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Degree of Doctor of Philosophy

Carbon dioxide mitigation potential in the Hungarian residential sector

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ABSTRACT OF THE DISSERTATION submitted by:
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for the degree of Doctor of Philosophy and entitled: Carbon dioxide mitigation potential in the Hungarian residential sector.

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The dissertation studies the ways of assessing the potential and costs of greenhouse gas mitigation in energy using sectors. It applies this knowledge to develop a model for estimating the potential for carbon dioxide (CO_2) mitigation and associated costs resulting from the application of energy efficient technologies and practices, as well as the use of fuel switch options at the point of energy demand, in the residential sector of Hungary. Currently such information is identified as a gap in knowledge whereas it is the key for designing evidence-based climate mitigation policies.

The research relies on extensive literature review on approaches to energy system assessment and related techniques; literature review and interviews with local expects on technological opportunities for CO_2 mitigation and their applicability to the Hungarian residential buildings; and a created database of the main efficient and low-carbon options available in the market. The research tool developed is a bