emission reductions account for 0.82 Mt CO_2 emissions. Existing buildings are major contributor (83%) to the total energy savings potential in the public building sector (Figure 31). This can be explained by the larger stock of existing buildings compared to the stock of the new construction, accelerated rate of retrofit of existing buildings, as well as the relatively low average new construction rate in public sector.

Gradual phase-in of the passive house level to new construction can potentially bring 0.84 TWh of energy savings in 2030. These savings corresponds to a reduction of 0.17 Mt CO_2 emissions.

Figure 31 Contribution of retrofit and new construction to the total energy saving potential



6.3.3 Potential by building standards

In total, passive energy standard contributes by major share to the total energy savings potential in the period 2011-2030 (approximately 70%). This is thanks to the gradual phase-in of this standard to majority of the existing buildings and all new buildings by 2019 (Figure 32 and Figure 33).

Figure 32 Contribution of building codes to energy savings for new construction, Passive accelerated scenario

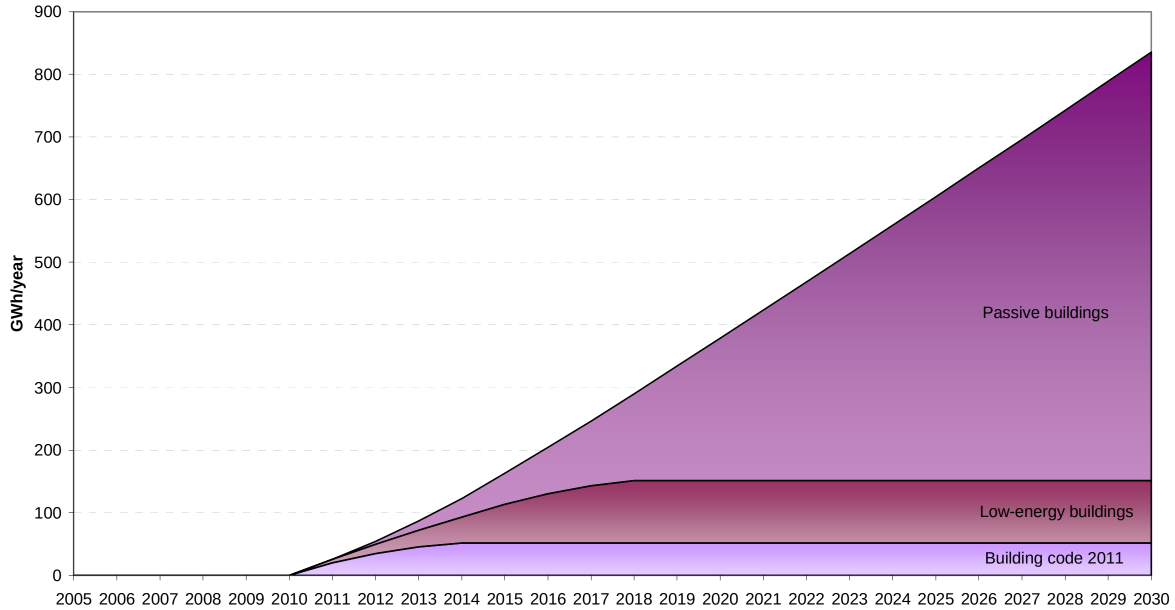
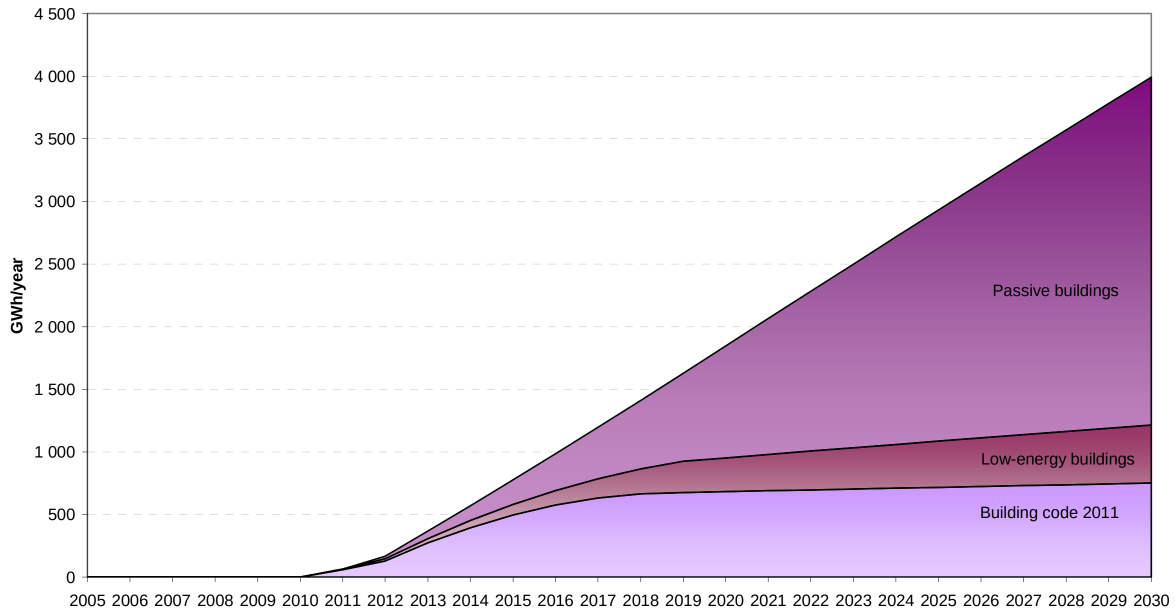


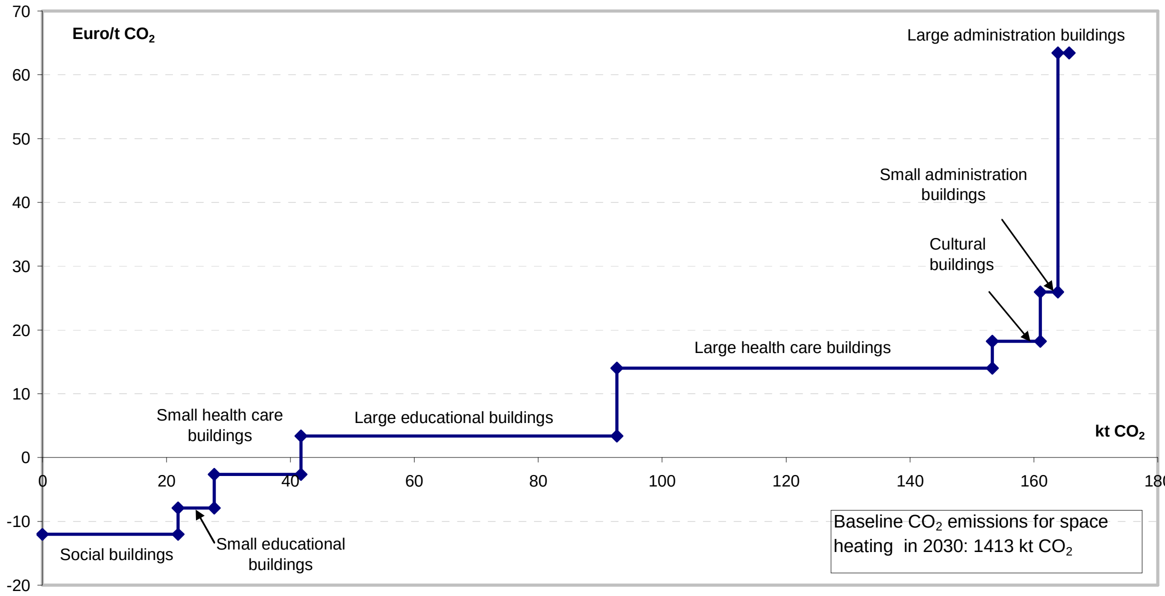
Figure 33 Contribution of building codes to energy savings for retrofit, Passive accelerated scenario



6.3.4 Cost effectiveness

The results of the cost-effectiveness analysis under the Passive accelerated scenario in the performance-based model show that the gradual phase-in of passive house standard is most cost-effective for social buildings both for new construction and retrofit within the projection period. This is due to their extremely high specific heating energy requirement. The social buildings are followed by educational buildings and health care, the order of which is reverse in new construction and retrofit (Figure 34 and Figure 35).

Figure 34 CO_2 mitigation potential in terms of the cost of CO_2 reductions for new construction



The least cost-effective are large administration buildings (in both cases - new construction and retrofit). This is due to a relatively low specific heating energy requirement and the relatively small number of buildings represented by this building type.

Figure 35 CO_2 mitigation potential in terms of the cost of CO_2 reductions for retrofit of existing buildings

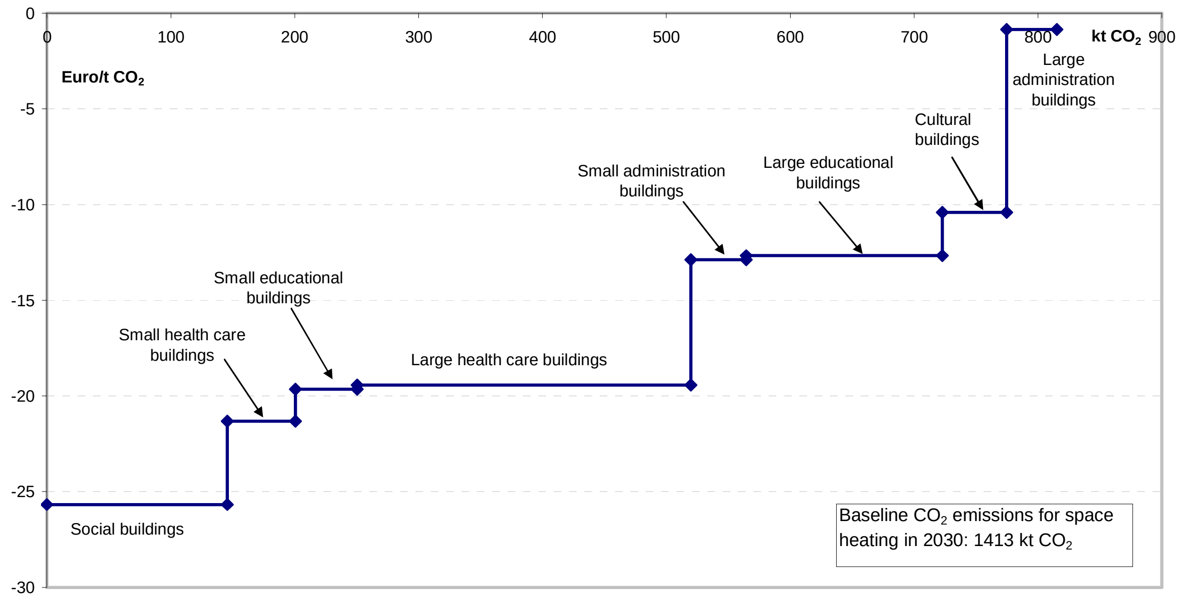


Table 35 shows the potential in the Passive accelerated scenario divided into retrofit and new construction measures, which are ordered by cost effectiveness. All retrofit measures are cost-effective, and several measures applicable to new construction entail negative costs of CO_2 reduction.

Table 35 CO_2 mitigation and energy saving potential in the Passive active scenario

Building type	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Cumulative investment 2011-2030	Cumulative energy cost savings 2011-2030
	kt CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	billion Euro	billion Euro
Public buildings built until 1990	815		4098		1.32	1.36
Retrofit - Small educational buildings	50	-20	252	0.004	0.07	0.08
Retrofit - Large educational buildings	158	-13	797	0.006	0.31	0.26
Retrofit - Small health care buildings	55	-21	277	0.004	0.08	0.09
Retrofit - Large health care buildings	269	-19	1356	0.004	0.40	0.45
Retrofit - Small public administration buildings	45	-13	223	0.006	0.08	0.07
Retrofit - Large public administration buildings	40	-1	202	0.008	0.11	0.07
Retrofit - Social buildings	146	-26	733	0.003	0.16	0.25
Retrofit - Cultural buildings	52	-10	259	0.006	0.11	0.08
Public buildings built after 2005	166		835		0.53	0.27
New construction - Educational small buildings	6	-8	29	0.007	0.01	0.01
New construction - Educational large buildings	51	3	258	0.013	0.16	0.09
New construction - Health care small buildings	14	-3	69	0.008	0.04	0.02
New construction - Health care large buildings	61	14	307	0.011	0.23	0.10
New construction - Public administration small buildings	3	26	14	0.013	0.01	0.00
New construction - Public administration large buildings	2	63	9	0.021	0.01	0.00

Building type	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Cumulative investment 2011-2030	Cumulative energy cost savings 2011-2030
	kt CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	billion Euro	billion Euro
New construction - Social buildings	22	-12	110	0.006	0.04	0.04
New construction - Cultural buildings	8	18	39	0.012	0.03	0.01
Total potential	**981**		**4934**		**1.85**	**1.63**

The most cost-effective measure is Retrofit in the social buildings (Figure 36, Table 36) given by high energy intensity of this type of existing buildings.

Figure 36 Cost curve, Passive accelerated scenario

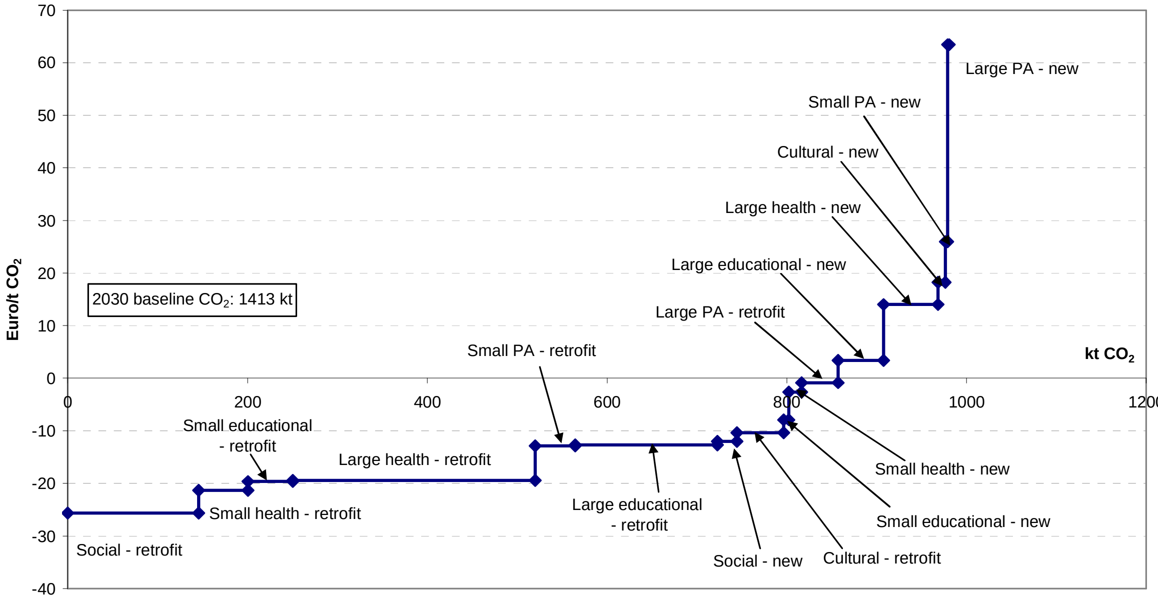


Table 36 CO_2 mitigation and energy saving potential in the Passive active scenario by cost-effectiveness

Building type	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Cumulative investment 2011-2030	Cumulative energy cost savings 2011-2030
	kt CO2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	billion Euro	billion Euro
Retrofit - Social buildings	146	-26	733	0.003	0.16	0.25
Retrofit - Small health care buildings	55	-21	277	0.004	0.08	0.09
Retrofit - Small educational buildings	50	-20	252	0.004	0.07	0.08
Retrofit - Large health care buildings	269	-19	1 356	0.004	0.40	0.45
Retrofit - Small public administration buildings	45	-13	223	0.006	0.08	0.07
Retrofit - Large educational buildings	158	-13	797	0.006	0.31	0.26
New construction - Social buildings	22	-12	110	0.006	0.04	0.04
Retrofit - Cultural buildings	52	-10	259	0.006	0.11	0.08
New construction - Small educational buildings	6	-8	29	0.007	0.01	0.01

Building type	CO_2 savings in 2030	Cost of mitigated CO_2 in 2030	Energy savings in 2030	CCE in 2030	Cumulative investment 2011-2030	Cumulative energy cost savings 2011-2030
	kt CO2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh	billion Euro	billion Euro
New construction - Small health care buildings	14	-3	69	0.008	0.04	0.02
Retrofit - Large public administration buildings	40	-1	202	0.008	0.11	0.07
New construction - Large educational buildings	51	3	258	0.013	0.16	0.09
New construction - Large health care buildings	61	14	307	0.011	0.23	0.10
New construction - Cultural buildings	8	18	39	0.012	0.03	0.01
New construction - Small public administration buildings	3	26	14	0.013	0.01	0.004
New construction - Large public administration buildings	2	63	9	0.021	0.01	0.003
Total	**981**		**4 934**		**1.85**	**1.63**

Cost-effective measures represent the majority of the total energy saving and CO_2 reduction potential in the Passive accelerated scenario (Table 37). None of the measures costs more than 100 Euro/t CO_2. In order to achieve the full potential of the Passive accelerated scenario for both existing buildings and new construction, approximately 1.85 billion EUR is needed on investments in the period 2011-2030.[64] This investment generates energy savings which result in savings on energy costs of 1.63 billion Euro.

Table 37 CO_2 mitigation and energy saving potential in the Passive active scenario by cost groups

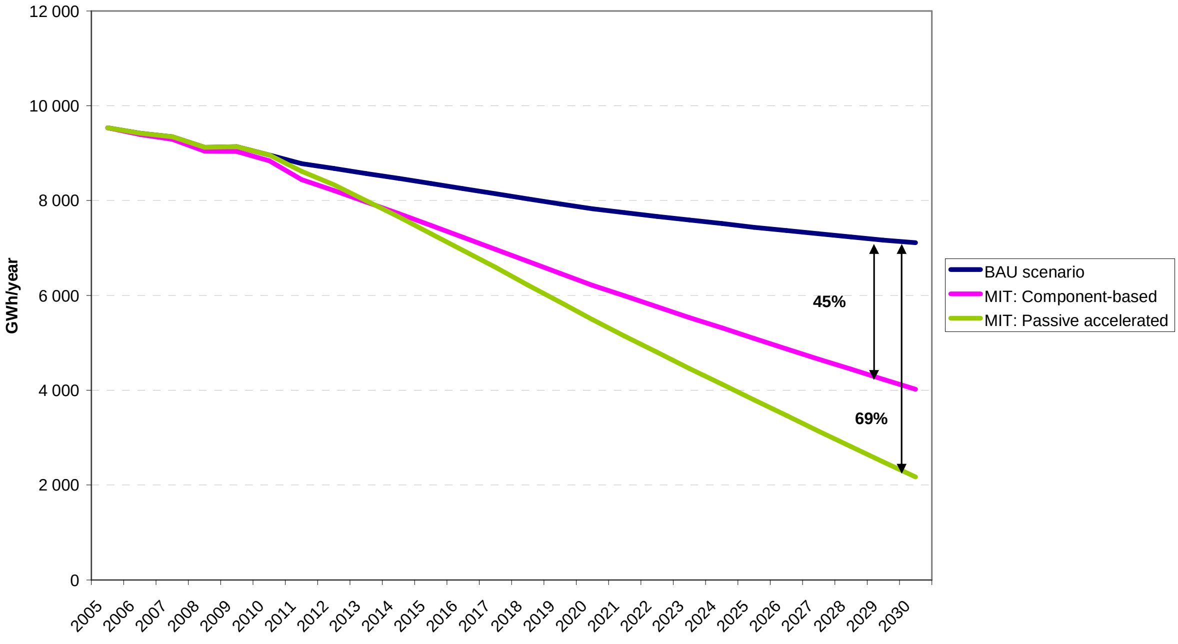
Cost group	CO_2 savings		Energy savings		Investment vs. energy cost savings	
	Cumulative CO_2 savings in 2030	% of the baseline CO_2 emissions in 2030	Cumulative energy savings in 2030	% of the baseline final energy in 2030	Cumulative investments 2011-2030	Cumulative energy cost savings 2011-2030
Euro/t CO_2	kt CO_2/yr.	%	GWh/yr.	%	billion Euro	billion Euro
<0	857	60.7%	4 307	60.6%	1.41	1.43
<20	976	69.1%	4 911	69.1%	1.83	1.62
<100	981	69.4%	4 934	69.4%	1.85	1.63

[64] Note that the cumulative investment is calculated as additional to the investment under BAU scenario. This includes both the investment that is above the BAU investment for the buildings which are retrofitted both under the BAU and mitigation scenario, as well as full investment for the buildings which are retrofitted beyond the natural rate of retrofit.

6.4 Comparison of the potential in the component-based and performance-based models

While the application of the individual abatement technologies in the component-based approach delivers an energy saving potential of approximately 3.2 TWh, the performance-based approach shows a much higher potential – 4.9 TWh (Figure 37), while the cost-effectiveness of the latter is much higher.

Figure 37 Comparison of the energy saving potential between the component-based and performance-based modelling approach



In both cases the energy cost savings offset the investment needed for implementation of the energy saving measures considered in the model (Table 38).

Table 38 Comparison of the results between the component-based approach and performance-based approach

	Energy savings and CO_2 reduction potential				Investment vs. savings	
	Energy savings potential in 2030	CO_2 mitigation potential in 2030	Total potential	Cost-effective potential	Total annual additional investment	Energy cost savings
Scenario/Unit	GWh	kt CO_2	% of BAU	% of BAU	billion Euro	billion Euro
Component-based model	3 238	645	45%	21%	1,72	1,21
Performance-based model (Passive accelerated scenario)	4 934	981	69%	61%	1,85	1,63

Comparison of the component-based and performance-based models reveals a vast difference of determination of mitigation potential by various modelling approaches.[65] This difference can be explained by several factors:

First, part of the difference in the two approaches can be explained by the application of several layers of high performance levels in the performance-based approach. While in the component-based approach the building components currently available on the market are assumed to be implemented over the whole modelling period with the same technical features, in the performance-based approach three different performance levels are assumed (the 2011 Building standard, low-energy and passive house standard). This multi-layered application of the different performance levels better represents the development of the construction market. During large part of the projection period, these three levels occur at the same time. Therefore, the phasing-in of several different performance levels at the same time could lead to higher energy savings than implementing only one type of energy performance level over the whole projecting period (as in the component-based model). The multi-layer application of different measures at the same time is not possible in the current Excel-based component-based model.

Second, another part of the difference is due to a so-called "synergy effect" that occurs when principles of passive house standard and integrated design are applied to construction or retrofit of the building. However, it is not known what portion of the difference this effect accounts for, as no quantification of this effect has been provided in the reviewed literature yet. The synergy effect gap between the two approaches implies that component-based approach is unable to incorporate certain techniques that are necessary when passive house standard is aimed for, such as ensuring air-tightness of the building through door-blow test of

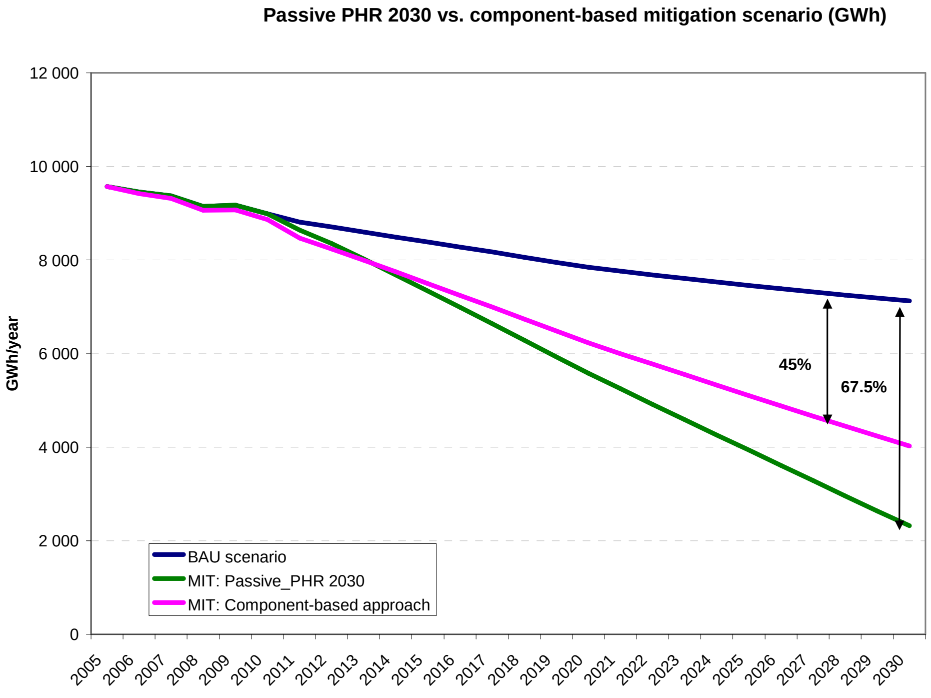
[65] Although BAU scenarios are based on different underlying assumptions in the two approaches, the resulting energy use and CO_2 emissions are very similar (see Annex III). Thus, difference in BAU is not playing any role in the difference between the results of the two approaches.

the building and elimination of heat leakages, elimination of thermal bridges, utilization of heat gains and thermal mass etc. Even if passive house components are applied to a building, it would not reach the passive house level without these passive house techniques. Therefore accounting only for the separate measures cannot ensure reaching the high efficiency level without these techniques. This may apply also to other performance levels, such as low-energy standard and 2011 Building code. And even if one attempts to estimate the potential and the costs of these highly specialized techniques (which would be already very ambitious endeavour), they cannot be applied in a piece-meal manner in order of cost-effectiveness, because they must be integrated across all phases of the building construction or retrofit. Therefore, the energy savings calculated through the component-based model cannot be as high as in the performance-based approach, which considers high efficiency performance levels of the building as a whole, and thus includes usage of the above mentioned passive house techniques.

Third, a part the difference between the two approaches can be explained by different assumptions behind the mitigation scenarios. While in the component-based scenario the high efficiency measures available on the market are applied in a uniform manner during the whole projection period (2011-2030), in the performance-based Passive accelerated scenario it is assumed that majority of the renovated buildings are retrofitted to the level of passive house standard by 2020. This target year is based on the revision of the EPBD directive (EC 2010) which sets strict requirements for new construction and major renovation. Thus, this assumption could imply that the performance-based approach is more ambitious than the mitigation scenario of the component-based model and thus, it may contribute to the gap between the two approaches.

As the Passive accelerated scenario was constructed in order to address the first research question of the Objective 1 of the dissertation (What is the optimal path towards significant reduction of energy use in the Hungarian public buildings up to 2030 considering the best available technologies on the market?), the assumptions behind this scenario are valid. However, in order to eliminate the effect of more ambitious targets in performance-based Passive accelerated scenario, another scenario was constructed, named Passive_PHR 2030, in order to better resemble the assumptions of the component-based mitigation scenario. Passive_PHR 2030 is based on an assumption that majority (85%) of the renovated buildings are retrofitted to the level of PHS by 2030 (and reaching only 30% of retrofitted buildings in 2020). The analysis showed however, that this assumption does not have a significant effect on reducing of the gap between the two modelling approaches (Figure 38).

Figure 38 Comparison of component-based and performance-based scenario



Therefore, the gap can be explained by the multi-layer application of the high efficiency performance layers and the synergy effect that can be reflected only by the performance-based approach.

Summary

This chapter presented the findings of performance-based modelling used for determination of the energy saving and CO_2 mitigation potential. The results show that this approach yields a 70% reduction compared to the 2030 BAU energy use in the Hungarian public buildings. This is much higher potential than the one estimated under the component-based model (approximately 45% of the 2030 BAU energy use, see Chapter 6). The difference between the two approaches (25% of 2030 BAU energy use) can be explained by difference in the modelling approach (multi-layered application of different high efficiency performance levels in the performance-based approach) and existence of the synergy effect of the holistic approach to the retrofit of the existing buildings. Therefore, they lead to different results. Nevertheless, using performance-based model proved to be a suitable modelling policy support tool. The biggest advantage of this approach is its flexibility and user-friendliness. This flexibility is given by the fact that the model does not deal with the components and the overall potential does not have to be calculated via iterations of individual measures. The flexibility is advantageous both for a. policy makers and b. designers and planners. The policy makers can utilize the model directly without having to rely on time-demanding and costly analyses of external modellers and consultants. Performance-based approach allows the user to change the timing of the implementation of the projected regulations and simultaneous implementation of different energy performance levels in the particular year. This is a clear advantage over the robust component-based approach, and makes the performance-based approach a suitable tool for modelling transition towards the radical reduction of energy and CO_2 emissions which needs to happen in the next 10-15 years in order to avoid dangerous climate change. Another, related, advantage is that the performance-based model can be easily updated by the user once new data occur.

On the other hand, the regulation based on performance-based approach gives a more flexibility to the designers and planners as they can choose the optimal combination of building components which fulfills the different required performance-based levels. However, this flexibility comes with increased responsibility for implementing the principles of integrated design from the very beginning of the design process, close cooperation of designers, developers, constructors and users, intensive training of architects and constructors and usage of computer models for optimization of the used building components that will guarantee the required performance level of the building. Moreover, like in the component-based approach, successful utilization of the existing potential (determined by the performance-based approach) requires timely implementation and strict enforcement accompanied by appropriate policies providing an enabling environment for energy efficiency measures (such as preferential loans and tax reductions conditioned on reaching very low energy performance levels).

The flexibility of the approach is shown in the next chapter where the performance-based model is used for construction of four scenarios representing different extents of mitigation effort in the public sector in Hungary.

CHAPTER 7. ASSESSMENT OF SCENARIOS - PATHWAYS TOWARDS A LOW-CARBON FUTURE

This chapter uses the performance-based approach (described in Chapter 6) for the construction of four scenarios. The scenarios represent different pathways that can lead to a low-carbon future and evaluates each of them in terms of energy savings and CO_2 mitigation potential, associated costs and energy costs savings.

This chapter first presents the studies where the performance-based approach has been used in scenario analysis already and how the current study contributes to development in this area. Then the assumptions of the scenarios are presented, followed by results, analysis and conclusions.

7.1 Performance-based approach used in scenario analysis in the building sector

To date, only a few sources have used the performance-based approach for modelling energy savings or CO_2 mitigation potential. First, Harvey (2009) presents a generic scenario for future energy use and energy intensity and formulates possible equations. The scenarios represent six cases varying based on the growth of the building area and the extent and timing of the reductions in energy intensity of new and old buildings. The second source using the performance-based approach for scenario analysis is a project conducted by Danish Building Research Institute (SBi) and described in Jensen et *al.* (2009) and Dyrbøl et *al*. (2009). The project presents the plans of five European member states to gradually implement the very low energy buildings (VLEB) as national standards for new buildings (see Table 29 for detail). The study constructs two scenarios – one projecting a gradual move towards the VLEB and one moving directly to the VLEB for all new buildings starting from 2009 (Jensen et *al*. 2009; Dyrbøl *et al*. 2009). The study distinguishes two categories within the considered building stock: residential and non-residential buildings. The scenarios logically show that there is significantly more potential when the VLEB standards are implemented as soon as possible. Along with the current research performance-based scenario analysis has been constructed (e.g. Ürge-Vorsatz 2010), and thus these two models are the first which examine the potential for both new and existing buildings. The value added of the dissertation model *i.a.* is that the model determines the cost-effective potential for different scenarios.

7.2 Main assumptions in the scenarios

The main objective of constructing the scenarios is to show different trajectories of mitigation action in the public sector. Specifically, the scenarios are aimed to show the following:

- a path towards sustainable building stock which significantly reduces the energy consumption in public buildings (by 2030)
- a path resulting from retrofitting the whole building stock (by 2030) at lower standards than the best available technology but which is prevalently applied today
- factors that influence development of the energy savings potential in different paths.

To fulfill these objectives four types of scenarios are constructed - one baseline (BAU) and three mitigation scenarios:

- BAU scenario
- Suboptimal accelerated scenario
- Passive 1% scenario
- Passive accelerated scenario

All three mitigation scenarios have the following common features:

- Base year is 2005
- Projection period is 2005-2030
- Mitigation action starts in 2011

- In the period 2005-2010 the mitigation scenarios are assumed to follow the same trajectory as the BAU scenario.
- All new buildings are built as PH as from 2019

In the following text the assumptions behind the four scenarios are described.

❖ Business-as-usual (BAU) scenario

As a BAU scenario BAU_{perf} used as a basis for the Passive accelerated scenario (described in Chapter 6) is used as BAU for all three mitigation scenarios in the scenario analysis. Table 39 provides details.

Table 39 Assumptions behind BAU scenario

BAU_{perf} scenario	
Existing buildings	• Rate of retrofit: 1% of the existing buildings built before 1990 • The retrofitted buildings are renovated either to the level of the currently prevailing partial retrofit (28% energy savings relative to building built before 1990) or to the level of 2006 Building code (50% energy reduction compared to buildings built before 1990). • Non-retrofitted: average energy use based on survey of energy audits[66]
New buildings	• All new buildings are built to the level of 2006 Building code

❖ Suboptimal accelerated scenario

The Suboptimal accelerated scenario assumes that all existing buildings (built until 1990) are retrofitted by 2030 (this implies accelerated rate of retrofit on average 4.6% p.a.). This scenario assumes that from 2011 most of the existing buildings (built until 1990) are retrofitted to the level of partial retrofit, while a small part is retrofitted to the level of 2006 Building code (which is continuation of the current, BAU trend). The partial retrofit is assumed to yield 28% reduction of energy consumption compared to the existing buildings (built before 1990).

[66] Survey includes energy audits of UNDP/Energy centre (2008), Csoknyai (2008), Nagy (2008).

This assumption is based on average energy savings reached through a retrofit programme in residential buildings – so-called Panel program in Székesféhervár (Pajér 2009), as no such data is currently available for the public buildings. This is due to the fact that although similar programme exists in public building sector, however, the energy savings of this programme have not been evaluated on the national level yet. It is assumed that since the Panel program was applied to hundreds of residential buildings across Hungary, similar energy savings apply to public buildings.

Partial retrofit means that only some building elements are renovated/replaced. For instance some of the renovation projects in Székesféhervár included only thermal insulation, another group added exchange of windows/doors while in the last group the insulation and window/door exchange was accompanied by renovation of heating system (energy savings in these groups were 18%, 26% and 36% p.a., respectively, the weighted average of which is 28% per building) (Pajér 2009).[67] For summary of the main assumptions see Table 40.

Table 40 Assumptions behind the Suboptimal accelerated scenario

Suboptimal accelerated scenario	
Existing buildings	• All existing buildings (built before 1990) are retrofitted by 2030 • Accelerated rate of retrofit of 4.6% of the existing buildings built before 1990 depending on building type (in 2005) • Out of the retrofitted buildings: 100% Suboptimal retrofit (28 % energy savings[68] compared to the energy consumption of buildings built before 1990) • Phase-out of 2006 Building code: 2011 • Non-retrofitted: average energy use based on UNDP/GEF audits
New buildings	• All new buildings are built to the level of PH from 2019

[67] Note that there are exceptions to the rule, and also renovation projects with higher energy savings are being implemented currently. For instance, energy savings should reach 53% in the project "Thermal insulation of public buildings" in Nyíregyháza under KEOP (KEOP-2009-5.30/A) (Nagy 2009) and 59% under the projects implemented by DVD Ltd. (own calculation based on Balaci, personal com., October 2009). These projects are, however, limited in number and their effect on sector's energy use at national level is hardly significant (DVD Ltd. has so far accomplished about 60 renovation projects).

[68] The energy savings potential of 28% is based on the average energy savings potential in the Panel program in Székesféhervár (Pájer 2009).

The costs of the partial retrofit are calculated by applying Csider's (2009) costs to the energy retrofit for Székesféhervár's Panel program (Pájer 2009). This cost is assumed to be constant over time as the technology is already mature and thus, there is no possibility for technology learning. Assumptions on new construction are the same as in the Passive accelerated scenario.

❖ Passive accelerated scenario

The Passive accelerated scenario is the same scenario as the one presented in Chapter 6 as the most ambitious mitigation scenario representing the performance-based approach. The main assumptions for building stock development are summarized in Table 41. Details on cost assumptions in the Passive accelerated scenario can be found in Chapter 6.

Table 41 Assumptions behind Passive accelerated scenario

Passive accelerated scenario	
Existing buildings	• All existing buildings (built before 1990) are retrofitted by 2030 • Accelerated rate of retrofit of approximately 4% p.a. of the existing buildings built before 1990 • Out of the retrofitted buildings these performance levels are achieved by 2020: • 5% 2011 Building code • 10% Low energy • 85% PH • Phase-out of partial retrofit: 2011 • Phase-out of 2006 Building code: 2013 • Non-retrofitted: average energy use based on UNDP/GEF audits
New buildings	• All new buildings are PH from 2019 • The rest is assumed 2011 (phase-out in 2015) and low-energy (phase-out in 2019) • Phase-out of 2006 Building code: 2011

❖ Passive 1% scenario

The Passive 1% scenario assumes that the existing buildings (built before 1990) are retrofitted to the level of passive, low-energy and 2011 Building code in such a way that the passive buildings make up the majority of the retrofitted buildings by 2020 (85% of the retrofitted building stock, and this remains constant until 2030). As the title reveals this scenario assumes a natural rate of retrofit (1% p.a. of existing buildings built before 1990). All new buildings are assumed to be built gradually to the level of passive standard by 2019, with a transition period including low-energy and 2011 Building code standards (Table 42).

Table 42 Assumptions behind Passive 1% scenario

Passive_1% scenario[69]	
Existing buildings	• Rate of retrofit: 1% of the existing buildings built before 1990 • Out of the retrofitted buildings these performance levels are achieved by 2020 • 5% 2011 Building code • 10% Low energy • 85% PH • Phase-out of partial retrofit: 2011 • Phase-out of 2006 Building code: 2013 • Non-retrofitted: average energy use based on UNDP/GEF audits
New buildings	• All new buildings are PH from 2019 • The rest is assumed 2011 (phase-out in 2015) and low-energy (phase-out in 2019) • Phase-out of 2006 Building code: 2011

The assumptions behind the costs for the different building standards and building types are the same as in the Passive accelerated scenario (see Chapter 6). The shares of the building standards on the new construction and retrofitted building stock are also the same for both Passive 1% and Passive accelerated scenarios.

Figure 39 and Figure 40 show the shares of building standards on the new construction and retrofitted building stock, respectively, in the Passive 1% scenario. These shares are the same as in the Passive accelerated scenario. The only difference between these two scenarios is the size of building stock to which the shares of retrofitted buildings are applied (1% p. a. of existing buildings built before 1990 in Passive 1% scenario and the total existing building stock built before 1990 in Passive accelerated scenario).

[69] The tables for the mitigation scenarios (Passive 1%, Passive accelerated and Suboptimal accelerated scenarios) describe solely the mitigation action, i.e. the action in period 2011-2030. In the period 2005-2010 the same assumptions apply as for BAU scenario.

Figure 39 Shares of various standards on the new construction stock in Passive 1% and Passive accelerated scenario

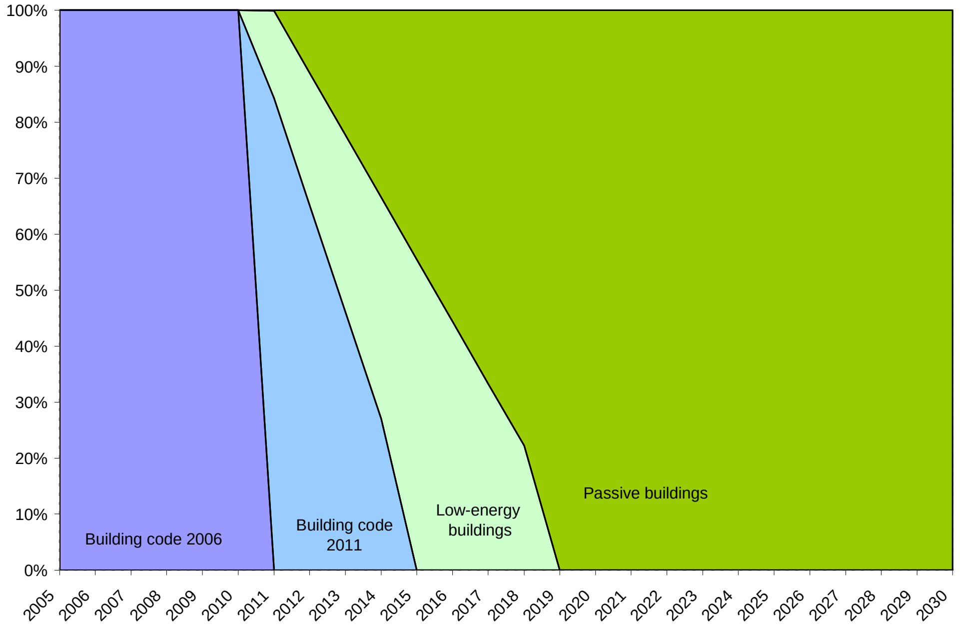


Figure 40 Shares of the building standards on the retrofitted building stock in Passive 1% and Passive accelerated scenario

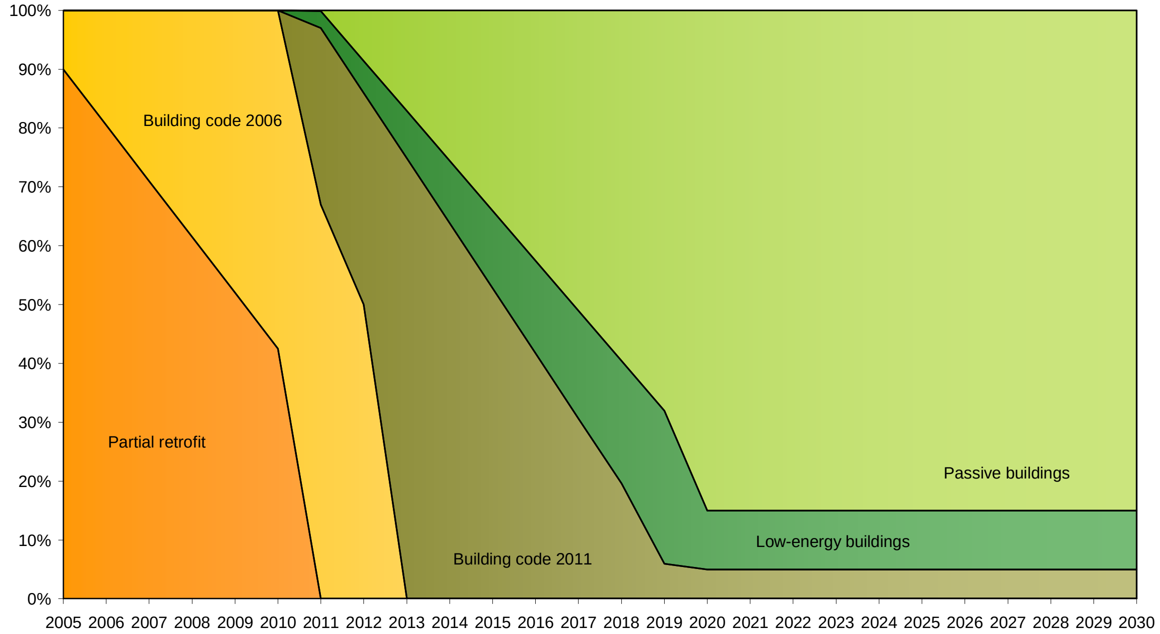


Table 43 summarizes the assumptions of the three mitigation cases and the BAU scenario.

Table 43 Assumptions for the four scenarios

Scenario assumptions	
BAU_{scen}	Existing buildings: retrofitted at 1% p.a. to the level of partial retrofit or 2006 Building code
	New buildings: according to 2006 Building code
All mitigation scenarios	New buildings: ❖ All new buildings are PH from 2019 ▪ The rest is assumed 2011 (phase-out in 2015) and low-energy (phase-out in 2019) ▪ Phase-out of 2006 Building code: 2011
Passive accelerated scenario	Existing: ❖ All existing buildings (built until 1990) are retrofitted by 2030 • Out of the retrofitted buildings these performance levels are achieved by 2020: • 85% PH • 10% Low energy • 5% 2011 Building code
Passive 1% scenario	Existing: ❖ Rate of retrofit: 1% p.a. of existing buildings ❖ Retrofitted: ❖ 85% PH ❖ 10% Low energy ❖ 5% 2011 Building code
Suboptimal accelerated scenario	Existing: • All existing buildings (built before 1990) are retrofitted by 2030 • Accelerated rate of retrofit • Majority buildings retrofitted to the level of partial retrofit, a small share of existing buildings retrofitted to the level of 2006 Building code

Assumptions for new buildings are the same in the three mitigation scenarios as to allow comparison of the effect of the rate and level of retrofit on the total and cost-effective energy saving potential in the existing buildings. This is based on the recast of the EPBD, which requires all new buildings occupied or owned by public authorities be built as near-to-zero energy buildings (EC 2010). The cost of achieving different energy performance levels are summarized in Table 33.

Note, that the costs of the passive standard for new construction are decreasing gradually to the level of 8% additional costs by 2020 (based on Veronica, 2008; Matzig, personal com., 2009 and Csoknyai, personal communication, 2009) and to the level of 16% for retrofit. All cost assumptions are the same as in Passive accelerated scenario.

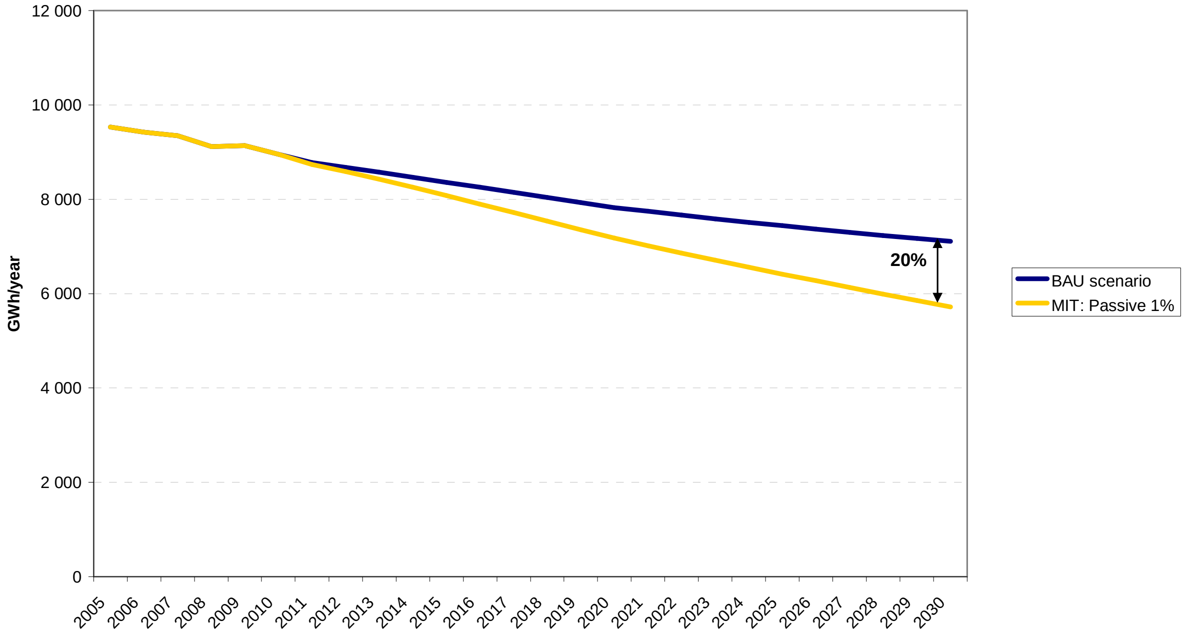
7.3 Plotting the results of the scenarios: four pathways into the future

This section provides the results of the modelling energy savings potential in each of the mitigation scenarios which are compared to the Business-as-usual scenario.

❖ Passive 1% scenario - results

The Passive 1% scenario projects development in energy savings potential when buildings currently retrofitted at natural rate of retrofit would be gradually retrofitted to the highest possible level of energy performance considered in the model – passive energy standard. The scenario shows that such an approach brings energy savings of 1.4 TWh (and 276 kt CO_2) by 2030, which corresponds to 20% energy savings compared to the BAU scenario (Figure 41).

Figure 41 Comparison of Passive 1% and BAU scenario



In both new construction and retrofit the passive house standard contributes significantly to the total energy savings potential. Figure 42 shows development of the contribution of the three building standards to the potential in 2011-2030 for new construction and

Figure 43 for retrofit of existing buildings.

Figure 42 Contribution of building codes to energy savings for new construction, Passive 1% scenario

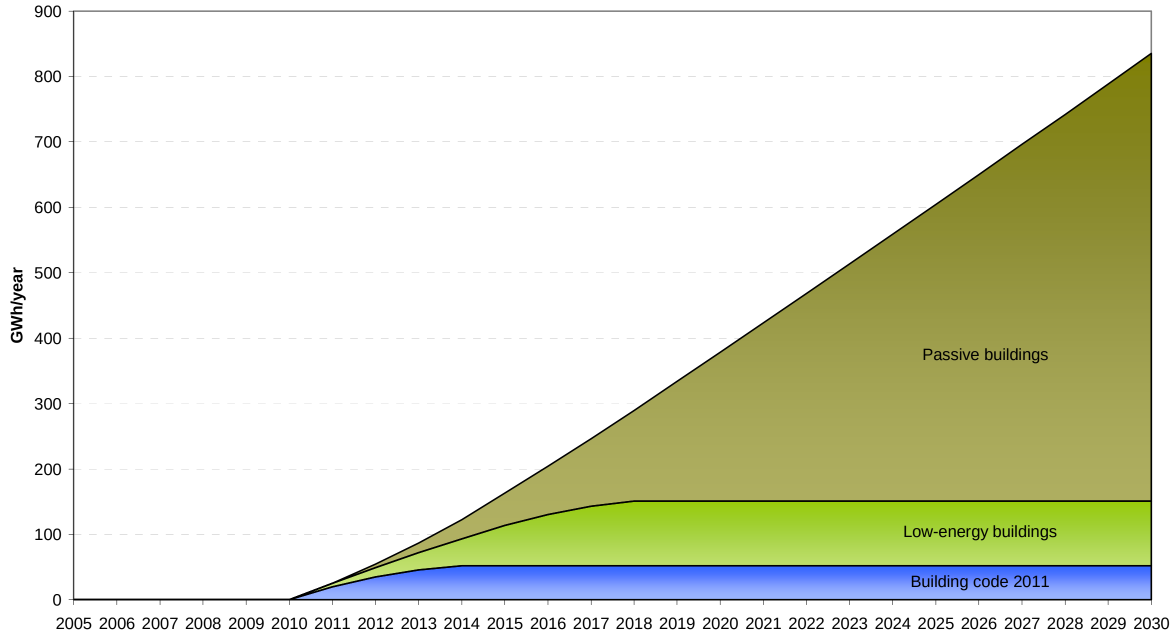
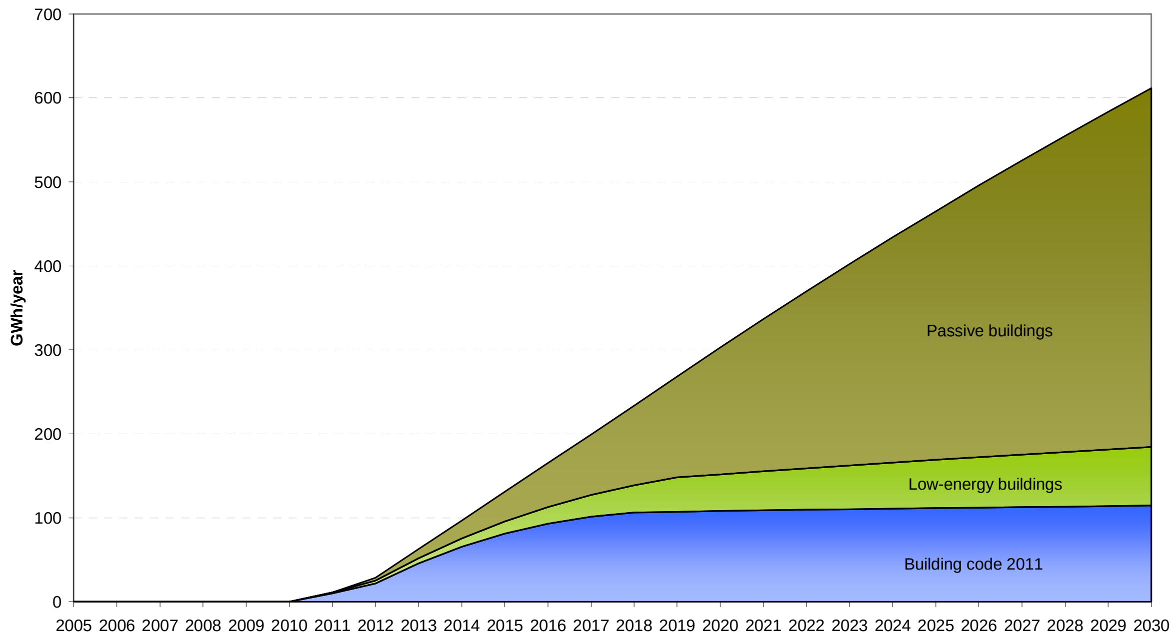


Figure 43 Contribution of building codes to energy savings for retrofit, Passive 1% scenario

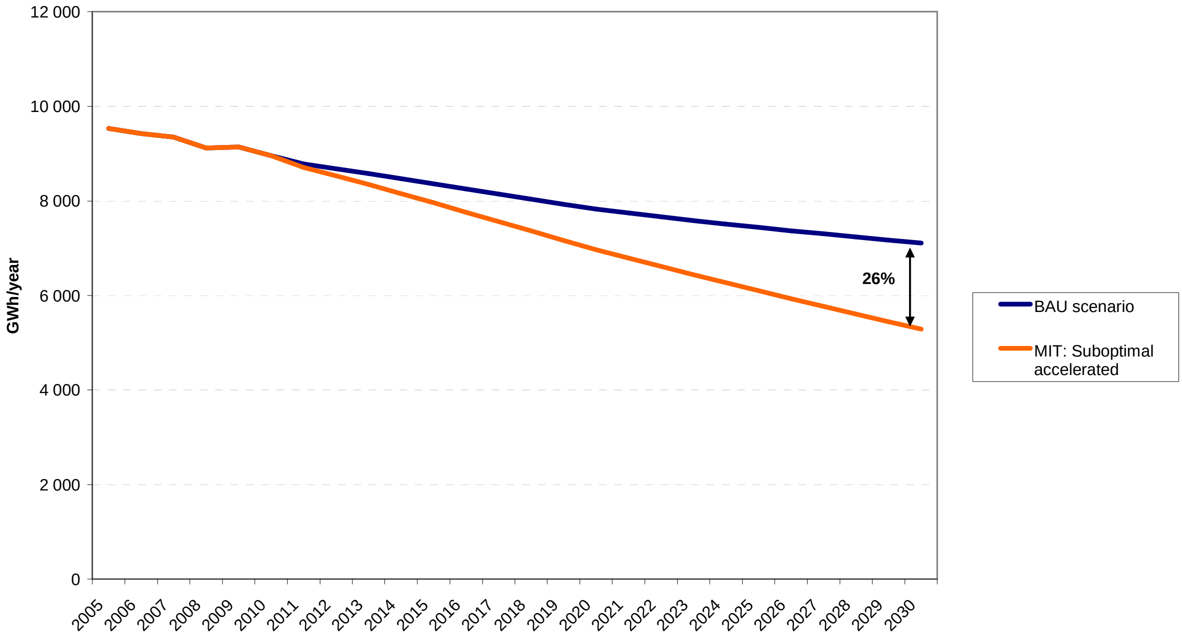


The total investment needed to realize the energy savings projected in the Passive 1% scenario reaches 0.61 billion EUR by 2030, and the energy cost savings generated by this investment equals to 0.46 billion EUR in the same period.

❖ Suboptimal accelerated scenario - results

Suboptimal accelerated scenario shows the energy savings potential for the next several decades provided that the current trend of energy efficiency programs is extended to cover the whole public building stock until 2030. The Suboptimal accelerated scenario leads to energy savings of 1.8 TWh (361 kt CO_2), which translates into 26% reduction of the final energy consumption when compared to the BAU scenario (Figure 44).

Figure 44 Comparison of Suboptimal accelerated and BAU scenario

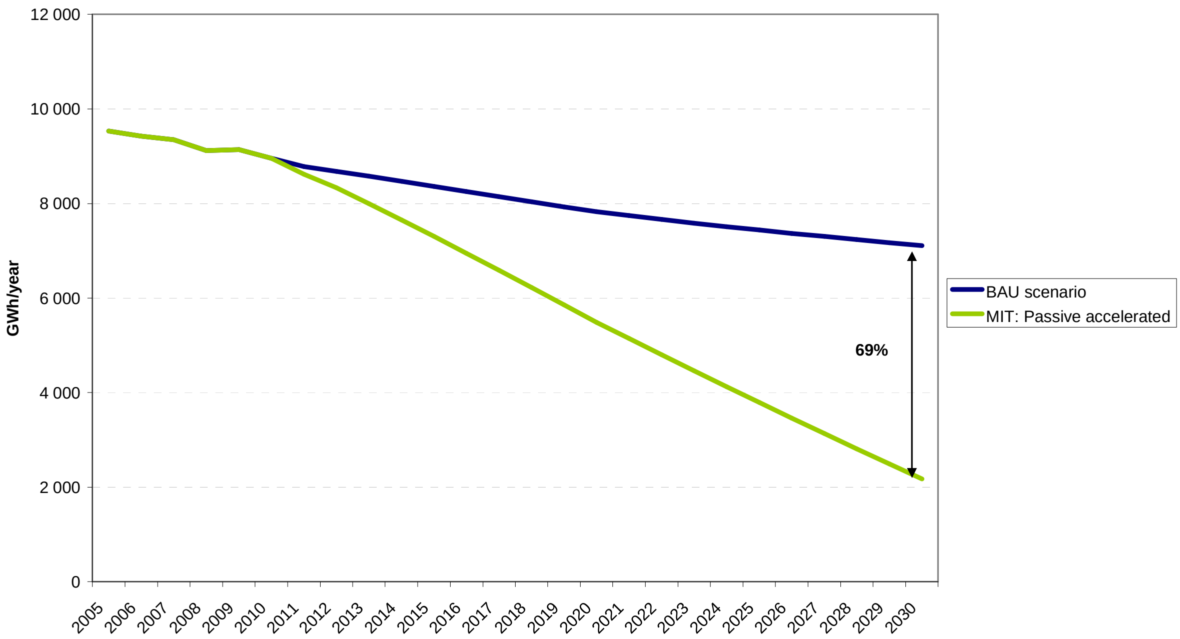


The total investment that would be spent on accelerated implementation of partial retrofit is 1.32 billion EUR in 2011-2030, while the energy cost savings are 0.60 billion EUR in the same period. This means that although this scenario requires high initial investment, it does not result in high energy cost savings, compared to the other large-scale scenario. Moreover, if all existing buildings are retrofitted to this suboptimal level by 2030, the opportunities to save more energy would be lost for several next decades, until the next renovation of these buildings is necessary. This leads to locking-in the relatively high energy consumption and the related CO_2 emissions in the retrofitted buildings for the upcoming decades.

❖ Passive accelerated scenario - results

The Passive accelerated scenario presents a path of energy savings potential when the high-performance transition of the existing building stock (built before 1990) happens in an accelerated manner (all existing buildings built before 1990 are retrofitted by 2030). The energy savings in the Passive accelerated scenario reach almost 4.9 TWh (981 kt CO_2 emissions), which corresponds to energy savings of 69% compared to BAU scenario (Figure 45).

Figure 45 Comparison of Passive accelerated and BAU scenario



Also in this scenario the passive energy standard has the highest share on the total energy savings and CO_2 mitigation potential both for the new construction as well as for retrofit of the existing buildings (Figure 46 and Figure 47).

Figure 46 Contribution of building codes to energy savings, new construction, Passive accelerated scenario

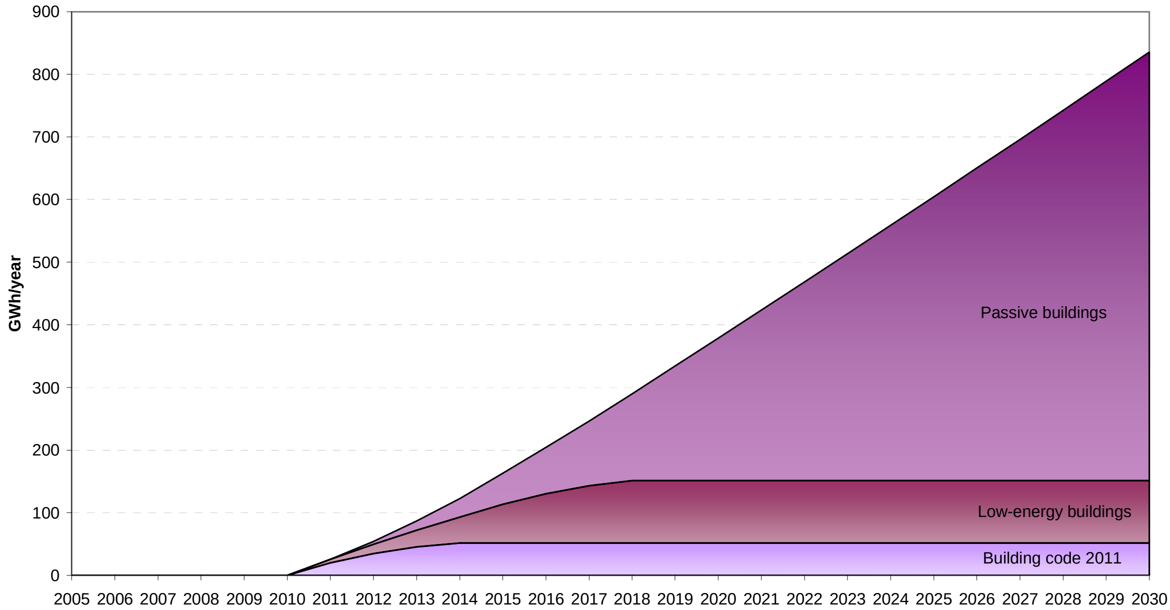
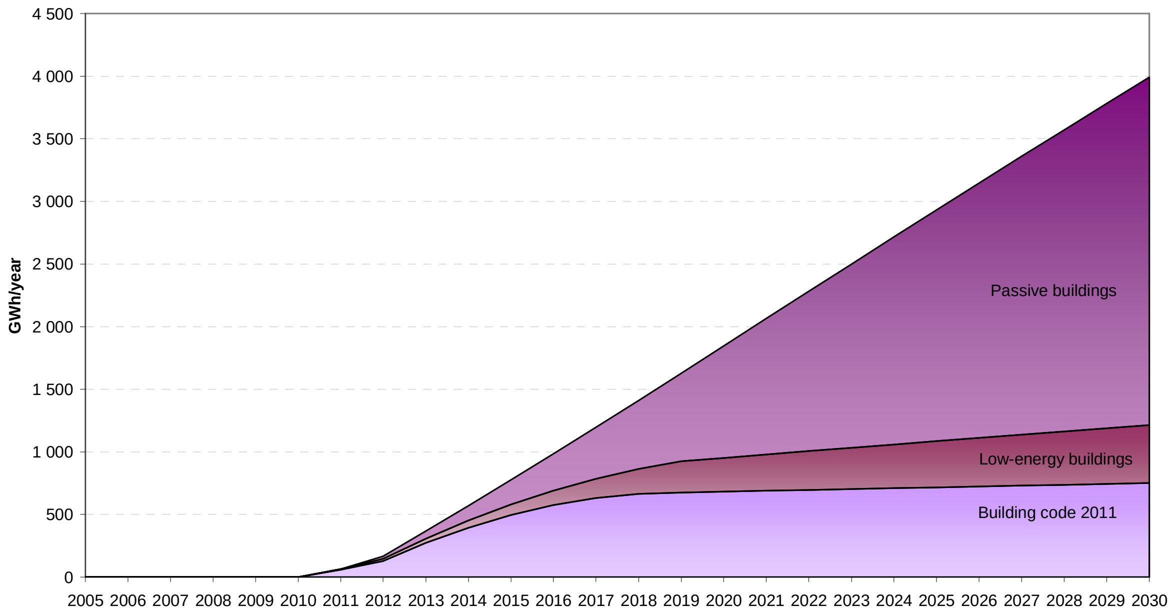


Figure 47 Contribution of building codes to energy savings, retrofit, Passive accelerated scenario



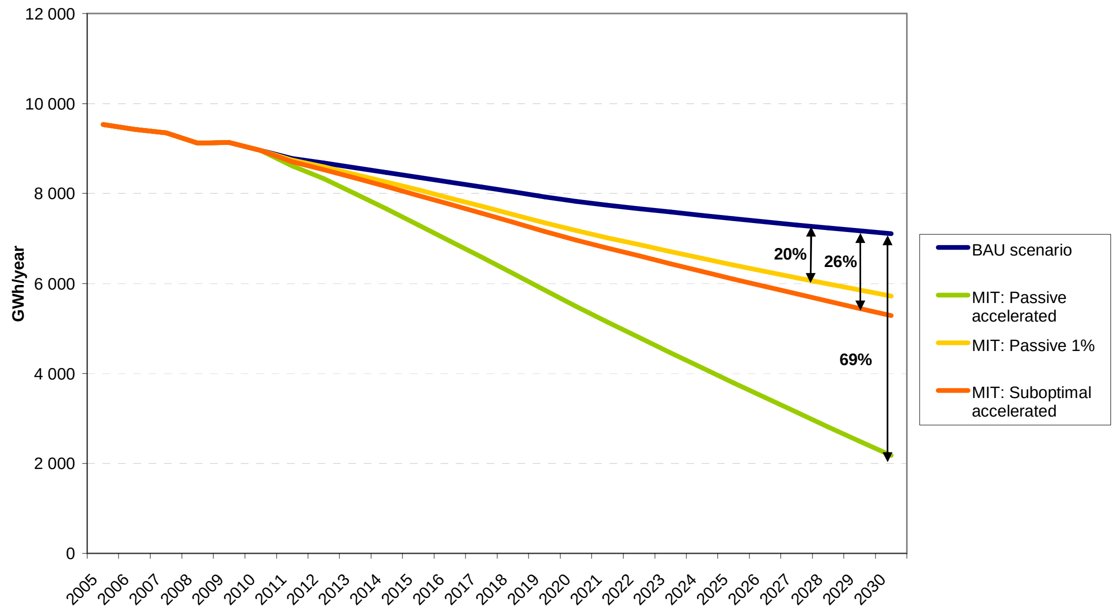
The total investment required under the Passive accelerated scenario over the projection period is 1.85 billion Euro, which would be partly paid back in form of energy costs savings of 1.63 billion Euro.

7.4 Comparison of the four pathways: towards low-carbon future

The analysis shows that energy savings are lowest in the case of the Passive 1% scenario and highest in the case of the Passive accelerated scenario. The Suboptimal scenario results in only slightly higher energy savings potential than the Passive 1% scenario even despite the fact that partial retrofit is applied to the whole existing building stock, while Passive 1% scenario is only applied to 1% of the existing building stock per year (i.e. in total to 19% of the existing building stock by 2030). This shows how important it is to set high standards for retrofit. The difference between the Passive 1% scenario and Passive accelerated scenario is approximately 50% of 2030 BAU energy use. This implies that once the optimal level of minimum standards of retrofit are set (with appropriate transition period for the market to develop), the rate of retrofit can make a large difference. As this high efficiency retrofit is applied at a large scale, the energy savings potential grows significantly.

Then, the difference between the application of the suboptimal retrofit at a large scale and the high efficiency retrofit at a large scale is significant. This difference, so-called lock-in effect, accounts for approximately 44% of 2030 BAU energy use (43.8%). In other words, due to application of partial retrofit to the whole existing building stock almost 44% less 2030 baseline energy use can be saved. The lock-in effect accounts for more than half of the total potential that can be reached under the Passive accelerated scenario. This means that application of the partial retrofit at an accelerated rate can reduce the total potential by more than a half. Figure 48 compares the four analyzed scenarios.

Figure 48 Comparison of BAU and three mitigation scenarios (GWh)



At the same time such extensive mitigation effort requires not only strict regulation on building energy performance, but also initial investment. The more ambitious the scenario, the higher the initial investment is needed. At the same time, the more ambitious the scenario, the higher the energy cost savings which can compensate the high initial investment.

Table 44 summarizes both the results of the scenarios in terms of energy saving and CO_2 mitigation potential, as well as the total annual investment needed for the different scenarios and the energy costs savings that can be achieved by 2030 under each scenario.[70]

Table 44 Energy savings and CO_2 reduction potential in the three mitigation scenarios

	Energy consumption			CO_2 emissions			Investment vs. savings	
	Business-as-usual in year 2030	Energy saving potential in year 2030	Energy saving potential in year 2030 (% of BAU)	Business-as-usual 2030	CO_2 mitigation potential 2030	CO_2 mitigation potential 2030 (% of BAU)	Total cumulative investment (2011-2030)	Cumulative energy cost savings (2011-2030)
Scenario/Unit	GWh	GWh	GWh	kt CO_2	kt CO_2	kt CO_2	Billion EUR	Billion EUR
Suboptimal accelerated	7 109	1 820	25.6%	1 413	361	25.6%	1.32	0.60

[70] Note that the investment is calculated as additional to the investment under the BAU scenario.

	Energy consumption			CO_2 emissions			Investment vs. savings	
	Business-as-usual in year 2030	Energy saving potential in year 2030	Energy saving potential in year 2030 (% of BAU)	Business-as-usual 2030	CO_2 mitigation potential 2030	CO_2 mitigation potential 2030 (% of BAU)	Total cumulative investment (2011-2030)	Cumulative energy cost savings (2011-2030)
Scenario/Unit	GWh	GWh	GWh	kt CO_2	kt CO_2	kt CO_2	Billion EUR	Billion EUR
Passive 1%	7 109	1 389	19.5%	1 413	276	19.5%	0.61	0.46
Passive accelerated	7 109	4 934	69.4%	1 413	981	69.4%	1.85	1.63

Table 44 shows that while Suboptimal accelerated scenario leads to only slightly higher energy savings potential than the Passive 1% scenario, it requires double investment than the latter scenario. In other words, comparable energy cost savings can be reached under Passive 1% scenario at half of the cost of the Suboptimal accelerated scenario. On the other hand, Passive accelerated scenario brings 2.7 times higher energy savings at only 40% higher total initial investment compared to the Suboptimal accelerated scenario. This implies that either of the two passive scenarios outperforms the Suboptimal accelerated scenario when both energy savings and initial investment is taken into account.

As the assumptions for new construction are the same in all three mitigation scenarios, it is important to look at the initial investments and energy cost savings of the existing buildings in detail. This is shown in Table 45 and Table 46. It is obvious that the assumption that all new buildings become passive by 2019 according to the Article 9 of directive 2010/31/EU requires significant additional investment. Although this investment will be paid back in form of lower energy bills, the government will have to create a strategy on implementation of these EPBD requirements, which will be accompanied by strong enforcement measures.

Table 45 Energy savings potential, cumulative investment and energy cost savings for new construction (2011-2030)

	New construction			
	Energy saving potential in year 2030	Energy saving potential in year 2030	Cumulative investment in 2030	Total energy cost savings in 2030
	GWh	% of total BAU	billion EUR	billion EUR
Suboptimal accelerated scenario	835	12%	0.53	0.27
Passive 1% scenario	835	12%	0.53	0.27
Passive accelerated scenario	835	12%	0.53	0.27

Table 46 Energy savings potential, cumulative investment and energy cost savings for retrofit (2011-2030)

	Existing buildings			
	Energy saving potential in year 2030	Energy saving potential in year 2030	Cumulative investment in 2030	Total energy cost savings in 2030
	GWh	% of total BAU	billion EUR	billion EUR
Suboptimal accelerated scenario	985	14%	0.79	0.33
Passive 1% scenario	554	8%	0.08	0.19
Passive accelerated scenario	4098	58%	1.32	1.36

Table 46 shows that with almost ten times higher initial investment the suboptimal retrofit brings not even double energy savings compared to the retrofit in the Passive 1% scenario.

On the other hand, Passive accelerated scenario brings more than four times higher energy savings as compared to the Suboptimal accelerated scenario and for that purpose this scenario requires only 70% higher investments. This means that Suboptimal accelerated scenario is underperforming both in terms of realizing the energy savings potential, as well as in terms of the total cost requirements compared to the two passive scenarios.

7.5 Scenario analysis up to 2050

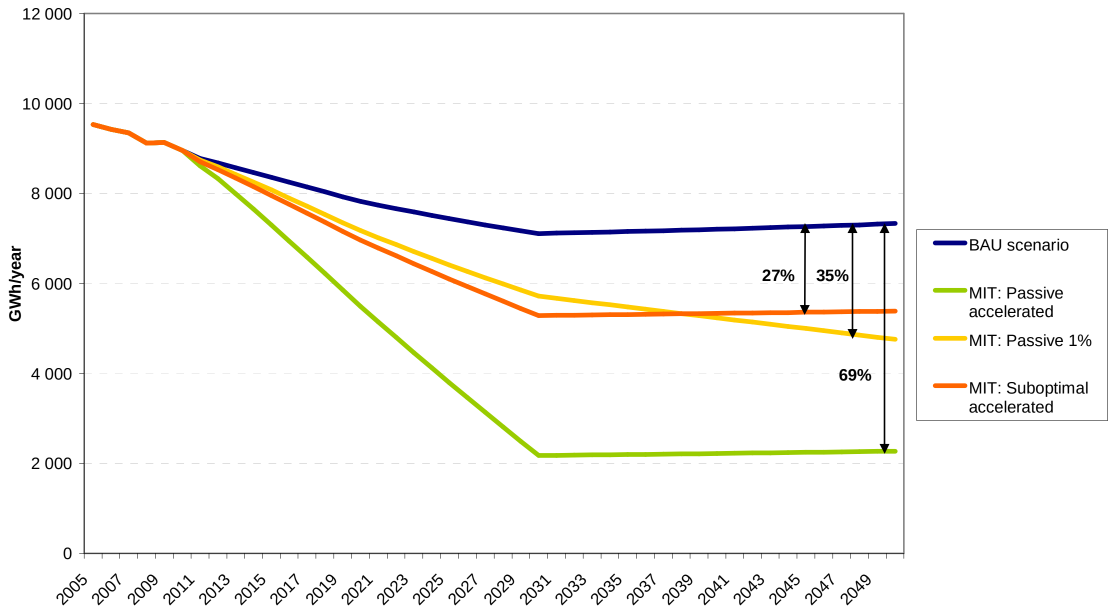
In order to see the effects of the different scenarios in the long-term, the analytical framework was extended up to 2050. This analysis is performed for both energy efficiency potential, CO_2 mitigation potential as well as the energy cost savings and investments. Note, that this analytical framework is not as detailed and precise as the 2030 framework and several assumptions are simplified.

After 2030 the building stock is projected in such a way that an assumed rate of new construction is applied to it.[71] The projected total building stock increases slightly in the period 2030-2050, however, does not reach the level of 2005. Heating energy efficiency, energy prices and emission factors are assumed to be constant as of 2030. Technology learning continues in this extended period in such a way, that in the period 2031-2050 the price of the technologies is half of the price in 2030).

Figure 49 shows energy savings potential up to 2050. While in both Suboptimal accelerated and Passive accelerated scenarios the whole building is retrofitted by 2030 and thus the energy savings potential after 2030 does not increase any further, energy savings continue to grow in the Passive 1% scenario.

[71] New construction rate is assumed at the level of 0.7% and is assumed to be constant in the period 2031-2050. As in the two accelerated scenarios all existing buildings are assumed to be retrofitted by 2030, it is assumed that no buildings are ceased after 2030. This assumption is applied to all scenarios.

Figure 49 Final energy savings potential for space heating up to 2050 (GWh)



The energy savings in Passive 1% overruns the energy savings potential of Suboptimal scenario in about 2040 and by 2050 is the potential achievable under Passive 1% scenario higher by one third compared to Suboptimal accelerated scenario.

Table 47 Final energy savings potential, investment and energy cost savings up to 2050

	Energy saving potential		CO_2 reduction potential		Investment vs. savings	
	Energy saving potential in year 2030	Energy saving potential in year 2030 (% of BAU)	CO_2 mitigation potential 2030	CO_2 mitigation potential 2030 (% of BAU)	Total cumulative investment (2011-2030)	Cumulative energy cost savings (2011-2030)
Scenario/Unit	GWh	GWh	kt CO_2	kt CO_2	Bil. Euro	Bil. Euro
Suboptimal accelerated	1 945	27%	386	27%	1.59	1.95
Passive 1%	2 573	35%	511	35%	0.93	1.89
Passive accelerated	5 059	69%	1 006	69%	2.13	5.21

Compared to the results of 2030 energy savings potential calculation, the highest increase in potential occurs in the Passive 1% scenario, where the potential increased by more than two thirds. The other two scenarios encounter just a slight increase (Table 47).

Table 48 Investment and energy cost savings in new and existing buildings by scenario up to 2050

	New construction	
	Cumulative investment (billion EUR)	Total energy cost savings (billion EUR)
Suboptimal accelerated	0.81	1.10
Passive 1%	0.81	1.10
Passive accelerated	0.81	1.10

	Existing buildings	
	Cumulative investment (billion EUR)	Total energy cost savings (billion EUR)
Suboptimal accelerated	0.79	0.85
Passive 1%	0.12	0.79
Passive accelerated	1.32	4.10

In all three scenarios investment into new construction continues to grow in the same pace after 2030 as before, however, the investment is lower due to technology learning. However, in both of the accelerated scenarios the investment into retrofit remains at the 2030 level due to the fact that all existing buildings have been retrofitted by 2030. The total investment is driven solely by new construction. Nevertheless, in Passive 1% scenario the investment continues to grow also after 2030 at similar pace as before. Energy cost savings continue to grow after 2030 in all three scenarios. Figure 50 depicts the interaction between investment needs and the resulting energy cost savings in the different scenarios.

Figure 50 Cumulative full investment and energy cost savings – Comparison of scenarios

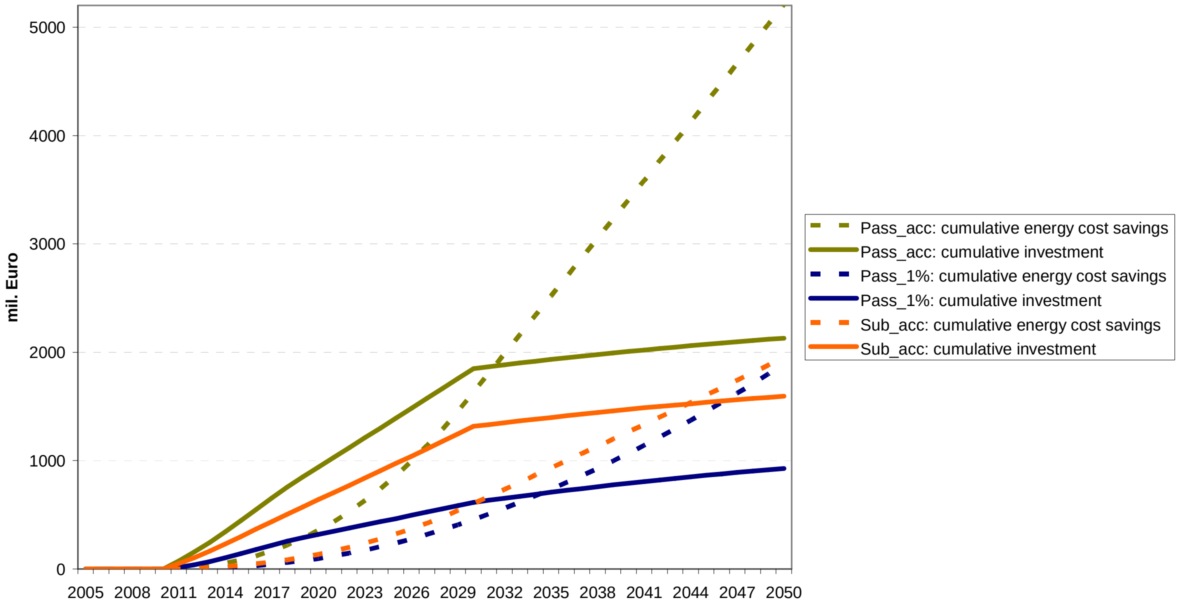


Figure 50 shows that the Passive accelerated scenario brings the highest energy cost savings, while the Suboptimal accelerated scenario brings only slightly higher energy cost savings at much higher investment.

7.6 Sensitivity analysis

The cost-effectiveness of the mitigation options is sensitive to the changing discount rate (Ürge-Vorsatz and Novikova 2008) as well as to changes in energy prices. In order to better understand the sensitivity of the performance-based model, the most ambitious, Passive accelerated scenario is examined in the sensitivity analysis from the following aspects:

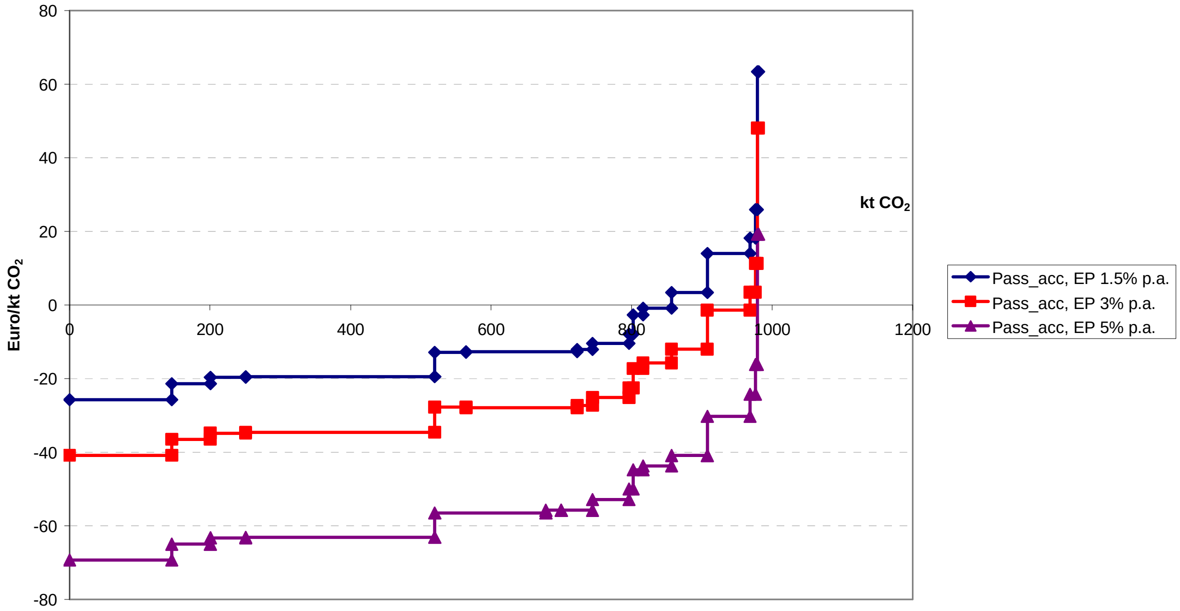
- energy prices
- discount rate
- rate of retrofit

7.6.1 Energy prices

Energy prices determine the saved energy costs, which determine the cost-effectiveness of the measure. In time of high uncertainty of development of energy prices due to various risks on the global energy market, it is necessary to examine the effect of several cases of energy price increase. The current model assumes an annual increase in energy prices of 1.5% p.a. (based on Petersdorff *et al.* 2005 and Novikova 2008). The sensitivity analysis examines the effect of the rate of increase in energy prices of 3% p.a. and of 5% p.a.

Figure 51 shows that the increase of energy prices shifts the cost curve (of the Passive accelerated scenario) downwards, in other words, the scenario becomes more cost-effective with increasing energy prices. The higher the price increase, the better the cost-effectiveness.

Figure 51 Cost curve, Passive accelerated scenario, energy price increase of 1.5%, 3% and 5% p.a.

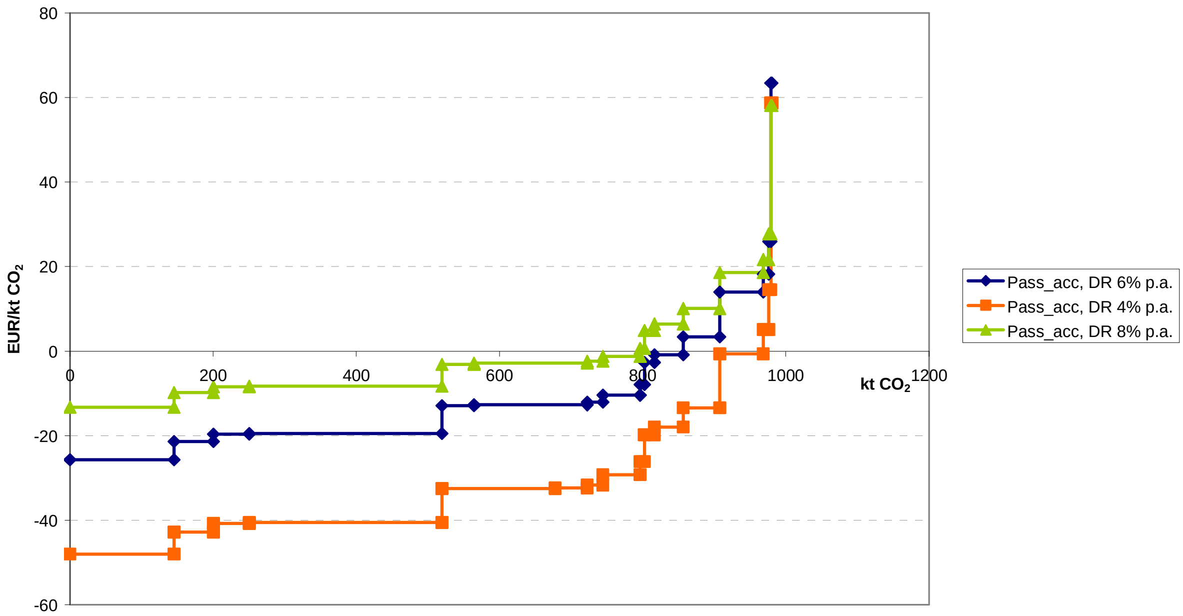


7.6.2 Discount rate

The discount rate shows how future costs and benefits are valued against the present value (according to EC 2008a). Lower levels of discount rate are usually described as social discount rate, while the higher levels of discount rate are private discount rates, often based on the opportunity cost of the capital, i.e. the market rate of investment (IPCC 2001: 466). The lower value is ascribed to future cash flows, the higher the discount rate and the lower the cost-effective potential. The default model assumes a discount rate of 6% p.a, i.e. social perspective (which means exclusion of any taxes and subsidies from consideration). The sensitivity analysis examines the cost-effectiveness of the most ambitious scenario for discount rates of 4% and 8% p.a.

Figure 52 shows that the cost-effective potential of the Passive accelerated scenario decreases with higher discount rate (8% p.a.) and increases with lower discount rate (4% p.a.).

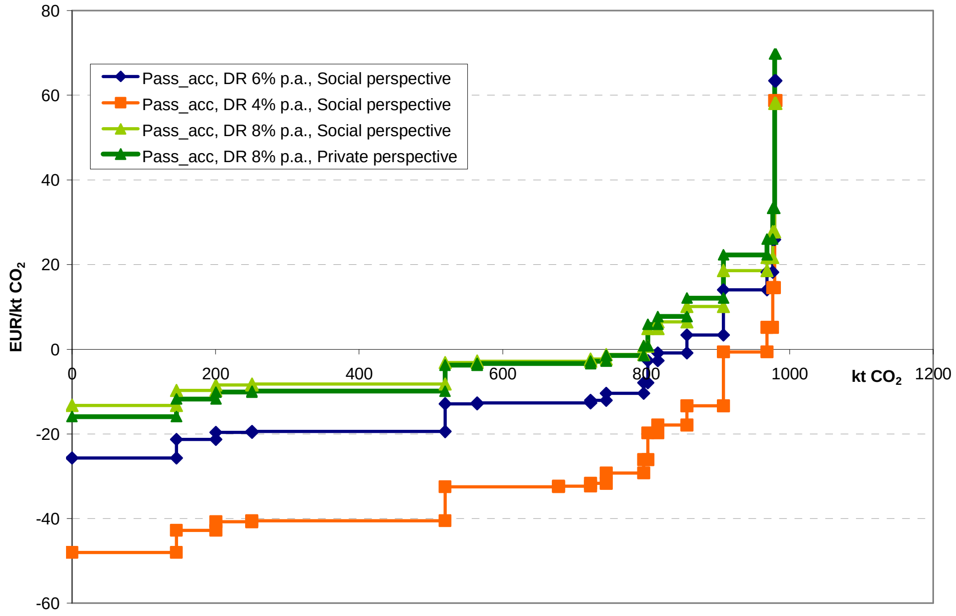
Figure 52 Cost curves, Passive accelerated scenario, discount rate of 4%, 6% and 8%



In addition, the private perspective was simulated by applying discount rate of 8% and the relevant taxes (VAT and energy tax) to the Passive accelerated scenario.

Figure 53 shows that inclusion of the taxes decreases the negative part of the cost curve, while it increases the positive part of the cost curve. Nevertheless, in comparison with the other two discount rates these changes are insignificant.

Figure 53 Cost curves, Passive accelerated scenario, comparison of social and private perspective



In addition to the well-established factors used in sensitivity analysis, sensitivity of the results of the model are further tested on another basic assumption – the rate of retrofit.

7.6.3 Rate of retrofit

The default model is based on an ambitious assumption that all existing buildings are retrofitted by 2030, which results in an average retrofit rate of 4.6% p.a. As literature relies on lower rates of retrofit, the results of the Passive accelerated scenario were examined against retrofit rates of 3% p.a. and 3.5% p.a. Higher retrofit rates are not considered as such acceleration in retrofit activity is not realistic due to limited capacity of the construction market.

Figure 54 Cost curves, Passive accelerated scenario, application of different retrofit rates

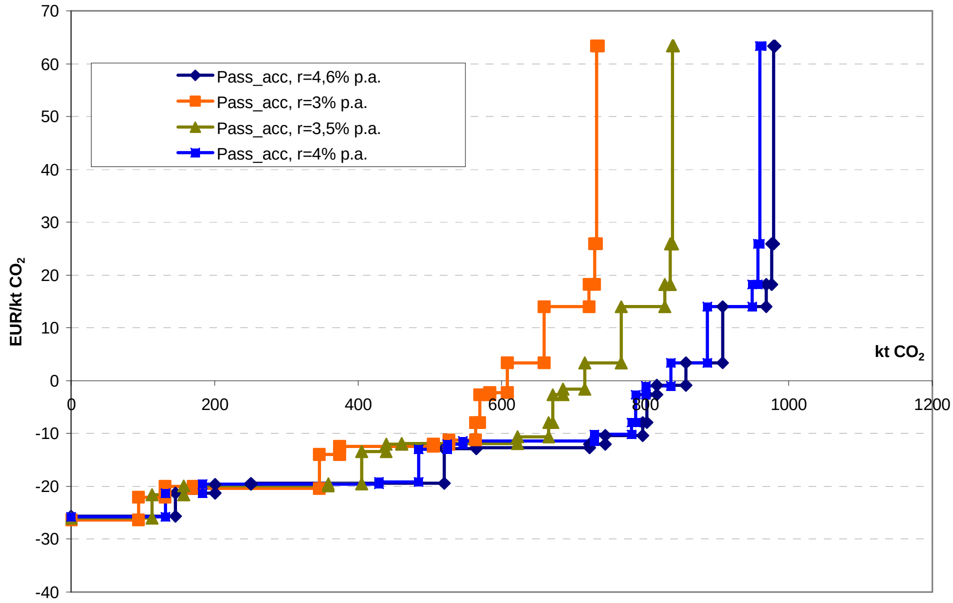


Figure 54 shows that the rate of retrofit influences both extent of the total potential as well as the extent of the cost-effective potential. Table 49 indicates that the higher the retrofit rate the higher the total potential. One can compare the results of sensitivity analysis with Passive 1% scenario – when the rate is 3 times higher (Passive 3%), the total potential increases 2.6 times.

Table 49 Passive accelerated scenario under different rates of retrofit

	Energy savings		CO_2 emissions		Investment vs. savings	
	Energy saving potential in year 2030	Energy saving potential in year 2030 (% of BAU)	CO_2 mitigation potential 2030	CO_2 mitigation potential 2030 (% of BAU)	Total cumulative investment (2011-2030)	Cumulative energy cost savings (2011-2030)
Scenario/Unit	GWh	GWh	kt CO_2	kt CO_2	bil. Euro	bil. Euro
Passive 1% scenario (1% p.a.)	1 389	20%	276	20%	0.61	0.46
Passive 3%	3 657	51%	727	51%	1.43	1.25
Passive 3.5%.	4 224	59%	840	59%	1.63	1.45
Passive 4%	4 791	67%	952	67%	1.83	1.65
Passive accelerated scenario (cca 4.6% p.a. - default)	4 934	69%	981	69%	1.85	1.63

Comparison of the different factors influencing cost-effectiveness of the scenario implies that the results are sensitive to the underlying assumptions. This has to be taken into account when interpreting the scenarios and especially when strategies are prepared based on the Passive accelerated scenario.

Summary

Chapter 7 presented and compared three mitigation scenarios against the BAU scenario and with this it provides answers to the research questions related to Objective 1 of the dissertation: first, Passive accelerated scenario performs as the path which reduces the energy consumption in the Hungarian public sector most significantly (by 69% compared to the BAU scenario). Second, scenario simulating partial renovation at an accelerated rate of retrofit results in 26% energy savings compared to 2030 baseline energy use, which is only slightly higher than the energy savings that can be achieved by applying gradual retrofit to passive house level to only 1% of the existing building stock per year. This implies that applying suboptimal retrofit at national level does not have a significantly greater impact than applying passive energy standard to only 1% of the building stock p.a. Therefore, it can be concluded that not only rate of retrofit, but even more importantly the level of energy performance to which existing buildings are retrofitted (and new ones are built) is a decisive factor that determines the utilization of the available technical potential in the building sector. This implies that in planning of any national retrofit program it is important to first carefully set an ambitious performance target level per building (in terms of kWh/(m^2.a)) and only then extend it to the whole building stock.

Moreover, the analysis brings two further messages. First, although through current retrofit programs energy is saved, this is not enough to create a significant impact on the national energy use and CO_2 emissions. If the whole stock of existing buildings (built before 1990) is gradually retrofitted only to the suboptimal level, these buildings will consume high levels of energy for the several next decades until the material is worn out and another renovation is needed. This way the high energy use patterns and the related CO_2 emissions are locked-in for several more decades in the existing infrastructure. Retrofitting these buildings to a higher efficiency level before the next renovation cycle is not cost-effective. This implies that it is not only vital to support large-scale retrofit, but even more importantly, it is necessary to assure that retrofit is performed to the highest possible level through strong legislation, well-targeted incentives and strict enforcement. This should be the leading idea of any subsidy program. No publically funded programs should support partial retrofit and retrofit to the level of new buildings requirements (such as the current 2006 Building code) unless these are themselves enhanced.

Second, the comparison of the Passive 1% and Passive accelerated scenarios shows that the rate of retrofit plays an important role in achieving higher energy savings once the energy standard is set to the level of best available technologies. By accelerating the rate of retrofit energy savings will be 3.5 times higher than when maintaining the natural rate of retrofit (while keeping the same level of energy performance). It is very important that existing buildings are retrofitted at such an accelerated rate of retrofit, not only due to energy savings, energy security and environmental reasons, but also due to other benefits to society. Not only does the energy efficiency investment save energy costs and in this way save public funds for other pressing public issues. Energy efficient investment also contributes to maintaining and creating jobs, reduces energy poverty, improves indoor air quality and by providing thermal comfort contributes to greater productivity and better living conditions. In the time of need for economy recovery, businesses can benefit from an accelerated rate of retrofit. Assuming 30% of the total investment (based on the average share of labor cost on investment for thermal insulation and window/door exchange reported in the energy audits of UNDP/Energy centre 2008) is spent on labor costs, then investment in implementation of the Passive accelerated scenario would lead to about 0.56 billion EUR investment in the construction business additional to the BAU scenario.

Sensitivity analysis shows that the model results are sensitive to changes in discount rate and energy prices in terms of cost-effectiveness of the measures. Rate of retrofit has also a significant effect on the results of the model both in terms of total potential and the cost-effectiveness of the applied measures.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

In this chapter first the main messages of the research are summarized, then recommendations are formulated based on the findings, and these are followed by summary of the contribution of the dissertation to the field of research, potential application of the research beyond the dissertation and suggestions for areas for further research.

8.1 Summary of the results

The impacts of the climate change can already be observed. If society is to prevent further or even irreversible changes in climate and biosphere, the GHG emissions should be reduced significantly in the course of the first half of this century (50-85% by 2050 and 20-40% by 2020). Several countries have already stated their strategies how to reach these ambitious levels of reduction. The EU has set a 20% reduction target for its energy consumption by 2020 compared to 2020 projections. At the same time, energy resources are scarce and energy prices are increasing due to instability in energy supply. Energy efficiency addresses several of these challenges: decreases the need for energy imports as well as reduces the GHG emissions produced by combustion of fossil fuels. At the same time energy efficiency brings further benefits: decreased energy costs for the end-users, improved indoor air quality and thermal comfort, increased productivity etc. It was found out that large cost-effective potential exists in the building sector.

The aim of the dissertation is to determine the energy and CO_2 savings potential in the Hungarian public building sector. One of the objectives of the dissertation is to find the optimal pathway to achieve significant energy CO_2 savings and to determine the risk of massive application of suboptimal levels of retrofit in the building sector, which can lead to a so-called “lock-in effect”, i.e. locking-in the emissions in the building structure for the next several decades until the next renovation takes place. The dissertation as one of the first studies attempts to quantify the "lock-in effect". Another objective is to determine the mitigation potential based on two different modelling approaches and compare their results.

Similarly to other reviewed studies focusing at energy savings potential in the building sector, the dissertation research is based on bottom-up modelling and uses cost-effectiveness analysis to determine the net costs of energy conservation and CO_2 mitigation. Similarly to the majority of such studies the dissertation also uses a component-based modelling approach, which determines the total energy savings potential based on the potentials of the improved individual building components. Although this approach is by now well established in the area, it is often criticized for not being capable of adequately reflecting recent advances in building design and construction know-how, most importantly the principles of integrated building design. And therefore, the dissertation complements the component-based approach with a new, performance-based approach, which determines the potential on the basis of the energy performance of the building as a whole and thus gives space for interactions of different technologies in the most optimal way in order to reach the required performance level. The dissertation is one of the few studies that utilize this type of approach for determination of the potential and construction of several low-energy scenarios.

The research design is divided into three main parts – definition of the scenarios, data collection and modelling analysis. In order to fulfil the objectives of the dissertation, three scenarios/pathways are designed – scenario where the whole building stock is gradually retrofitted to passive house level, scenario where only part of the building stock is gradually retrofitted to the passive house level and scenario where the whole building stock is retrofitted to suboptimal level by 2030.

The modelling methodology is divided into several steps: first, the common modelling basis for the two modelling approaches (so-called frozen-efficiency scenario) is constructed based on development of building typology, building stock projections, calculation of average heating energy requirements for different building types and calculation of the final energy consumption and CO_2 emissions. Consequently, the base year energy use is calibrated based on available statistical sources and estimates. Second, BAU and mitigation scenarios are constructed separately for both types of analysis, i.e. component- and performance-based scenario. After this the mitigation potentials in the two models are compared. Then, three scenarios are constructed based on the performance-based model – the most ambitious Passive accelerated, less ambitious Passive 1% and the so-called Suboptimal accelerated scenario. Comparison of the first and the third scenario shows the lock-in effect. And finally, the sensitivity analysis is conducted in order to see the effect of different variables on the main outcomes.

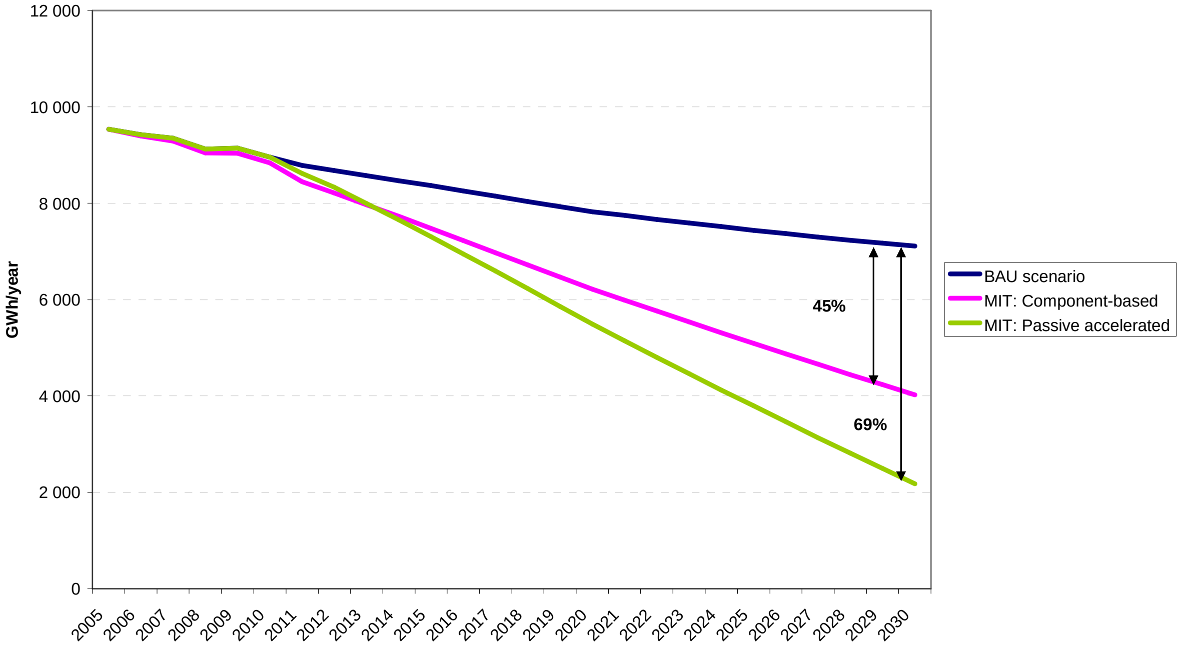
The main differences in construction of the mitigation scenarios in the two approaches is that while in the component-based approach individual energy efficiency measures are installed, in the performance-based approach different levels of energy performance are applied to the new and existing buildings.

The individual energy efficiency measures in the component-based approach include insulation of the building shell components (external wall, windows, roof, basement), exchange of windows, installation of condensing boilers and temperature management. The component-based approach results into a total potential of 45% compared to 2030 BAU scenario energy consumption, and a cost-effective potential of 21% of the 2030 BAU energy use. The most cost-effective measures in the Hungarian public buildings are temperature management, exchange of windows and insulation of the external walls. Insulation of roof and basement are on average the least cost-effective measures, however it is important to stress that only full implementation of all interrelated measures assures that the above stated total potential is achieved.

In the performance-based approach, three levels of energy building performance have been considered – 2011 building standard with specific final energy requirement of 60kWh/(m^2.a); low energy performance level of 30 kWh/(m^2.a) for new construction and 45 kWh/(m^2.a) for retrofit; and passive energy standard of 15 kWh/(m^2.a) for new construction and 25 kWh/(m^2.a) for retrofit. The performance-based approach shows that the most cost-effective potential exists in retrofitting social, health care and educational buildings, as well as in new construction of the three above mentioned building types, as these rank among the most energy intensive public buildings.

Comparison of the component-based and performance-based approaches revealed a large gap between the two approaches. While the component-based approach provides approximately 45% energy savings compared to 2030 BAU scenario, the performance-based approach results in 69% energy savings relative to the BAU scenario in 2030 (Figure 55).

Figure 55 Energy savings potential resulting from the component- and performance-based modelling approaches

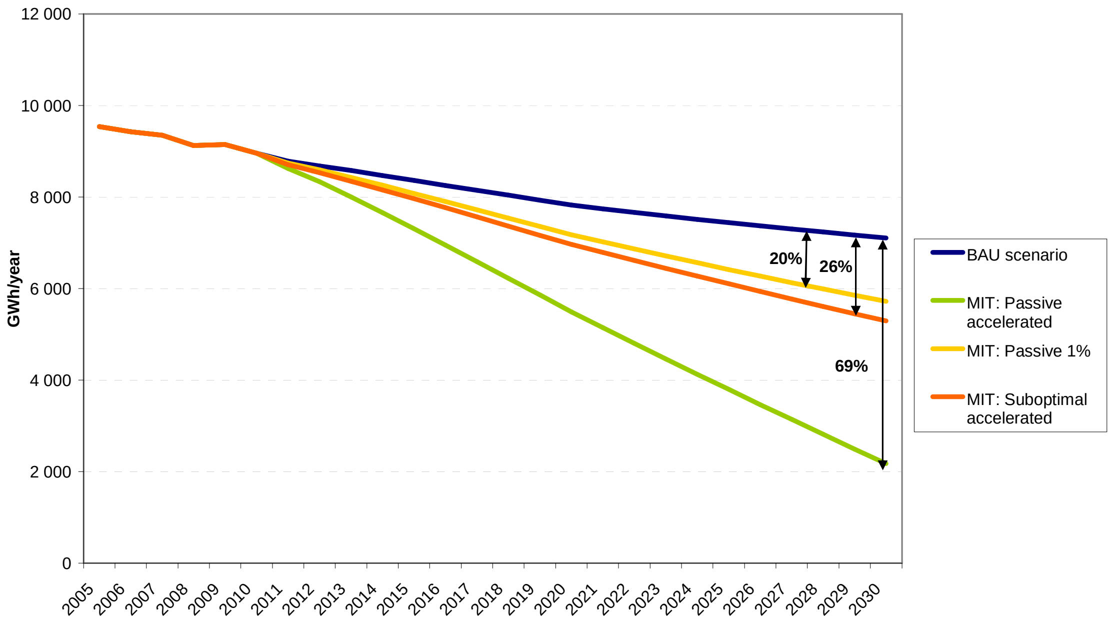


The difference in the results of the two approaches (24% of 2030 BAU energy use) can be explained by difference in the modelling approach (multi-layered application of different high efficiency performance levels in the performance-based approach) and existence of the synergy effect of the holistic approach to the retrofit of the existing buildings. While the multi-layered character of the performance-based approach is closer to reality, it also makes this approach more ambitious. On the other hand, the systemic approach to the building as a whole in the performance-based approach makes it possible to consider also the advanced high-performance techniques, which cannot be reflected in the piecemeal approach of the component-based approach.

The analysis showed that the performance-based modelling tools can provide a flexible support tool for energy and climate policy makers. The flexibility of these modelling tools lies in the possibility to set different performance levels to be implemented with consideration to timing of the phase-out of the existing performance levels and gradual phase-in of the new levels. Several performance levels can be applied simultaneously. Parallel implementation of different types of abatement measures cannot be fully realized in the current Excel-based component-based model. The flexibility and greater user-friendliness of the performance-based approach (compared to component-based) are the main reasons why the performance-based approach is used for scenario analysis.

The main question behind construction of the scenarios is what are the risks linked to mass application of the partial (suboptimal) retrofit and to compare it to the scenario with the highest energy savings potential (Passive accelerated scenario). Based on the results the risk of such retrofit is that more than half of the potential can be lost for the several next decades until the next renovation cycle starts. The scenario analysis showed that lock-in effect can reach up to approximately 44% of the BAU (43.8%) energy use by 2030. This means that almost 44% of the 2030 BAU energy use would be locked–in in the existing infrastructure until the next renovation cycle if the whole building stock was retrofitted to suboptimal level instead of passive or low-energy level (Figure 56).

Figure 56 Summary of the scenario analysis – energy savings potential scenarios (GWh)



Passive accelerated scenario can bring 2.7 times higher energy savings than the Suboptimal accelerated scenario at investment only 70% higher as compared to Suboptimal scenario (Table 50).

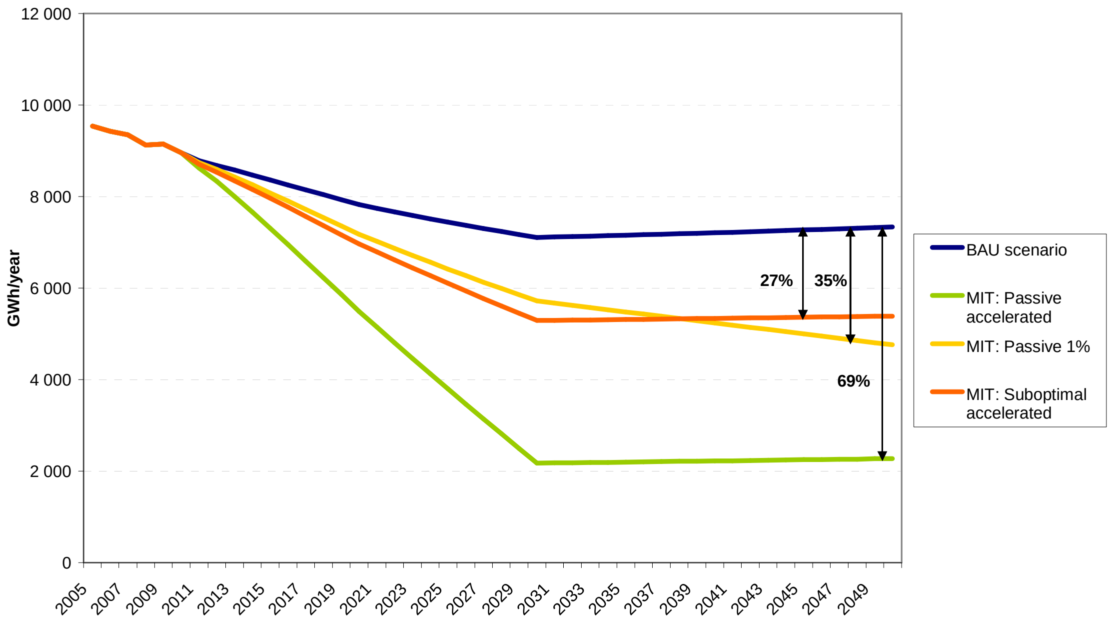
Table 50 Summary results of the scenario analysis

	Energy consumption			CO_2 emissions			Investment vs. savings	
	Business-as-usual in year 2030	Energy saving potential in year 2030	Energy saving potential in year 2030 (% of BAU)	Business-as-usual 2030	CO_2 mitigation potential 2030	CO_2 mitigation potential 2030 (% of BAU)	Total cumulative investment (2011-2030)	Cumulative energy cost savings (2011-2030)
Scenario/Unit	GWh	GWh	GWh	kt CO_2	kt CO_2	kt CO_2	Billion EUR	Billion EUR
Suboptimal accelerated	7 109	1 820	25.6%	1 413	361	25.6%	1.32	0.60
Passive 1%	7 109	1 389	19.5%	1 413	276	19.5%	0.61	0.46
Passive accelerated	7 109	4 934	69.4%	1 413	981	69.4%	1.85	1.63

The analysis also shows that if the building stock is retrofitted to suboptimal level at an accelerated rate (Suboptimal accelerated scenario) the resulting energy savings are only slightly higher than if the building stock is retrofitted to high level of energy performance at only 1% retrofit rate per year (Passive 1% scenario). Moreover, this incremental increase in energy savings as compared to Passive 1% scenario requires double investment of that under the Passive 1% scenario.

The advantages of prioritizing quality over quantity in terms of retrofit are even more obvious once the modelling framework is extended to 2050. While all existing buildings are retrofitted under the Suboptimal accelerated scenario by 2030, the energy savings in Passive 1% scenario are growing further and by 2050 reach a level almost 30% higher than that under the Suboptimal accelerated scenario.

Figure 57 Final energy savings potential for space heating up to 2050 (GWh)



The results of the scenario analysis show the importance of setting the right (and ambitious) level for retrofit of existing buildings (built before 1990). Once the right level of energy performance of the building is set, then the retrofit can be extended to a larger scale. The results of the sensitivity analysis for different rate of retrofit can be used in decision-making process upon what scale of retrofit can be aimed for in case of the Hungarian public building stock.

Once such an ambitious performance level is determined, it should be announced well in advance, so that in the transition period the construction industry, educational institutions, planners and designers can adjust to the planned changes. The transition period of around 10 years, as used in the model, should provide enough time for the industry to react to the planned changes (see e.g. Laustsen 2008). As the target year for new public buildings given by the EPBD directive is 2019, the transition period is shorter and therefore the government should provide the construction industry with the right stimulus that would start up the necessary market transformation.

8.2 Discussion of the results

The dissertation results can be compared to several relevant studies. The results of the component-based model in the dissertation in terms of the total potential are comparable to those in the study of Novikova (2008) for Hungarian residential sector (Table 51) as well as to the study of Szlávik *et al.* (1998) for Hungarian residential and communal sector. The lower share of the cost-effective potential can be explained by higher cost-effectiveness of the energy efficiency measures in the residential buildings and different assumptions of the cost-effectiveness analysis. Longer time frame in the dissertation research also contributes to the higher share of the total potential on the baseline in the public sector.

Table 51 Comparison of the results of the dissertation's component-based approach with a similar component-based study

Study	Region	Sector	Discount rate	Retrofit rate (% p.a.)	Energy savings potential		Target year
					Total potential (% of BAU)	Cost-effective potential (% of BAU)	
Dissertation research – component-based approach	Hungary	Public	6%	5%	45%	21%	2030
Novikova (2008)	Hungary	Residential	6%	5.5%	42%	29%	2025
Szlávik *et al.* (1998)	Hungary	Residential and communal	3-5%	NA	45%	31%	2030

Similarly, the results of the performance-based model in the dissertation can be compared to the results of the recently conducted performance-based studies, such as Ürge-Vorsatz *et al.* (2010), the recent study under the Global Energy Assessment (GEA) and Petrichenko (2010). The study of Ürge-Vorsatz *et al.* (2010) quantifies employment impacts of a large-scale retrofit in Hungarian public and residential buildings. The study under GEA described in Ürge-Vorsatz (2010) focuses on drawing several low-energy scenarios for five world regions up to 2050. Although none of these studies examined the cost-effectiveness analysis of the potential, all of them constructed several scenarios and thus are suitable for comparison to the scenario analysis conducted in the dissertation (Table 52). Petrichenko (2010) calculates the energy savings potential in Russia and quantifies the lock-in effect.[72]

The total energy savings potential in the different S-DEEP scenarios in the employment study of Ürge-Vorsatz *et al.* (2010) depend on the rate of retrofit. The most similar scenarios to the dissertation's Passive accelerated scenario are S-DEEP1 and S-DEEP2 scenarios. The results of the dissertation's most ambitious scenario are in the middle of these two scenarios both in terms of annual retrofit rate and in terms of total potential. Although quantification of the lock-in effect is not among the main objectives of the study, it can be calculated based on the available data. As the retrofit rate of 5.4% p.a. is considered highly unrealistic, the lock-in effect is calculated for the retrofit rate of 3.4% p.a., which is 32% of 2030 BAU energy use (Table 52). This is relatively lower compared to the lock-in effect calculated in the dissertation (approximately 44% of 2030 BAU energy use). This can be explained by two reasons: first, higher energy savings assumption for S-SUB of the study of Ürge-Vorsatz (2010); and second, lower retrofit rate of the S-DEEP 2 scenario as compared to the dissertation's Passive accelerated scenario. Nevertheless, if the average of S-DEEP 1 and S-DEEP 2 scenarios was considered, the result is much closer to the lock-in effect calculated in the dissertation.

Table 52 Comparison of the dissertation research with similar performance-based studies

Study	Region/ Sector	Target year	Name of scenario	Retrofit rate (% p.a.)	Energy savings potential	
					Total potential (% of BAU)	Cost-effective potential (% of BAU)
Dissertation research*	Hungary/ Public	2030	Passive accelerated	4.58%	69.4%	61%
			Passive 1%	1%	19.5%	11%
			Suboptimal accelerated	4.58%	25.6%	5.4%
			Lock-in effect	-	43.8%	NA

[72] Petrichenko (2010) utilizes a methodology that has been developed within the GEA.

Study	Region/ Sector	Target year	Name of scenario	Retrofit rate (% p.a.)	Energy savings potential: Total potential (% of BAU)	Energy savings potential: Cost-effective potential (% of BAU)
Ürge-Vorsatz *et al.* (2010)	Hungary/ Residential and public	2030[73]	S-DEEP1	5.4%	85%	NA
			S-DEEP2	3.4%	57%	NA
			S-DEEP3	2.3%	39%	NA
			S-SUB	3.4%	25%	NA
			Lock-in effect 1 (S-DEEP 1 vs. S-SUB)	-	60%	NA
			Lock-in effect 2 (S-DEEP 2 vs. S-SUB)	-	32%	NA
Petrichenko (2010)	Russia/ Residential, public and commercial	2050	Advanced buildings	NA	54%	NA
			A-class buildings	NA	42%	NA
			Advanced construction	NA	29%	NA
			Incremental diffusion	NA	1.76%	NA
			Lock-in effect 1 (Incremental diffusion vs. Advanced buildings)	-	52%	NA
			Lock-in effect 1 (Incremental diffusion vs. A-class buildings)	-	40%	NA
Global Energy Assessment	World/ Residential and commercial	2050	Lock-in effect	3%	35% (compared to 2005)	NA

* The figures representing dissertation are based on the results calculated with discount rate of 6%.

The study of Petrichenko (2010) shows that introducing high-efficiency standard only to new buildings leads to 29% potential by 2050, however renovation of the existing buildings can lead up to 54% energy savings in the same period. The lock-in effect ranges between 40-52% which is in line with the dissertation research. (Retrofit rates are not reported.)

As the data of the scenario analysis under GEA and described in Ürge-Vorsatz (2010) is not available for year 2030, and may be a subject to further changes, comparison of lock-in effect is only possible based on the 2050 data. The lock-in effect in the GEA study accounts for 35%

[73] Although the target year of the study is 2050, figures in the Table 52 are based on the available data for 2030, the target year of the dissertation.

of 2005 energy use, which is less than the lock-in effect identified in the dissertation which is approximately 44% of energy use in 2005. Although it would be expected that the lock-in effect in 2050 is higher than in 2030, it can be explained by two facts: first, retrofit rate in the GEA study is lower than the rate used in the dissertation; and second, GEA study includes all world regions and allows for certain energy demand development in the developing countries and elimination of energy poverty, which leads to increase in total BAU world energy use, and thus lower lock-in effect (while BAU in the dissertation is decreasing over time).

In summary, the comparison shows that the results of the dissertation are in line with other recent research on energy efficiency potential. Nevertheless, the exact proximity of the results depends on the retrofit rates, which vary across the studies.

8.3 Recommendations

Based on the research, several recommendations can be formulated. First, for the adequate modelling of the energy saving potential it is necessary to have data on the average annual energy consumption and the average floor area per different types of institution. As in some cases, there is no data available on the number of buildings, but only number of institutions, it would be beneficial that the Hungarian Central Statistical Office (KSH) collects this data as well and makes it publicly available.

To collect the annual energy consumption data in the public buildings it is necessary that energy consumption is monitored by the managers of the public buildings on a regular basis and evaluated by a designated central institution. This institution could handle energy consumption data from different sectors of the economy (residential buildings, industry, transport, energy supply sector). This institution should prepare a questionnaire that includes data on the energy consumption as well as some qualitative inquires on the state, function and usage of the building. The energy audits should be archived electronically as to avoid the problem with storage, handling and processing of the data. This way a central database could be established and the results of the specific average energy consumption and specific average energy requirement for different public building types could be regularly updated and evaluated, while the results of these evaluations should be made publicly available.

Moreover, Hungary possesses of a large collection of energy audits conducted in public buildings. For the current research only a sample of over 100 audits was used for the calculations due to limitations in time, human and financial resources. However, in order to get even more precise information on specific energy requirement for different types of public (and residential) buildings, the audits collected within the UNDP/GEF Hungary Public Sector Energy Efficiency Project should be fully processed and analyzed. Otherwise this wealth of information will be lost.

Second, building codes in several countries, including Hungary, seem to be focused in detail on new buildings in the residential sector, while less attention is paid to the public buildings. However, it is important that the building codes consider the specifics of the different building types in terms of their building energy features, function and occupancy and distinguish between such sectors as education, health care and social care, administration, and cultural buildings, as their final energy use and the related energy savings potential depend on the energy usage patterns in these different types of buildings. Even more importantly, the building codes should set strict quantified requirements for retrofit of the buildings (both residential and public) taking due regard to the advanced technologies available on the market. These requirements should also consider the different building types, their function and usage. Building codes should use performance-based levels as the main requirements supplemented by component-based requirements in order to ensure the required building energy performance (such as in Hungary). Plans to implement low-energy and passive energy standard should be announced well in advance (about 10 years) in order to provide enough time for the construction industry to prepare for these new requirements. These could be presented in form of a road map indicating the phase-in and phase-out of different building codes in time resulting in full implementation of passive house standard. It is important that commissioning is a required part of the construction process. The building codes should also include requirements regarding efficient use of materials, waste prevention and water treatment. The compliance to the building codes should be strictly enforced by an independent authority.

Third, as the public sector plays a special role in promoting energy efficiency (see e.g. EC 2006b), the transition towards passive buildings in this sector should be faster than in other types of buildings. In order to allow faster transition towards very low energy buildings (set by a long-term plan and building standards) the barriers to energy efficiency in municipalities should be identified and eliminated (e.g. by improved access to finance, technical assistance including energy audits etc). Legislation should set requirements for the municipalities to designate a special budget for energy management within municipality management, appoint an energy manager in the municipality and prepare municipal multi-annual energy strategy, which would include annual reporting of municipal energy consumption. In order to fulfill these obligations the municipalities should be given more competences in the field of energy management and should be allowed to reinvest the energy cost savings that they achieve through implementation of the energy saving measures. As the success of the implemented energy efficiency measures depends on the behaviour of its users, it is necessary that the awareness of the users is raised regularly by provision of the relevant information. The information on annual energy consumption of the public buildings should be publicly available, not only for new, but also for existing buildings.

Financial support should be provided only to the passive energy standard or higher performance. Experience from other support programmes shows that if both the low-energy and passive energy standard is supported by a similar amount, most of the beneficiaries realize the low-energy standard, which requires lower initial investment (Csoknyai, personal com. 2009). The level of support has an effect also on the retrofit rate of the existing building stock. Support from public finances should not be provided for new construction or retrofit realized to the suboptimal level or below the requirements of the current building code. Otherwise significant amounts of energy and emissions would be locked-in for the next several decades and the public funds would be not used efficiently. Support should be conditioned on commissioning of all energy systems in the building.

Fourth, it is important that in the transition period (which in the case of implementing Passive accelerated scenario starts in 2011) the passive energy technology is integrated into the curricula of the technical universities. This should be accompanied by practical experience with planning and construction process of a real passive or zero energy building. Both students and professors should be encouraged to get experience in countries where this technology has become widely available on the market or even became a standard. The students should be led by the principles of integrated design process in which the planners, builders and developers work together from the start of the construction process.

8.4 Contribution of the dissertation

The main contribution of the current research lies in two areas. The first is practical – the study originated as a reaction to a policy need in Hungary and it filled the information gap on energy savings and mitigation potential for space heating in the public sector in Hungary. Another practical contribution is that the specific energy requirements (for space and water heating and electricity) for different types of Hungarian public buildings are analyzed and published for the first time. As this kind of data is rare for the whole public sector, it can be applied in other countries in the region as well. And, since the energy used in the public sector is not reported in the statistics (neither domestic nor international), dissertation represents the first steps towards calculating it. Second, from the methodological point of view, the dissertation, as far as we know, is the first study which compares component-based and performance-based approaches applied to the same building stock and country. Further, although there have been scenario analyses conducted using the performance-based approach before (Novikova 2008, Dyrbøl *et al*. 2009, Harvey 2009), they either did not conduct such an analysis for both new and existing buildings, or not in such a robust manner. Thus, together with the ongoing research of GEA (see e.g. Ürge-Vorsatz 2010) and Petrichenko (2010) this is one of the first performance-based scenario analyses for both new and existing buildings. Moreover, the dissertation research is the first performance-based study determining the cost-effective potential in the building sector (at the time of writing).

8.5 Further application of the research beyond dissertation

Thanks to its user-friendliness, the performance-based model can be used in policy analysis both in Hungary and in other countries. In the first case, the model can be used to develop medium-term strategies on how to reach the targets set by the recast of the EPBD – i.e. by 2019 all new public buildings and by 2020 all other new buildings must become near-to-zero energy buildings (Article 9, EC 2010). The model can be used to develop strategies for improvement of the existing building stock in the municipality ownership, regional energy efficiency strategies or to develop sectoral substrategies that are parts of national climate strategy, energy efficiency action plan or even energy security strategy. Based on the current model and its scenarios, new scenarios can be constructed based on changed assumptions – e.g. on timing of the mitigation action, performance levels etc. One could for instance also use the model to find out how to halve the current energy consumption in the public building stock by certain year and what are the conditions under which this can be achieved.

In the second case, the model can be applied to other countries provided that the country specific data on building stock is available. Preferably, one should also base the building projections on the country-specific trends in the building stock and related indicators. Nevertheless, when greater precision is sought, country-specific costs of different performance levels should be supplied. Further precision can be achieved by applying average specific heating energy requirements calculated on a basis of a sample of national energy audits. These should be adjusted to climate conditions of the specific country. The model can be easily applied in the countries of the V4 region, for other countries application of the Hungarian specific heating energy requirement should be considered carefully.

8.6 Areas for further research

This study focuses on energy efficiency potential in the public building sector for space heating. It does not consider hot water and electricity, nor the use of technologies utilizing renewable energy sources. Energy savings potential for electricity (for the public sector) is covered by Novikova (*Forthcoming*). Thus, important topics for further research would be to investigate the energy savings potential for hot water (especially in hospitals, kindergartens and social buildings) as well as utilization of renewable energy sources. The user-friendliness of the model could be further improved by including an interface that would serve as a platform for the user to set the main assumptions. Another important area for further research is further examination of the synergy effect gap between the component- and performance-based approaches. This could be done by a thorough study focused on comparison of the existing component-based studies to their recent performance-based counterparts (e.g. comparing McKinsey 2009a and GEA world study). Lock-in effect should be also examined closer. The dissertation provides an overview of the lock-in effect in the most recent studies which focus on buildings, this overview could be extended to include studies of other sectors (such as industry, transport etc.), where quantification of lock-in effect exists. The lock-in effect should be assessed for the same levels of retrofit rate and projection period. Moreover, more research should focus on studying technology learning of the passive house standard, which could be done by comparing the costs of the passive house buildings and the total number of such buildings over time. Further research could also extend the performance-based model to include life cycle energy and water use during the whole lifetime of the building.

BIBLIOGRAPHY

"Mitigation potential in Hungarian buildings". 2008. Workshop organized within the frame of the project "Greenhouse gas mitigation scenarios for Hungary up to 2025", 6 October 2008, Central European University, Budapest.

Aleklett, K., Höök, M., Jakobsson, K., Lardelli, M., Snowden, S. and Söderbergh, B. 2010. The Peak of the Oil Age – Analyzing the world oil production Reference Scenario in World Energy Outlook 2008. Energy Policy. 2010, 38(3):1398-1414.

Balaci, A. (Director for creativity, DVD Ltd., London/Budapest). Personal communication and data on energy savings projects, 21 October 2009, Budapest.

Barker, T., Bashmakov, I., Alharthi, A., Amann, M., Cifuentes, L., Drexhage, J., Duan, M., Edenhofer, O., Flannery, B., Grubb, M., Hoogwijk,. M., Ibitoye, F. I., Jepma, C. J., Pizer, W.A., Yamaji, K. 2007. Mitigation from a cross-sectoral perspective. In Climate Change 2007. Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., eds.]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007.

Barreto, L. and Kypreos, S. 2004. Endogenizing R&D and market experience in the "bottom-up" energy-systems ERIS model. Technovation. 2004, 24(8): 615-629.

Bastian, Z., Feist, W., Baumgärtner, C., Ebel, W., Gollwitzer, E., Grove-Smith, J., Kaufmann, B., Krick, B., Schnieders, J., Schulz, T., Stärz, N., Darup, B.S. 2009. Altbaumodernisierung mit Passivhauskomponenten. Darmstadt: Passivhaus Institut; November 2009. URL: http://www.passiv.de/04_pub/Literatur/Altbauhandbuch/Altbauhandbuch_PHI.pdf [Last visited 29 August 2010]

Bencsik, J. 2009. Energy efficiency in Tatabánya. Presentation at the conference Opportunities for climate change and energy efficiency action in an economic crisis: Catalysing a green recovery. 20 October 2009, Central European University, Budapest.

Blesl, M., Remme, U. 2005. Macroeconomic extension of the TIMES model: TIMES-MACRO. Presentation at the ETSAP semi-annual Workshop. November 2005, Oxford.

Blok, K. 2007. Introduction to energy analysis. Amsterdam: Techne Press, 2007.

Blok, K., de Jáger, D., Hendriks, C. 2001. Summary Report for Policy Makers. Report is a part of the study: Economic evaluation of sectoral emission reduction objectives for climate change. Updated. URL: http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm [Last visited 18 December 2009].

Bressand, F., Zhou, N., Lin, J. 2007. Energy use in commercial building in China: current situation and future scenarios. In: Conference proceedings of eceee 2007 Summer study: Saving energy - just do it! 4-9 June 2007, La Corre sur Loup. 1065-1071.

Brown, M. A., Chandler, J., Lapsa, M.V., Sovacool, B., K. 2007. Carbon Lock-In: Barriers To Deploying Climate Change Mitigation Technologies. Oak Ridge: Oak Ridge National Laboratory, 2007. URL:

http://portal.acs.org/preview/fileFetch/C/WPCP_012129/pdf/WPCP_012129.pdf [Last visited on 8 December 2009]

Clapp, C., K. Karousakis, B. Buchner, J. Chateau. 2007. National and sectoral GHG mitigation potential: A comparison accross models. Paris: OECD/IEA, November 2007. URL: http://www.oecd.org/dataoecd/42/33/44050733.pdf [Last visited 27 July 2010]

Council of the European Union (CoEU). 2007. Presidency conclusions of Brussels European Council 8/9 March 2007. 7224/1/07 REV 1. Brussels: Council of the European Union, 2 May 2007. URL: http://register.consilium.europa.eu/pdf/en/07/st07/st07224-re01.en07.pdf [Last visited on 29 December 2009]

Csider, L. 2009. Energiahatékonyság. Egy sikeres program a panelfelújítás támogatására. [Energy efficiency. A successful program of support of renovation of panel buildings.] Presentation at German-Hungarian Chamber of Commerce. URL: http://www.ahkungarn.hu/fileadmin/user_upload/Dokumente/Bereich_HF/Dienstleistungen/Kooperationsboersen/HrCsider.pdf [Last visited on 13 November 2009]

Csoknyai, T. 2008a. Energy audits 1998-1999. Courtesy of Tamás Csoknyai, provided in August 2008.

Csoknyai, T. (lecturer at the Technical University of Budapest, BME). 2008b. Personal and email communication April - December 2008.

Csoknyai, T. (lecturer at the Technical University of Budapest, BME). 2009. Personal and email communication, July - December 2009.

Csoknyai, T. (lecturer at the Technical University of Budapest, BME). 2010. Personal and email communication, January - August 2010.

Csoknyai, T. 2005. Solanova project: solar-supported integrated eco-efficient renovation of large residential buildings made with industrialized technology. In: PLEA2005 – The 22nd Conference on Passive and Low Energy Architecture, 13-16 November 2005, Beirut, Lebanon.

DEFRA and Enviros 2006. Review and development of carbon dioxide abatement curves for available technologies as part of the Energy Efficiency Innovation Review. Final report by Enviros Consulting Ltd. London: Enviros Consulting, January 2006. URL: http://www.decc.gov.uk/assets/decc/what%20we%20do/supporting%20consumers/saving_energy/analysis/enviros-report.pdf [Last visited 15 January 2009]

Dyrbøl, S. 2009. Energy savings and CO_2 emission reduction of changing European building codes to very low energy standards. Presentation of the Study made for EuroACE by O.M. Jensen, K.B. Wittchen, K.E Thomsen, Danish Building Research Institute, SBi. Presentation at the European Union Sustainable Energy Week, 12 February 2009, Brussels. URL: http://www.rockwool.com/files/rockwool.com/Energy%20Efficiency/Library/EuropeanNationalStrategiesToMoveTowardsVeryLowEnergyBuildings.pdf [Last visited 12 December 2009]

Dyrbøl, S., Eriksen, K. E., Thomsen, K. E., Wittchen, K. B., Jensen, O. M.. 2009. Energy and carbon impact of very low energy building. In: Conference proceedings of the eceee 2009 Summer Study: Act! Innovate! Deliver! Reducing energy demand sustainably. 1-6 June 2009, La Colle sur Loup. 1553-1560.

Eichhammer, W., Fleiter, T., Schlomann, B., Faberi, S., Fioretto, M., Piccioni, N., Lechtenböhmer, S., Schüring, A., Resch, G. 2009. Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries. Final Report for the European Commission Directorate-General Energy and Transport. Karlsruhe/Grenoble/Rome/Vienna/Wuppertal: Fraunhofer, ENERDATA, ISIS, Technical university of Vienna, Wuppertal institute for climate, environment and energy, 15 March 2009. URL: http://ec.europa.eu/energy/efficiency/studies/doc/2009_03_15_esd_efficiency_potentials_short_report.pdf [Last visited 20 January 2010]

ETK. 2006-2009. Építőipari költségbecslési segédlet 2006, 2007, 2008, 2009. [Building costs handbook 2005, 2006, 2007, 2008, 2009] Budapest: ETK, 2006, 2007, 2008, 2009.

EurActive 2009. G8 2050 climate pledge fails to convince. [Published 10 July 2009] [about 3 screens] URL: http://www.euractiv.com/en/climate-change/g8-2050-climate-pledge-fails-convince/article-183932# [Last visited 13 December 2009]

European Commission (EC). 2001. Green paper - Towards a European strategy for the security of energy supply. Technical document. Brussels: European Commission, 2001.

European Commission (EC). 2002. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Brussels: Official Journal of European Union. [Published on 4 March 2003.]

European Commission (EC). 2006a. Green paper. An European strategy for sustainable, competitive and secure energy. COM (2006) 105 final. Brussels: European Commission, 8 March 2006. URL: http://ec.europa.eu/energy/strategies/2009/2009_07_ser2_en.htm [Last visited on 12 December 2009]

European Commission (EC). 2006b. Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Official Journal of European Union: Brussels. [Published on 27 April 2006.]

European Commission (EC). 2007. Limiting global climate change to 2 degrees Celsius. The way ahead for 2020 and beyond. COM(2007) 2 final. Brussels: European Commission, 10 January 2007. URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0002:FIN:EN:PDF [Last visited 2 February 2010]

European Commission (EC). 2008a. Guide to cost-benefit analysis of investment projects. Structural Funds, Cohesion Fund and Instrument for Pre-Accession. Brussels: European Commission, July 2008. URL: http://ec.europa.eu/regional_policy/sources/docgener/guides/cost/guide2008_en.pdf [Last visited April 14 2009]

European Commission (EC). 2008b. Proposal for a directive of the European Parliament and of the Council on energy performance of buildings (recast) (presented by the Commission). COM 2008 (780) final. Brussels: European Commission, 13 November 2008. URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0780:FIN:EN:PDF [Last visited 15 December 2009]

European Commission (EC). 2008c. Second strategic energy review. An EU energy security and solidarity action plan. COM (2008) 781 final. Brussels: European Commission, 13 November 2008.

European Commission (EC). 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on energy performance of buildings (recast). Strassbourg, 19 May 2010. Brussels: Official Journal of the European Union. Published on 18 June 2010.

Eurostat 2010a. Proportion of population aged 65 and over. Path: EUROSTAT/Statistics Database/Population and social conditions/Population/Demography/Population/ Proportion of population aged 65 and over. Extraction: 18 July 2008 and 21 January 2010. URL: http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&language=en&pcode=tps00028&plugin=1 [Last visited 21 January 2010]

Fisher, B.S., Nakicenovic, N., Alfsen, K., Corfee Morlot, J., de la Chesnaye, F., Hourcade, J.-Ch., Jiang, K., Kainuma, M., La Rovere, E., Matysek, A., Rana, A., Riahi, K., Richels, R., Rose, S., van Vuuren, D., Warren, R. 2007: Issues related to mitigation in the long term context, In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., eds.] Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007.

FOTÁV 2009. Nem lakossági (nem háztartási célú) távhőszolgáltatási díjak. [Non-residential (not for household purposes) district heating tariffs] for years 2004, 2006, 2007 and 2008. Tarifatáblázat. [Tariff tables] URL: http://www.fotav.hu/default.asp?m=0&s=18 [Last visited 11 February 2009]

Gaglia, A. G., Balaras, C. A., Mirasgedis, S., Georgopoulou, E., Sarafidis, Y., Lalas, D. P. 2007. Empirical assessment of the Hellenic non-residential building stock, energy consumption, emissions and potential energy savings. Energy Conversion and Management. 2007, 48(4): 1160-1175.

Georgopoulou, E., Sarafidis, Y., Mirasgedis, S., Balaras, C.A., Gaglia, A., Lalas, D.P. 2006. Evaluating the need for economic support policies in promoting greenhouse gas emission reduction measures in the building sector: The case of Greece. Energy Policy. 2006, 34(15): 2012-2031.

Gere, Tünde (captain, senior officer at the Coordination Department, Hungarian Prison Service Headquarters). 2010. Email communication, May 2010.

Goldstein, G. A., Greening, L.A. (eds.) 2001. Energy planning and the development of carbon mitigation strategies. Using the MARKAL family of models. Washington D.C., USA: International Resource Group, 2001.

Gruber, E. and Schlomann, B. 2009. Improving the database of electricity efficiency in tertiary buildings by monitoring and surveying. In: Conference proceedings of the eceee 2009 Summer Study: Act! Innovate! Deliver! Reducing energy demand sustainably. 1-6 June 2009, La Colle sur Loup. 889-900.

Gupta, S., Tirpak, D. A., Burger, N., Gupta, J., Höhne, N., Boncheva, A. I., Kanoan, G. M., Kolstad, C., Kruger, J. A., Michaelowa, A., Murase, S., Pershing, J., Saijo, T., Sari, A. 2007: Policies, Instruments and Co-operative Arrangements. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth

Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., eds.] Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007.

Hanley, N., Shogren, J.F., White, B. 2001. Introduction to Environmental Economics. Oxford: Oxford University Press.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M. Royer, D.L., Zachos, J.C. 2008. Target Atmospheric CO_2: Where Should Humanity Aim? Open Atmos. Sci. J. 2008, 2: 217-231.

Harvey, L. D. D. 2006. Handbook on low-energy buildings and district-energy systems. Fundamentals, techniques and examples. London, Sterling, VA: Earthscan, 2006.

Harvey, L. D. D. 2009. Reducing energy use in the buildings sector: measures, costs and examples. Energy Efficiency. 2009, 2(2): 139-163.

Hegger, M., Fuchs, M., Stark, T., Zeumer, M. 2008. Energy Manual. Munich: Edition Detail, 2008.

Hermelink, A. 2007. Solanova. The real social housing. Presentation at EUSEW, 1 February 2010, Brussels. URL: http://www.solanova.eu [Last visited 15 July 2009].

Hermelink, A. 2009. How deep to go: remarks on how to find the cost-optimal level for building renovation. Report commissioned by European Council for an Energy Efficient Europe, prepared by Ecofys. August 31 2009. URL: http://www.eceee.org/press/Understanding_the_economics_of_renovation/ [Last visited 10 April 2010]

Hoogwijk, M., van Vuuren, D. P., Boeters, S., Blok, K., Blomen, E., Barker, T., Chateau, J., Grübler, A., Masui, T., Nabuurs, G.-J., Novikova, A., Riahi, K., de la Rue du Can, S., Sathaye, J., Scrieciu, S., Urge-Vorsatz, D., van Vliet, J. 2008. Sectoral Emission Mitigation Potentials: Comparing Bottom-Up and Top-Down Approaches. Report within the project Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change (WAB). URL: http://www.ecofys.com/com/publications/documents/BUTD_Mitigation_potential_final_summary_20080909.pdf [Last visited on 26 July 2010.]

Hui, S.C.M. 2002. Using performance-based approach in building energy standards and codes. In: Proceedings of the Chonqing-Hong Kong Joint Symposium 2002, 8-10 July 2002, Chongqing, China, A52-61.

Hungarian Commission on Sustainable Development (HCSD). 2009. The Fifth National Communication to the UNFCCC. Prepared by Hungarian Commission on Sustainable Development, Ministry for Environment and Regional Policy. Budapest, 10 December 2009. HUN/COM/5 E. URL: http://unfccc.int/resource/docs/natc/hun_nc5.pdf [Last visited on 30 December 2009]

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: Mitigation. Cambridge: Cambridge University Press, 2001.

Intergovernmental Panel on Climate Change (IPCC). 2007. Summary for Policymakers. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., eds.], Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007.

International Energy Agency (IEA). 2006. Energy Technology Perspectives 2006. Scenarios and Strategies to 2050. In support of the G8 Plan of Action. Paris: IEA/OECD, 2006.

International Energy Agency (IEA). 2007. Energy Balances of OECD Countries, 2004-2005. 2007 Edition. Paris: IEA/OECD, 2007.

International Energy Agency (IEA). 2008a. IEA Energy balances of OECD countries. IEA Statistics. Paris: IEA/OECD, 2008.

International Energy Agency (IEA). 2008b. Energy Statistics of the OECD countries. Paris: IEA/OECD, 2008.

International Energy Agency (IEA). 2008c. Energy Technology Perspectives. Scenarios and Strategies to 2050. Paris: IEA/OECD, 2008.

Itard, L., Meijer, F., Vrins, E. H. H. 2008. Building renovation and modernization in Europe State of the art review. Delft: OTB Research Institute for Housing, Urban and Mobility Studies, 31 January 2008. URL: http://www.eracobuild.eu/fileadmin/documents/Final_Report_Erabuild_Susren_050208.pdf [Last visited 10 November 2010]

IZES. 2003. Keep cool. Refurbishment of an office building in a former barracks-territory to a passive-office building. ebök Ingenieurbüro für Energieberatung Haustechnik und ökologische Konzepte. URL: http://www.energyagency.at/publ/pdf/keepcool_bpp_germany.pdf [Last visited 1 July 2009]

Jakob, M. 2004. Marginal costs and co-benefits of energy efficiency investments. The case of the Swiss residential sector. Energy Policy. 2004, 34(2): 172-187.

Jarzemska, M. 2009. Building refurbishment programme in Poland. In: Proceedings of the workshop on effective policies to improve efficiency and on new financing instruments. 28-29 September 2009, Istanbul. URL: http://re.jrc.ec.europa.eu/energyefficiency/ [Last visited 20 October 2009]

Jensen, O. M., Wittchen, K.B, Thomsen, K. E., EuroACE. Sbi 2009:03: Towards very low energy buildings - Energy saving and CO_2 emission reduction of changing European building codes to very low energy standards. Hørsholm: Danish Building Research Institute, SBi, Aalborg University, 2009. URL: http://www.euroace.org/EuroACE%20documents/EuroACE%20-%20SBi_2009-03%20Towards%20very%20low%20energy%20building%20-%20February%202009.pdf [Last visited 30 January 2010]

Joosen, S. and Blok, K. 2001. Economic Evaluation of Carbon Dioxide Emission Reduction in the Household and Services Sectors in the EU. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Bottom-up Analysis. Final Report. Utrecht: Ecofys, January 2001. URL: http://ec.europa.eu/environment/enveco/climate_change/pdf/summary_report_policy_makers.pdf [Last visited 20 January 2010]

Kiss, Zoltán. (D-ÉG PEST Kft., Budai Áruház). Personal communication., 27 February 2009, Budapest.

Kistelegdi, István. (University of Pécs). Personal communication, February 5 2009, Passzivház konferencia, Budapest.

Koopmans, C. C. and te Velde, D. W. 2001. Bridging the energy efficiency gap: using bottom-up information in a top-down energy demand model. Energy Economics. 2001, 23(1): 57-75.

Kovacsics, István. (Engineer at EGI Contracting Engineering Co. Ltd., Budapest). 2009. Personal communication, 2008-2009, Budapest.

Kraft, M. E. and Furlong, S. R. 2007. Public policy. Politics, analysis, and alternatives. 2nd edition. Washington, D.C.: Congressional Quarterly.

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2010a. Stadat online table 2.1.4. Number of employed persons by industries, economic branches and sex (1998–). URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_annual/tabl2_01_04iea.html [Last visited 22 January 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2010b. Stadat online table 2.3.6 Real estates owned by the municipalities (2000-). URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_annual/i_zri001b.html [Last visited 29 August 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2010c. Stadat online table 2.4. Public health (1960–) URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_long/tabll2_4e.html [Last visited 20 January 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2010d. Stadat online table 2.5.1. Physicians', general practitioners (GP), hospital services, pharmacies, dental care (1990–). URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_annual/tabl2_05_01ie.html [Last visited 22 January 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2010e. Stadat online tables 2.6.3 (Kindergartens), 2.6.4, 2.6.5, 2.6.6, 2.6.7 (Primary and secondary schools), 2.6.9 (Universities). URL: http://portal.ksh.hu/portal/page?_pageid=38,593156&_dad=portal&_schema=PORTAL [Last visited 22 January 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2010f. Stadat online table 2.6.1. Pupils and students in full-time and part-time education (1990-). URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_annual/tabl2_06_01iea.html [Last visited 22 January 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2010g. Stadat online table 1.1. Population, vital statistics (1949–) URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_long/h_wdsd001a.html [Last visited 20 January 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2010h. Stadat online table 2.1.4. Number of employed persons by industries, economic branches and sex (1998–). URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_annual/tabl2_01_04iea.html [Last visited 20 January 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2009a. Table 3.1.2 Value and distribution of gross value added by industries (1995–). Stadat-tables.

KSH Online. URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_annual/tabl3_01_02iec.html [Last visited 13 December 2009]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office]. 2009b. Table 2.1.20.2 Average statistical staff number of employees in the national economy (2008–) – NACE Rev. 2*. Stadat-tables. KSH Online. URL: http://portal.ksh.hu/pls/ksh/docs/eng/xstadat/xstadat_annual/tabl2_01_20_02ie.html [Last visited 13 December 2009]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2000. The real property of the municipalities 2000. Budapest: KSH, 2000. ULR: http://portal.ksh.hu/pls/ksh/docs/hun/xftp/idoszaki/onking/onking00.pdf [Last visited 15 February 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2003. The real property of the municipalities 2003. Budapest: KSH, 31 December 2003.

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2004. The real property of the municipalities 2004. Budapest: KSH, 31 December 2004.

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2005. The real property of the municipalities 2005. Budapest: KSH, 31 December 2005. URL: http://portal.ksh.hu/pls/ksh/docs/hun/xftp/idoszaki/onking/onking05.pdf [Last visited 15 February 2010]

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2006. The real property of the municipalities 2006. Budapest: KSH, 31 December 2006.

KSH (Központi Statistikai Hivatal) [Hungarian Statistical Central Office] 2007. The real property of the municipalities 2007. Budapest: KSH, 31 December 2007.

Kypreos, S. 2005. A MERGE Model with Endogenous Technological Change and the Cost of Carbon Stabilization. Paper published by Fondazione Eni Enrico Mattei. URL: http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm [Last visited 15 June 2010]

Lang, Günter. 2009. (Director of IG Passivhaus, Austria). Email communication, October 2009.

Laustsen, J. 2008. Energy efficiency requirements in building codes, energy efficiency policies for new buildings. IEA Information paper. In support of the G8 Plan of Action. Paris: OECD/IEA, March 2008.

Layberry, R. and Hinnelis, M. 2007. Transforming UK non-residential buildings: achieving a 60% cut in CO_2 emissions by 2005. Paper In: Conference proceedings of eceee 2007 Summer study: Saving energy - just do it! 4-9 June 2007, La Corre sur Loup, 1101-1104.

Lechtenböhmer, S. and Schüring, A.. *Forthcoming.* The potential for large scale savings from insulating residential buildings in the EU. Energy Efficiency.

Lechtenböhmer, S., Grimm, V., Mitze, D., Thomas, S., Wissner, M. 2005. Target 2020: Policies and Measures to reduce Greenhouse gas emissions in the EU. A report on behalf of WWF European Policy Office. Final report. Wuppertal: Wuppertal Institute for Climate, Environment and Energy, September 2005. URL: http://assets.panda.org/downloads/target_2020_low_res.pdf [Last visited 16 April 2009]

Lechtenböhmer, S., Thomas, S. and Zeiss, C. 2009. The role of energy efficiency in the framework of the EU energy and climate strategy – a policy-based scenario analysis. In: Conference proceedings of the eceee 2009 Summer Study: Act! Innovate! Deliver! Reducing energy demand sustainably. 1-6 June 2009, La Colle sur Loup. 11-20.

Lehtilä, A. and Pirilä, P. 1996. Reducing energy related emissions. Using an energy systems optimization model to support policy planning in Finland. Energy Policy. 1996, 24 (9): 805-819.

Levine, M., Ürge-Vorsatz, D., Blok, K., Geng, L., Harvey, D., Lang, S., Levermore, G., Mongameli Mehlwana, A., Mirasgedis, S., Novikova, A., Rilling, J., Yoshino, H. 2007. Residential and commercial buildings. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., eds.] Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007.

Loulou, R., Goidstein, G., Noble, K. 2004. Documentation of the MARKAL family of models: Part II-MARKAL-MACRO. URL: http://www.etsap.org/tools.htm [Last visited 8 April 2010]

Lueth, O., Jattke, A., Schoettle, H., Wietschel, M. and Rentz, O. 1997. Emission reduction strategies for Central and Eastern Europe. Energy Policy. 2006, 25(3): 305-312.

Lysen, E.H. 1996. Trias Energetica. Paper presented at Eurosun Conference, 16-19 September 1996, Freiburg.

Magyar közlöny. 2006. Ministerial decree 7/2006. (V. 24.) TNM r. Az épületek energetikai jellem zõinek meghatározásáról. (p. 5134) Budapest, 24 May 2006.

Mantzos, L. and Capros, P. 1998. The PRIMES Version 2 Energy System Model: Design and features. E3M-Lab/lnstitute of Communication and Computer Systems, National Technical University of Athens.

Matzig, Roland. (Architos, Mannheim, Passive house - certified architect). 2009. Personal communication, 5 February 2009, Passzivház konferencia, Budapest.

McKinsey. 2007a. Costs and potentials of greenhouse gas abatement in Germany. Report on behalf of BDI initiative – Business for Climate. McKinsey & Company, Inc., 2007. URL: http://ccsl.iccip.net/costsandpotentials.pdf [Last visited 13 July 2008]

McKinsey. 2007b. Appendix: UK cost abatement curve. In: CBI 2007. Climate change: everyone’s business. Final report. London: Confederation of British Industry (CBI), November 2007. URL: http://www.mckinsey.com/clientservice/sustainability/Costcurves.asp [Last visited on 26 January 2010]

McKinsey. 2007c. Reducing U.S greenhouse gas emissions: How much at what cost? U.S greenhouse gas abatement mapping initiative. Executive report. McKinsey & Company, Inc., December 2007. URL: http://www.mckinsey.com/clientservice/sustainability/Costcurves.asp [Last visited on 26 January 2010]

McKinsey. 2008. Costs and potentials of greenhouse gas abatement in Czech republic – Key findings. McKinsey & Company, Inc., November 2008. URL:

http://www.mckinsey.com/clientservice/sustainability/Costcurves.asp [Last visited on 26 January 2010]

McKinsey. 2009a. Pathways to a low-carbon economy. Version 2 of the global greenhouse gas abatement cost curve. McKinsey & Company, Inc., January 2009. URL: http://www.mckinsey.com/clientservice/ccsi/costcurves.asp [Last visited 20 December 2009]

McKinsey. 2009b. Swiss greenhouse gas abatement cost curve. McKinsey & Company, Inc. Zurich, January, 2009. URL: http://www.mckinsey.com/clientservice/sustainability/Costcurves.asp [Last visited on 26 January 2010]

McKinsey. 2010a. Assessment of greenhouse gas abatement potential of Poland by 2030. Final report. McKinsey & Company, Inc. Warsaw, January 2010. URL: http://www.mckinsey.com/clientservice/sustainability/Costcurves.asp [Last visited on 26 January 2010]

McKinsey. 2010b. China's green revolution. Prioritizing technologies to achieve energy and environmental sustainability. McKinsey&Company. February 2009. URL: http://www.mckinsey.com/clientservice/ccsi/costcurves.asp [Last visited on 26 January 2010]

MEH (Magyar Energia Hivatal, Hungarian Energy Office). 1999-2005. Annual report on activities of the Hungarian Energy Office. Budapest, 1999-2005. Collection of annual reports. Available at: http://www.eh.gov.hu/home/html/index.asp?msid=1&sid=0&lng=2&hkl=148. [Last visited on 3 June 2008.]

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., Allen, M. R.. 2009. Background questions and answers to paper "Greenhouse-gas emission targets for limiting global warming to 2°C". Nature. 2009, 458(7242): 1158.

Messner, S. and Strubegger, M. 1995. User's guide for MESSAGE III. Working Paper WP-95-69. Laxenburg: International Institute for Applied System Analysis, 1995.

Ministry of Environment and Ministry of Industry and Trade of the Czech Republic. (MoE and MIT). 2005. Národní alokační plán České republiky 2005 až 2007. [National Allocation Plan of the Czech Republic for the period 2005-207.] Prague: Ministry of Environment and Ministry of Industry and Trade of the Czech Republic, 2005. URL: http://portal.gov.cz/wps/dokumenty/NAP%20final%20varianta%20III.pdf [Last visited 29 August 2010]

Ministry of Environment and Ministry of Industry and Trade of the Czech Republic. (MoE and MIT). 2006. Národní alokační plán České republiky 2008 až 2012. [National Allocation Plan of the Czech Republic for the period 2008-2012.] Praha: Ministry of Environment and Ministry of Industry and Trade of the Czech Republic, 2006. URL: http://www.mzp.cz/C1257458002F0DC7/cz/narodni_alokacni_plan/$FILE/OZK-NAP_2-20081008.pdf [Last visited 30 December 2009]

Ministry of Environment and Water (MEW). 2007. National Allocation Plan of the Republic of Hungary for the period 2008-2012. Unofficial English translation. Budapest: Ministry of Environment and Water, January 2007.

Ministry of Environment of the Czech republic (MoECR). 2009. Fifth National Communication of the Czech Republic on the UN Framework Convention on Climate Change including Supplementary Information Pursuant to Article 7.2 of the Kyoto Protocol. Prague: Ministry of Environment of the Czech republic, 2009. URL: http://unfccc.int/resource/docs/natc/czenc5.pdf [Last visited 30 December 2009]

Ministry of the Environment [of the Republic of Poland] (MoEPL). 2006. Fourth National Communication under the United Nations Framework Convention on Climate Change. Republic of Poland. Published by Institute of Environmental Protection. Warsaw: Ministry of the Environment, 2006. URL: http://unfccc.int/resource/docs/natc/polnc4.pdf [Last visited 30 December 2009]

Ministry of the Environment of the Slovak republic (MoESR). 2005. The Fourth National Communication of the Slovak republic on Climate Change. Bratislava: Ministry of the Environment of the Slovak republic, Slovak Hydrometeorological Institute, 2005. URL: http://unfccc.int/resource/docs/natc/slknc4.pdf [Last visited on 30 December 2009]

Ministry of the Environment of the Slovak republic (MoESR). 2006. Národný alokačný plán na roky 2008 - 2012. [National Allocation Plan for the period 2008-2012]. Bratislava: Ministry of the Environment of the Slovak republic, July 2006. URL: URL: http://www.enviro.gov.sk/servlets/page/868?c_id=2542&o_id=5429 [Last visited 30 December 2009]

Mirasgedis, S., Sarafidis, Y., Georgopoulou, E., Lalas, D. P. and Papastavros, C. 2004. Mitigation policies for energy related greenhouse gas emissions in Cyprus: the potential role of natural gas imports. Energy policy. 2004, 32(8): 1001-1011.

Molnar, S. 1997. Assessment of Mitigation Measures and Programs in Hungary. Applied Energy. *1997*, 56(3-4): 325-339.

Nagy, P. 2008. Energy audits conducted in Nyíregyháza within the Display campaign project in 2004-2006. Courtesy of Nagy Péter, provided in September 2008.

Nagy, P. 2009. Municipality of Nyíregyháza: Energy efficiency in Nyíregyháza town. Presentation at the conference: Opportunities for climate change and energy efficiency action in an economic crisis: Catalysing a green recovery. 20 October 2009, Central European University, Budapest.

National Observatory of Athens (NOA) 2003. CO_2 emissions reduction in the residential and tertiary sectors. Technical Report prepared for the Ministry for Environment Physical Planning and Public Works. Athens: National Observatory of Athens, 2003.

NIR (National Inventory Report) 2009. NIR 2009 submission v1.3. URL: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4771.php [Last visited 13 December 2009]

Norhaus, W.D. and Boyer, J. 2000. Warming the world. Economic models of global warming. Cambridge: The MIT Press.

Novikova, A. 2008. Carbon dioxide mitigation potential in the Hungarian residential sector. PhD dissertation. Budapest: Central European University, 2008. URL: http://web.ceu.hu/envsci/projects/Potentials/Publications.html

Novikova, V. *Forthcoming*. The economic potential of carbon dioxide emission mitigation from efficiency improvement in electricity end-use in the Hungarian tertiary sector. [PhD thesis] Budapest: Central European University.

Novikova, V., Ürge-Vorsatz, D. , Korytarova, K. 2009. Carbon Dioxide Mitigation Potential in the Hungarian Public Sector. Report on behalf of the Ministry of Environment and Water of the Republic of Hungary. Budapest: Ministry of Environment and Water of the Republic of Hungary, June 2009.

ODYSSEE. 2009. Enerdata online. URL: http://odyssee.enerdata.eu [Last visited April 2 2009]

Pajér, S. 2009. A panelprogram tapasztalatai Székesfehérváron. Presentation at the Fifth national conference KLÍMAVÁLTOZÁS - ENERGIATUDATOSSÁG – ENERGIAHATÉKONYSÁ. 16-17 April 2009, Szeged.

Parsons, D. W. 1995. Public policy: an introduction to the theory and practice of policy analysis. Aldershot: E. Elgar, 1995.

Passive House Institute (PHI). 2010. EnerPHit. Certification as "Quality-Approved Energy Retrofit with Passive House Components". Criteria for Residential-Use Refurbished Buildings. 17.08.2010. URL: www.passiv.de [Last visited on 29 August 2010]

Passivhaus Institut (PHI) 2003. Certification as "Quality Approved Passive House". Additional Criteria for Non-Residential Buildings. [Last changes made 07 August 2003. Translated into English 17 October 2007.] 7 August 2003. URL: http://www.passiv.de/07_eng/phpp/Certification_Non-Residential.pdf [Last visited 20 January 2010]

Petersdorff, C., Boermans, T., Harnisch, J., Joosen, S., Wouters, F. 2005. Cost effective climate protection in the building stock of the New EU Member States. Beyond the EU Energy perfomance of Buildings Directive. ECOFYS, Germany. URL: http://www.rockwool.com/files/rockwool.com/Energy%20Efficiency/Library/CosteffectiveClimateReport.pdf [Last visited 13 January 2010]

Petrichenko, K.V. 2010. Low-energy Future of Russian Building Sector. Master of Science thesis. Budapest: Central European University, 2010.

PHI Database of passive house buildings. 2009. Passivhaus Institut. URL: http://www.passivhausprojekte.de/projekte.php [Last visited 18 July 2009]

PIER (Public Interest Energy Research) and California Energy Commission. 2003. Attachment V: Developing Greenhouse Gas Mitigation Supply Curves for In-State Sources. Attachment to the report Climate Change Research, Development, and Demonstration Plan. Sacramento: California Energy Commission, August 2003. URL: http://www.energy.ca.gov/reports/2003-04-16_500-03-025FA-V.PDF [Last visited 20 April 2008]

Pillen, N., Bertoldi, P., Grether, S. 2007. GreenBuilding – Europe wide renovations of non-residential buildings. Paper In: Conference proceedings of eceee 2007 Summer study: Saving energy - just do it! 4-9 June 2007, La Corre sur Loup. 1019-1025.

Polish UNFCCC Executive Bureau, National Fund for Environmental Protection and Water Management and Ministry of Environment. 2001. Third National Communication to the Conference of the Parties to the United Nations Framework Convention on Climate Change. Republic of Poland. Warsaw: Institute of Environmental

Protection. URL: http://unfccc.int/resource/docs/natc/polnc3.pdf [Last visited 30 December 2009]

Product catalogues: Junkers 2008, Vaillant 2008-2009, Termomax 2008, Viessman 2009.

Ramanathan, V. and Feng, V. 2008. On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. Proceedings of the National Academy of Sciences of the United States of America. 105 (no. 38): 14245-14250.

Richarz, C., Schulz, C., Zeitler, F. 2007. Energy efficiency Upgrades. Principles. Details. Examples. Edition Detail. Berlin: Institut fur internationale Architektur-Dokumentation, Munich: Birkhauser, 2007.

Rockwool. 2009. Public buildings in front. [1 screen] URL: http://www.rockwool.com/energy+efficiency/energy+efficiency+in+buildings/public+buildings+in+front. [Last visited October 24 2009]

Schellnhuber, H. J. 2008. Global warming: Stop worrying, start panicking? Proceedings of the National Academy of Sciences of the United States of America 105 (no. 38): 14245-14250.

Seebregts, A.J., Goldstein, G.A., Smekens, K.. 2001. Energy/Environmental Modelling with the MARKAL Family of Models. [Posted on the web 06 December 2001] URL: http://www.etsap.org/reports/markal.html [Last visited 08 April 2007]

SEG (Scientific Expert Group on Climate Change) 2007. Confronting climate change: avoiding the unmanageable and managing the unavoidable [Bierbaum, R.M., Holdren, J. P., MacCracken, M.C., Moss, R.H., Raven, P.H., eds.] Report prepared for the United Nations Comission on Sustainable Development. Washington, DC: Sigma Xi, Research Triangle Park, NC and the United Nations Foundation, 2007.

Smeds, J. and Wall, M. 2007. Enhanced energy conservation in houses through high performance design. Energy and Buildings. 2007, 39: 273-278.

Štatistický register organizácií (SRO) [Statistical registry of organizations]. Database. URL: Statistical registry of organizations [Retrieved 10 May 2010]

Stern, N. 2007. The Economics of Climate Change: The Stern Review. Cambridge: Cambridge University Press. URL: http://www.hm-treasury.gov.uk/stern_review_report.htm [Last visited on 12 December 2009]

Strubegger, M., Totsching, G., Zhu, B. 2004. MESSAGE: a technical model description. Appendix in: Schrattenholzer, L., A. Miketa, K. Riahi, R. A. Roehl: Achieving a sustainable global energy system: identifying possibilities using long-term energy scenarios. Cheltenham, Northampton: Edward Elgar Publishing, 2004.

Systemexpert Consulting (eds.) 2002. 3rd National Communication for the UNFCCC. Hungary. 2002. Budapest: Systemexpert Consulting Ldt. URL: http://unfccc.int/resource/docs/natc/hunnc3.pdf [Last visited 30 December 2009]

Szalay, Zsuzsana. 2008. (Budapest University of Technology and Economics BME, Budapest). Email communication, April and May 2008.

Szekér, László. (Architect, Board member of Hungarian Green Building Council). 2009. Personal communication, Budapest, 20 July 2009.

Szlávik, M., Palvolgyi, T., Ürge-Vorsatz, D. and Fule, M. 1999. Economics of GHG Limitations. Country Case Study. Hungary. Roskylde: UNEP Collaborating Centre for Energy and Environment, Riso National Laboratory. URL:

http://www.airimpacts.org/documents/local/Hungary.pdf [Last visited 15 August 2010]

Thomsen, K.E, Wittchen, K.B, EuroACE. 2008. European national strategies to move towards very low energy buildings. Sbi 2008:7. Danish Building Research Institute, Aalborg University, March 2008. URL: http://www.rockwool.com/files/rockwool.com/Energy%20Efficiency/Library/EuropeanNationalStrategiesToMoveTowardsVeryLowEnergyBuildings.pdf [Last visited 30 January 2010]

Tichý, M. 1997. GHG Emission Mitigation Measures and Technologies in the Czech Republic. AppliedEnergy. 1997, 56 (3/4): 309-324.

Tol, R. J. S. 2000. Modelling the costs of emission reduction: different approaches. Pacific and Asian Journal of Energy. 2000, 10(1): 1-7.

Turton, H., L. Barreto. 2006. Long-term security of energy supply and climate change. Energy Policy. 2006, 34(15): 2232-2250.

Ürge-Vorsatz, D. 2010. Free lunch we are paid to eat or mission impossible? The role of the building sector in controlling the climate change. Presentation at the Energy Policy Research Group, 8 January 2010, Central European University, Budapest.

Ürge-Vorsatz, D. and Novikova, A. 2008. Potentials and costs of carbon dioxide mitigation in the world's buildings. Energy policy. 2008, 36(2): 642-661.

Ürge-Vorsatz, D., Malikova, Y., Szeszler, A., Gilyian, C. 2000. Lighting municipally financed buildings in Hungary. Market assessment. With special focus on energy efficiency potentials and barriers. Research Report. Budapest, August 2000.

UNDP/Energy Centre 2008. Energy audits collected under the UNDP/GEF Hungary Public Sector Energy Efficiency Project in 2002-2008. [Utilization of data approved by UNDP in 2008. Energy audits were accessed in Energy centre, Budapest.]

Unruh, G. 2002. Escaping Carbon Lock-in. *Energy Policy. 2002*, 30(4): 317-325.

Varga, A. P. 2008. Mérd Magad projekt 15 önkormányzati iskola. Energetikai körkép [Check it out! 15 local schools. Energy audits.]. Pakole Kft. Presentation at the conference Check it out! Energy at schools. 2 April 2008, Budapest. URL: http://www.energiaklub.hu/dl/merdmagad/konferencia_eloadas_iskolai_auditok_eredmenyei_varga_andras.pdf [Last visited 26 July 2010.]

Vattenfall. 2007. Global mapping of greenhouse gas abatement opportunities up to 2030. Buildings sector deep-dive. Vattenfall, June 2007. URL: http://www.vattenfall.com/www/ccc/ccc/577730downl/index.jsp [Last visited January 2008]

Veronica 2004. Pasívní dům – zkušenosti z Rakouska a české začátky [Passive house – experience from Austria and first examples from Czech republic]. Veronica, Brno, 2004. First edition.

Veronica 2008. Pasívní dům II – zkušenosti z Rakouska a české začátky [Passive house II – experience from Austria and first examples from Czech republic]. Veronica, Brno, 2008. Second extended edition. URL: http://www.veronica.cz/dokumenty/pasivni_dum_2008.pdf [Last visited 18 August 2010]

Wing, I. S. 2006. The synthesis of bottom-up and top-down approaches to climate policy modelling: Electric power technologies and the cost of limiting US CO_2 emissions. Energy Policy. *2006*, 34(18): 3847-3869.

Zöld, A. 2007. Implementation of the EPBD in Hungary: Status August 2006. P13. 19-01-2007. Country review. EPBD Building Platform. URL: www.buildingsplatform.eu [Last visited 13 August 2009]

Zöld, A. and Csoknyai, T. 2007. Technical improvement of housing envelopes in Hungary. In: COST C16 Improving the Quality of Existing Urban Building Envelopes – Facades and Roofs. L. Braganca, C. Wetzel, V. Buhagiar, L.G.W. Verhoef (eds.) IOS Press, 2007.

ANNEX I. BUILDING TYPES AND THEIR CHARACTERISTICS

1. Educational buildings

1.1 Educational sector: one-storey buildings (kindergartens and nurseries)

Figure 58 Building pattern of an educational one-storey building built until 1990

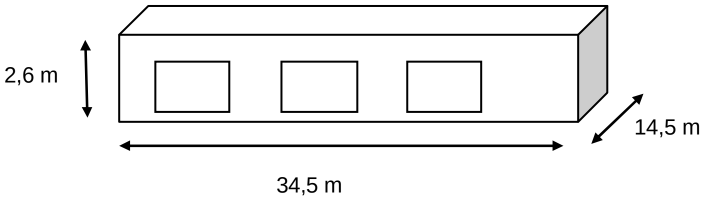


Table 53 Characteristics of an educational one-storey building built until 1990

Number of floors	1		
Wall length, side 1	34.5	m	
Wall length, side 2	14.5	m	
Ground floor area	501	m^2	
Gross floor area	501	m^2	
Height of the floor	2.6	m	
Height of the building	2.6	m	
Volume of the building	1301	m^3	
Wall surface (excl. doors and windows)	196	m^2	
Roof area	501	m^2	
Basement area	501	m^2	
Windows and balcony doors	51	m^2	20% of wall surface
Exit doors (2x)	8	m^2	4

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

1.2 Educational sector: traditional buildings built before 1900 and between 1901-1945

Figure 59 Building pattern of the educational traditional building built before 1900 and between 1901-1945

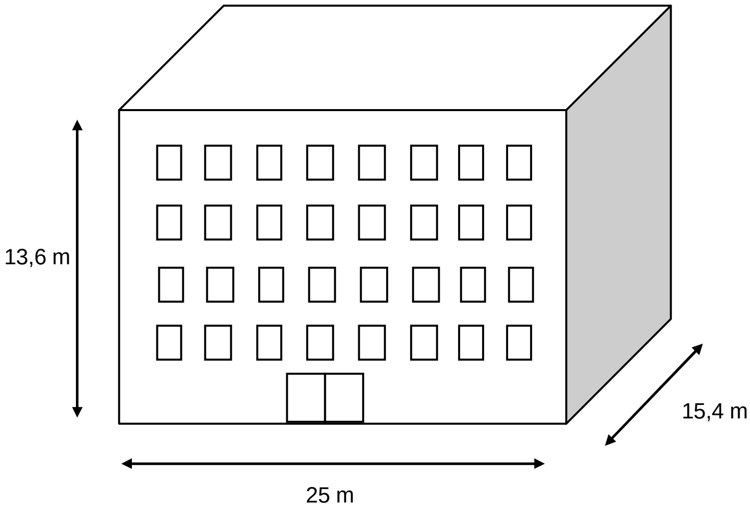


Table 54 Characteristics of an educational traditional building built before 1900 and between 1900-1945

Number of floors	4		
Wall length, side 1	25	m	
Wall lenths, side 2	15.4	m	
Ground floor area	386	m^2	
Gross floor area	1544	m^2	
Height of the floor	3.4	m	
Height of the building	13.6	m	
Volume of the building	5248	m^3	
External wall surface excluding doors and windows	750	m^2	
Roof area	386	m^2	
Basement area	386	m^2	
Windows/terrace/balcony doors	330	m^2	30% of surface
Exit door	20	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

1.3 Educational sector: panel/ industrialized buildings built between 1946-1990

Figure 60 Building pattern of educational industrialized building built between 1946-1990

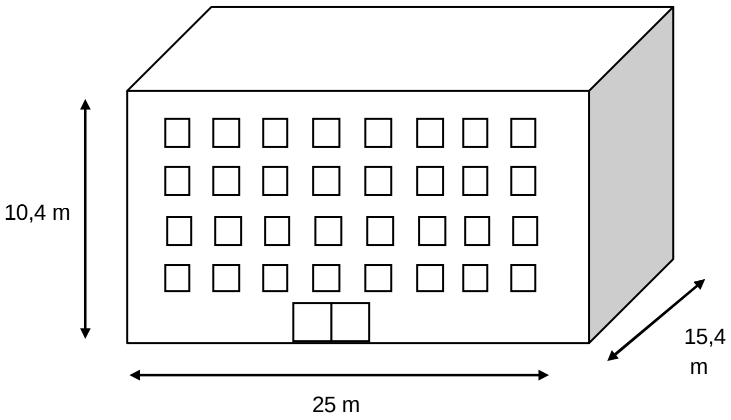


Table 55 Characteristics of educational industrialized building built between 1946-1990

Number of floors	4		
Wall length, side 1	25	m	
Wall length, side 2	15.4	m	
Ground floor area	386	m^2	
Gross floor area	1544	m^2	
Height of the floor	2.6	m	
Height of the building	10.4	m	
Volume of the building	4013	m^3	
Wall surface (excluding windows and doors)	653	m^2	
Roof area	386	m^2	
Basement area	386	m^2	
Area of windows/terrace/baclony doors	168	m^2	20% of wall surface
Exit door	20	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

2. Health care buildings

2.1 Health care sector: one-storey buildings (doctors' offices and ambulance stations)

Figure 61 Building pattern of a health care one-storey building built until 1990

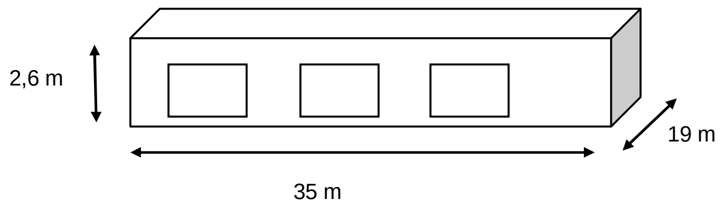


Table 56 Characteristics of a health care one-storey building built until 1990

Number of floors	1		
Wall length, side 1	35	m	
Wall length, side 2	19	m	
Ground floor area	659	m^2	
Gross floor area	659	m^2	
Height of the floor	2.6	m	
Height of the building	2.6	m	
Volume of the building	1713	m^3	
Wall surface (excl. doors and windows)	216	m^2	
Roof area	659	m^2	
Basement area	659	m^2	
Windows and balcony doors	56	m^2	20% of wall surface
Exit doors (2x)	8	m^2	4 dooors

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

2.2 Health care sector: traditional health care buildings (built before 1900 and between 1901-1945)

Figure 62 Building pattern of a health care traditional building built before 1900 and between 1901-1945

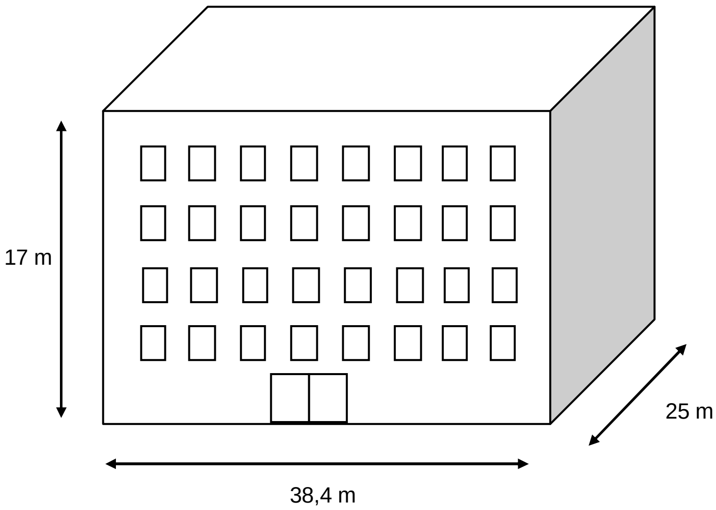


Table 57 Characteristics of a health care traditional building built before 1900 and between 1901-1945

Number of floors	5		
Wall length, side 1	25	m	
Wall lenths, side 2	38.4	m	
Ground floor area	960	m^2	
Gross floor area	4799	m^2	
Height of the floor	3.4	m	
Height of the building	17	m	
Volume of the building	16318	m^3	
External wall surface excluding doors and windows	1489	m^2	
Roof area	959.875	m^2	
Basement area	959.875	m^2	
Windows/terrace/balcony doors	647	m^2	30% of surface
Exit door	20	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

2.3 Health care sector: panel/ industrialized buildings built between 1946-1990

Figure 63 Building pattern of a health care industrialized building built between 1946-1990

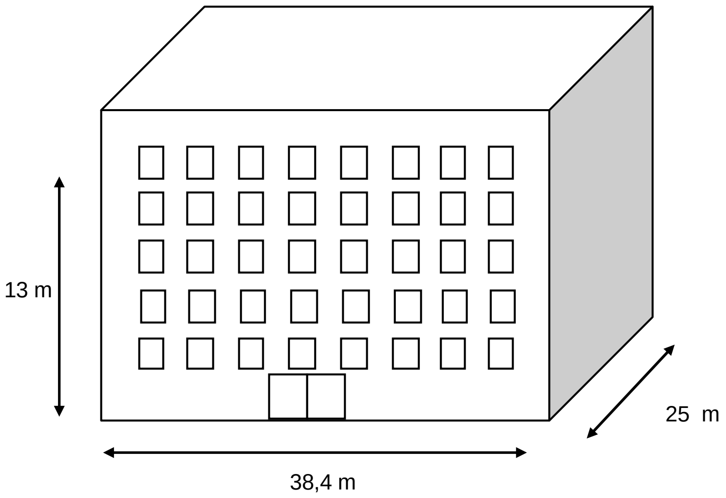


Table 58 Characteristics of a health care industrialized building built between 1946-1990

Number of floors	5		
Wall length, side 1	25	m	
Wall length, side 2	38.4	m	
Height of a building	13	m	
Ground floor area	960	m^2	
Gross floor area	4799	m^2	
Height of the floor	2.6	m	
Height of the building	13	m	
Volume of the building	12478	m^3	
Wall surface (excluding windows and doors)	1299	m^2	
Roof area	960	m^2	
Basement area	960	m^2	
Area of windows/terrace/baclony doors	330	m^2	20% of wall surface
Exit door	20	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

3. Public administration buildings

3.1 Public administration: small buildings (built until 1990)

Figure 64 Building pattern of a small public administration building (built until 1990)

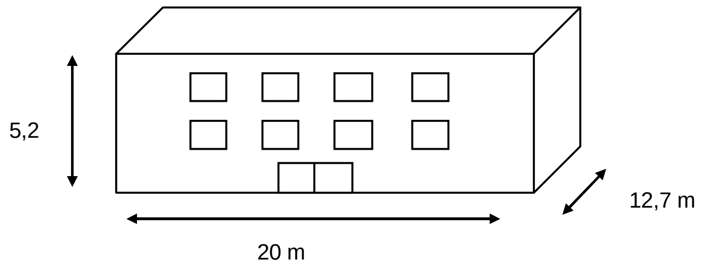


Table 59 Characteristics of a small public administration building (built until 1990)

Number of floors	2	m	
Wall length, side 1	20	m	
Wall length, side 2	12.7	m	
Ground floor area	253	m^2	
Gross floor area	507	m^2	
Height of the floor	2.6	m	
Height of the building	5.2	m	
Volume of the building	1317	m^3	
Wall surface (excluding windows and doors)	264	m^2	
Roof area	253	m^2	
Basement area	253	m^2	
Area of windows/terrace/baclony doors	68	m^2	20% of wall surface
Exit door	8	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

3.2 Public administration: large buildings (built until 1990)

Figure 65 Building pattern of large public administration building (built until 1990)

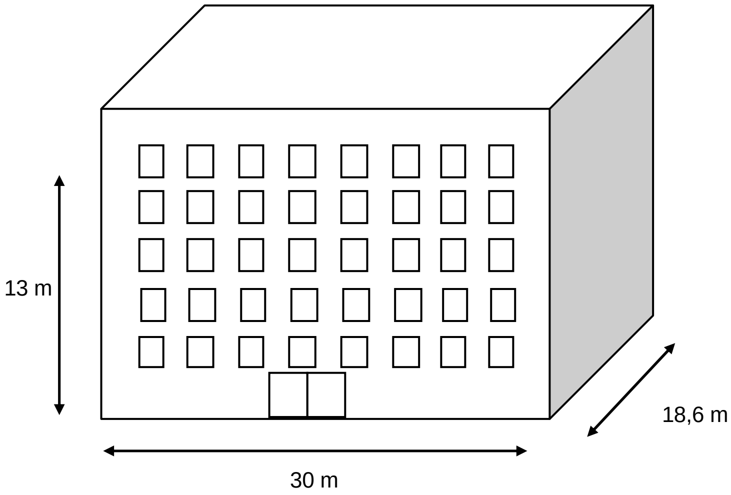


Table 60 Characteristics of a large public administration building (built until 1990)

Number of floors	5	m	
Wall length, side 1	30	m	
Wall length, side 2	18.6	m	
Ground floor area	559	m^2	
Gross floor area	2794	m^2	
Height of the floor	2.6	m	
Height of the building	13	m	
Volume of the building	7264	m^3	
Wall surface (excluding windows and doors)	739	m^2	
Roof area	559	m^2	
Basement area	559	m^2	
Area of windows/terrace/baclony doors	506	m^2	Assumption: 40% of wall surface
Exit door	20	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

4. Social buildings (built until 1990)

Figure 66 Building pattern of a social building (built until 1990)

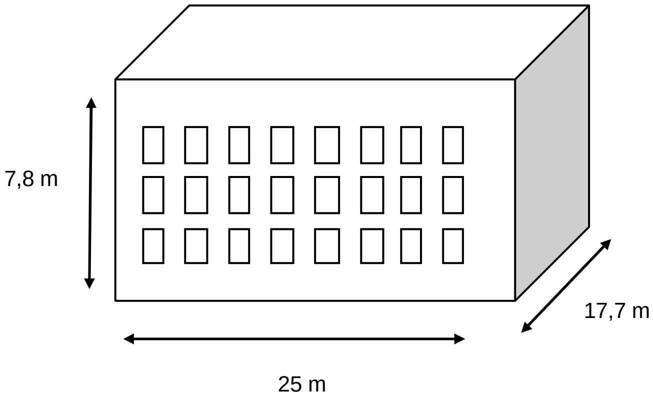


Table 61 Characteristics of a social building (built until 1990)

Number of floors	3	m	
Wall length, side 1	25	m	
Wall length, side 2	17.7	m	
Ground floor area	443	m^2	
Gross floor area	1329	m^2	
Height of the floor	2.6	m	
Height of the building	7.8	m	
Volume of the building	3455	m^3	
Wall surface (excluding windows and doors)	513	m^2	
Roof area	443	m^2	
Basement area	443	m^2	
Area of windows/terrace/baclony doors	133	m^2	20% of wall surface
Exit door	20	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

5. Cultural buildings (built until 1990)

Figure 67 Building pattern of a cultural building (built until 1990)

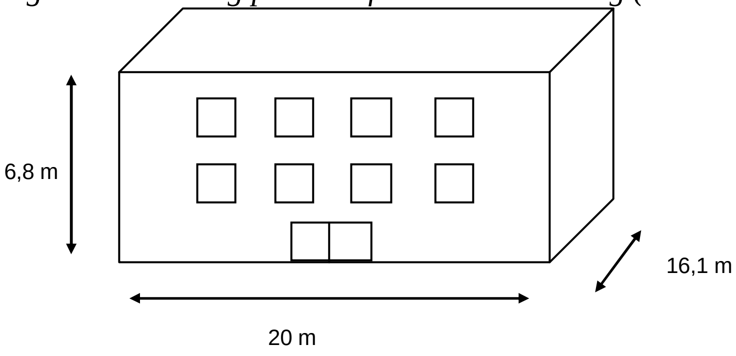


Table 62 Characteristics of a cultural building (built until 1990)

Number of floors	2	m	
Wall length, side 1	16.1	m	
Wall length, side 2	20	m	
Ground floor area	321	m^2	
Gross floor area	642	m^2	
Height of the floor	3.4	m	
Height of the building	6.8	m	
Volume of the building	2183	m^3	
Wall surface (excluding windows and doors)	372	m^2	
Roof area	321	m^2	
Basement area	321	m^2	
Area of windows/terrace/baclony doors	98	m^2	20% of wall surface
Exit door	20	m^2	1 m x 2 m

Source: based on Novikova (2008) and energy audits (UNDP/Energy centre 2008, Nagy 2008, Csoknyai 2008a)

ANNEX II. SELECTED MODELS USED IN CURRENT ENERGY AND CLIMATE POLICY

Table 63 Selected models used in current energy and climate policy analysis

Name of the model	Full name	Class/Description	Comments/Application	References	Extensions/Modifications
MARKAL (late 1970s)	MARKet ALlocation	Bottom-up dynamic model. Optimization model that produces the least-cost solution subject to (given) emission or other constraints.	Applied in more than 40 countries in national and local energy planning and development of carbon mitigation strategies (incl. CR (MIT, SEVEn, SRC International) and SR (Ministry of Economy).	Developed by Energy Technology Systems Analysis Programmc (ETSAP) of the IEA. Goldstein *et al.*(2001), Seebregts *et al.*(2001), Loulou *et al.* (2004)	MARKAL-MACRO, MARKAL-ED (MED), MARKAL-M1CRO, MATTER, MARKAL-EQUITY. SÁGE, TIMES. Global MARKAL Model (GMM)
TIMES (1999)	The Integrated MARKAL-EFOM System	Bottom-up: Expands the robustness of MARKAL, which allows simultaneous analysis of several problems at the time.	Replacement for MARKAL, introduced in 1999.	Goldstein *et al.* (2001) Loulou *et. al.* (2004) Blesl and Remme (2005).	TIMES-MACRO
ERIS (2000)	Energy Research and Investment Strategies	Bottom-up: A multi-regional energy-systems bottom-up optimization model with endogenized technology learning (reflecting both commercial investment and R&D costs).	E.g. analysis of potential synergies of implementing energy security policy and climate policy in the long-term; endogenizing R&D and market experience.	Barreto and Kypreos (2004), Turton and Barreto (2006).	ERIS was extended by Turton and Barreto (2006) so that it can be linked to MAGICC climate model.
DICE and RICE (1994, 1996)	Dynamic Integrated model of Climate and Economy	Top-down: DICE - one of the first dynamic economic models of climate change, highly aggregated.	E.g. economic analysis of implementation of the Kyoto Protocol.	Nordhaus and Boyer (2000).	Regionalized version RICE (Regional dynamic Integrated model of Climate and the Economy), presented in 1996.
MESSAGE (since 1970s)	Model of Energy Supply Systems Alternatives and their General Environmental Impacts	Bottom-up: A multi-regional systems engineering optimization model. It finds the optimal energy flow from primary energy resources to useful energy demands for the exogenously given demand under the given constraints (emissions etc).	Used for calculation of the IPCC SRES scenarios at IIASA etc.	Messner and Strubegger (1995); Strubegger *et al.* (2004).	

Name of the model	Full name	Class/Description	Comments/Application	References	Extensions/Modifications
MERGE	Model for Evaluating Regional and Global Effects	Integrated assessment model (IAM) that provides a framework for assessing climate-change management proposals. Includes endogenized technological learning.	MERGE considers market (through production losses), and non-market climate change induced damages (through losses in global welfare).	Kypreos (2005)	MERGE can model not only learning by doing (LBD), but also learning-by-searching (LBS) and learning subsidies.
PRIMES (Version 2)		Hybrid model combining engineering-orientation with economic market-driven representations. It is a partial equilibrium model for the EU energy system.	PRIMES involves market regimes and model the behaviour of economic agents. The model was used in the long-term projections (up to 2030) for the EU and accession countries.	Mantzos and Capros (1998), National Technical University of Athens	ACE (Accession Countries Energy) model for the acceding (EU-12+Turkey)and neighboring countries (Switzerland, Norway)
MACRO		A top-down stylized macro-economic growth model. MACRO is applied to the energy models, where it balances the non-energy part of the economy of a given region.	The MACRO model also captures autonomous effects and macro-economic feedbacks between the energy sector and the rest of the economy, such as the impacts of higher energy prices *(e.g.,* resulting from $C0_2$ control) on economic activities.		
EFOM (since 1970s)	Energy Flow Optimization Model	A quasi-dynamic bottom-up energy system optimization model.	Was used as a supply part of the energy modelling complex of the European Commission used also for Poland, Czech republic, Slovakia, and Baltic countries.	Lehtilä and Pirilä (I996); Lueth *et al.* (1997).	EFOM-ENV, EFOM-CHP
ENPEP	Energy and Power Evaluation Program	A hybrid model that employs both engineering and a market-based simulation approach to project future energy supply/demand balances, emissions, and to evaluate alternative energy technologies.	Applied in several countries, including Hungary, Bulgaria, Cyprus, Jordan etc.	Molnar (1997), Mirasgedis (2004)	Includes modules: BALANCE, IMPACT, ELECTRIC, WASP, LDC (for computing electricity load-duration curves). This package represents an integrated approach of energy system modelling.
LEAP (since the 1980s)	Lon-range Energy Alternative Planning System	Scenario-based integrated energy-environment modelling tool; accounting framework.	Widely applied in both developed and developing countries (incl. Czech Republic).	Heaps (2002)	

ANNEX III. BAU SCENARIOS IN THE TWO METHODOLOGICAL APPROACHES

Figure 68 Comparison of BAU scenarios in component-based and performance-based scenarios (GWh)

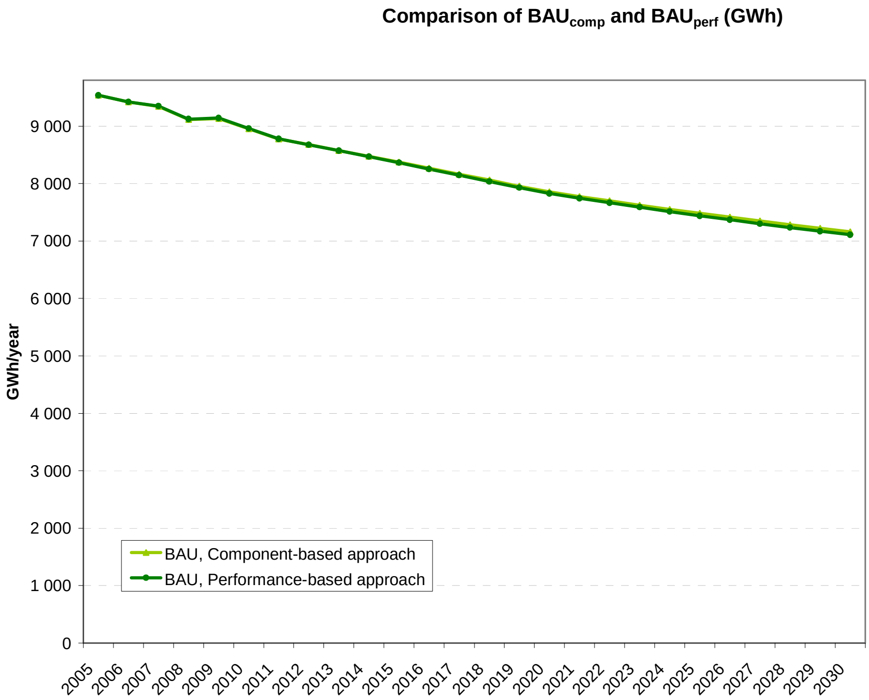
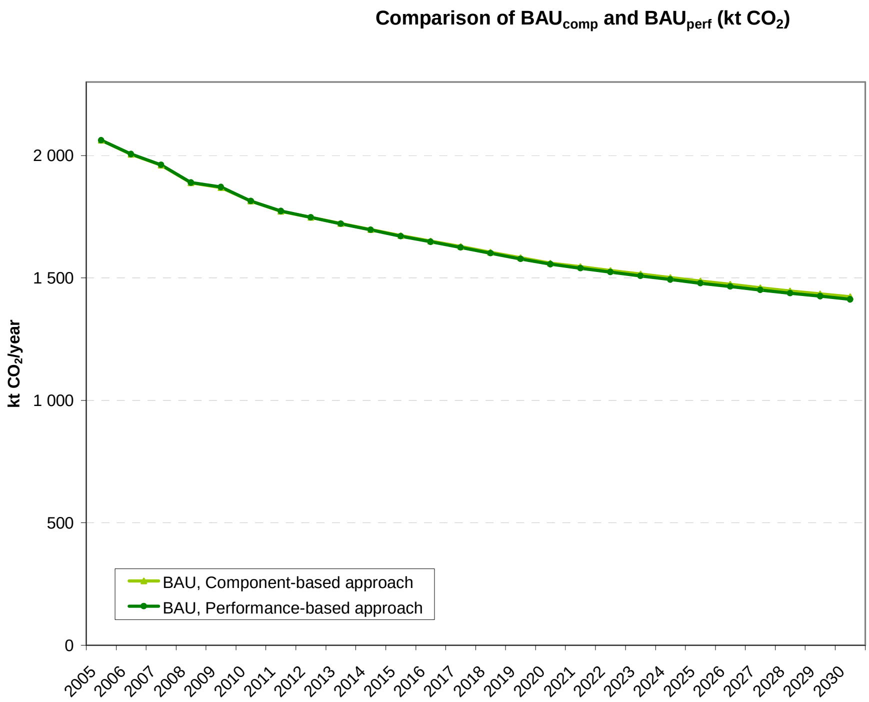


Figure 69 Comparison of BAU scenarios in component-based and performance-based scenarios (kt CO_2)



ANNEX IV. COMPONENT-BASED APPROACH: INDIVIDUAL COST CURVES PER BUILDING TYPE

Figure 70 Cost curve for small educational buildings

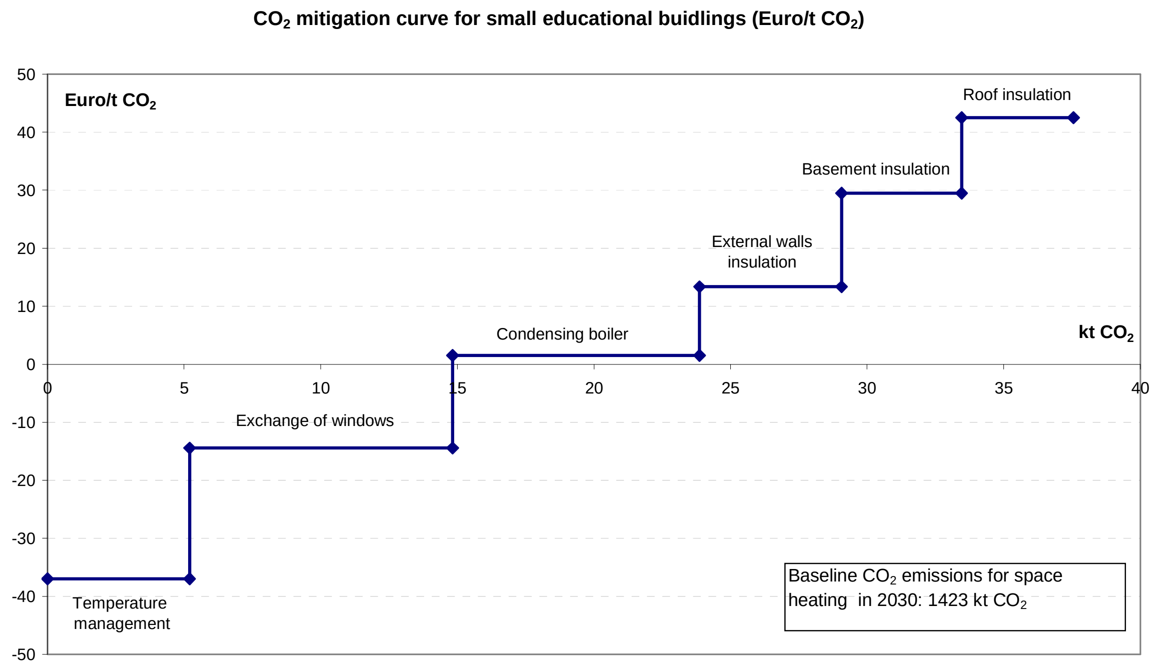


Figure 71 Cost curve for large educational buildings

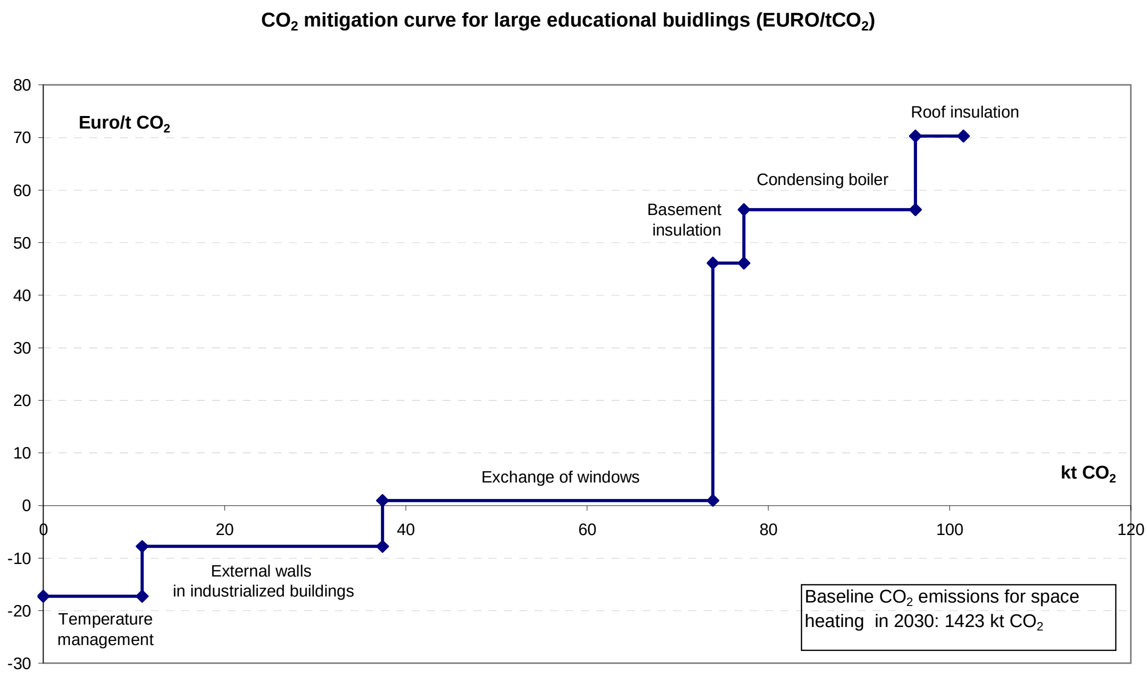


Figure 72 Cost curve for small health care buildings

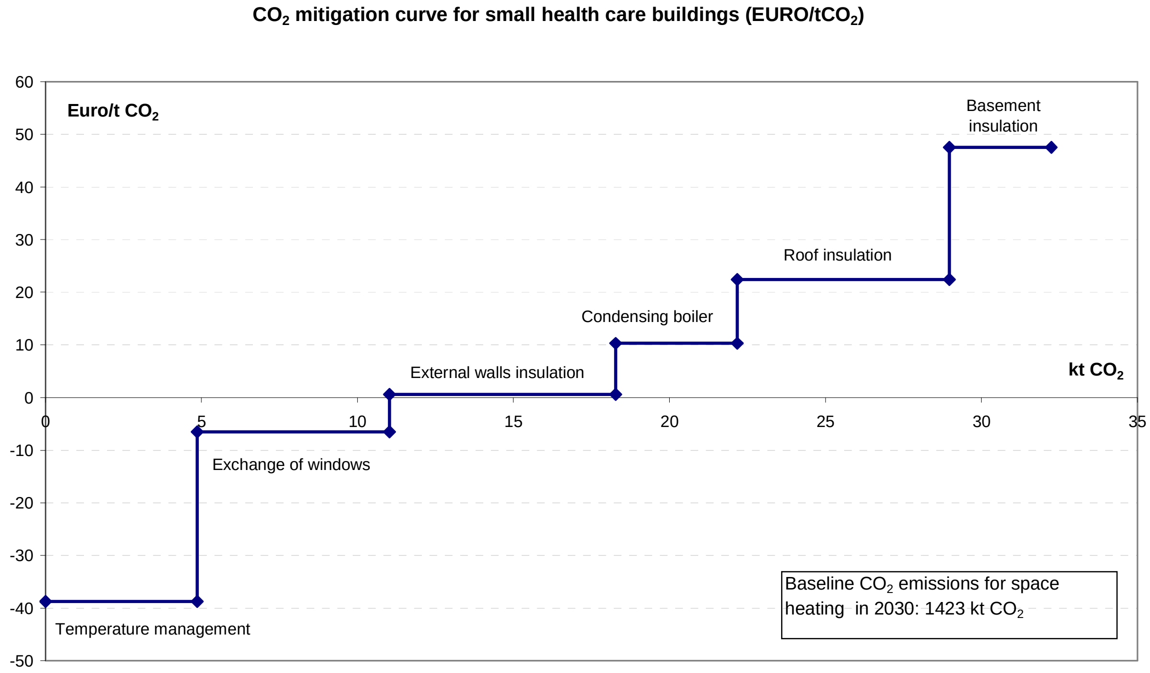


Figure 73 Cost curve for large health care buildings

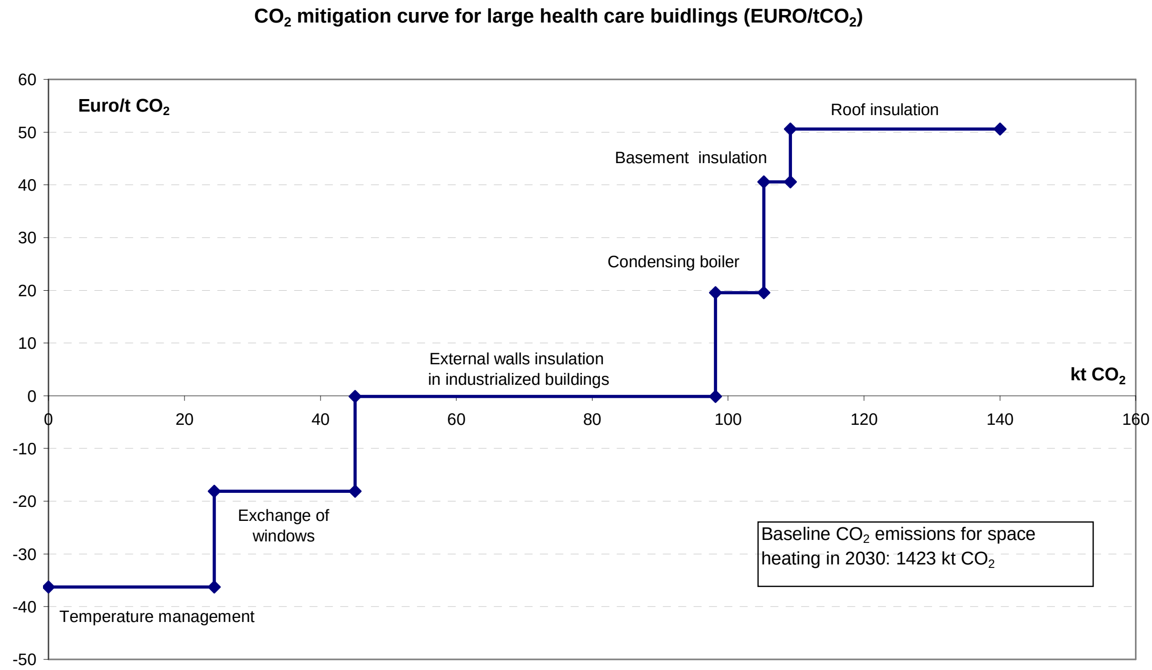


Figure 74 Cost curve for small public administration buildings

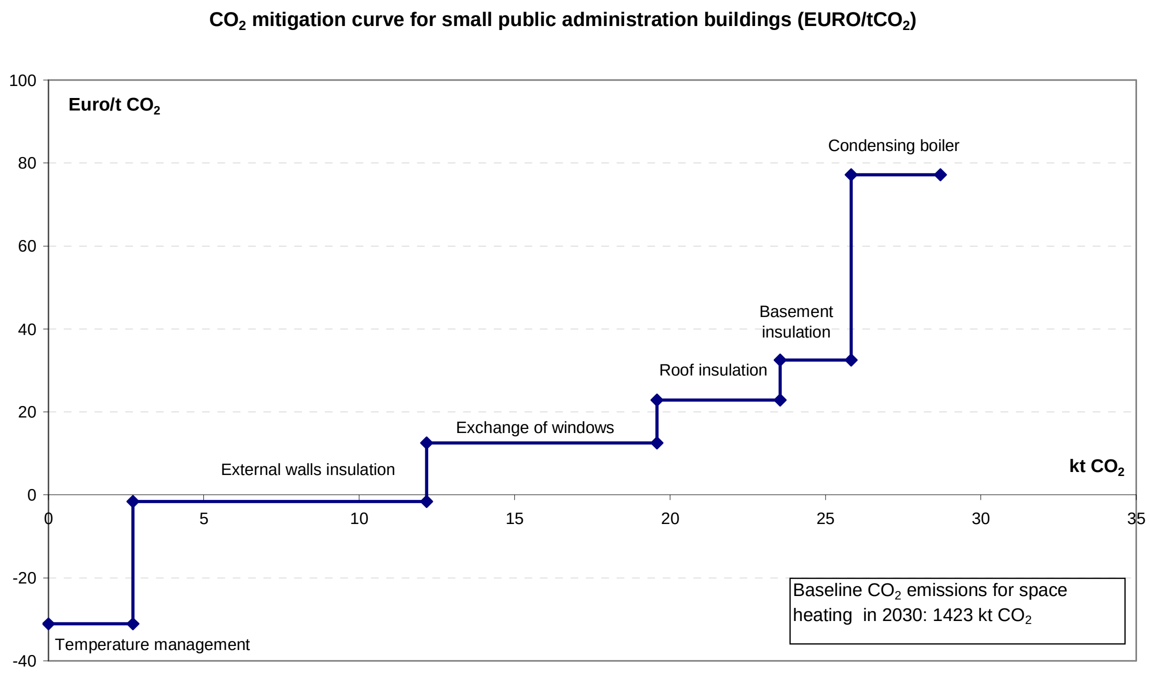


Figure 75 Cost curve for large public administration buildings

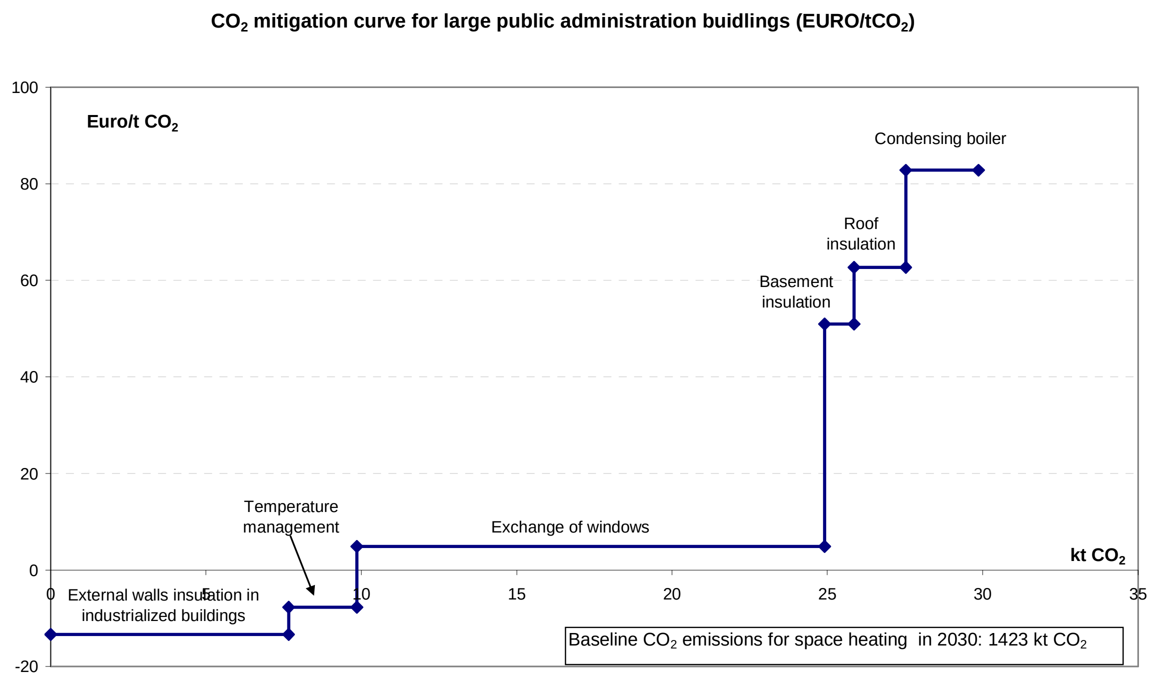


Figure 76 Cost curve for social buildings

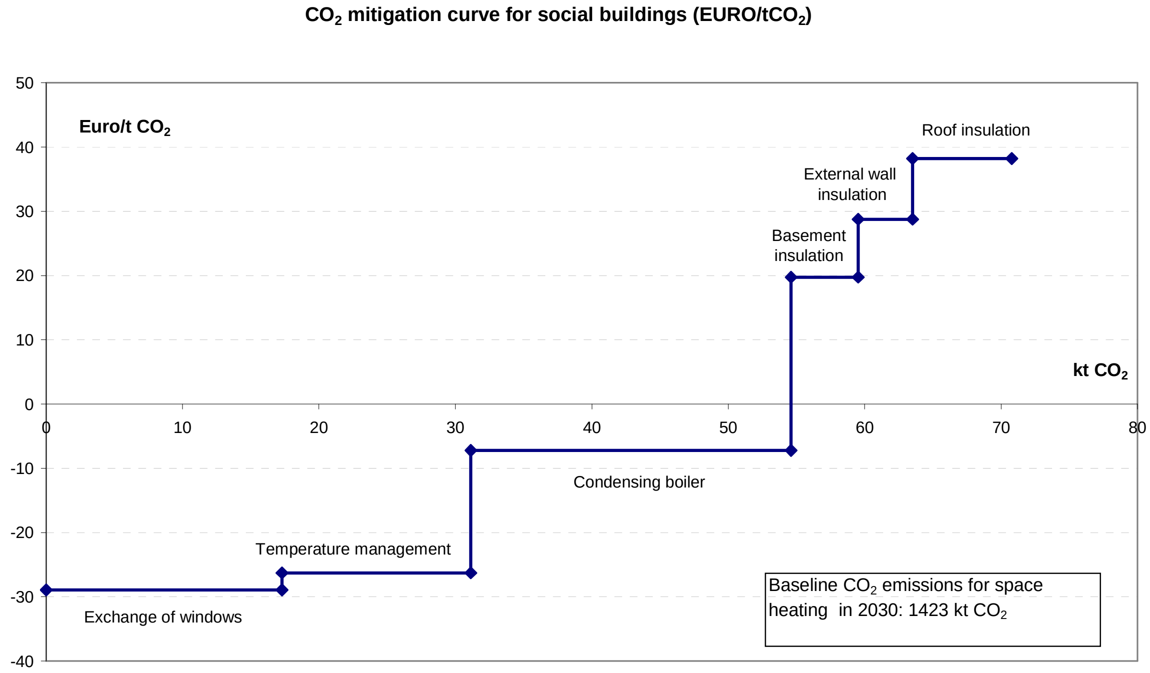


Figure 77 Cost curve for cultural buildings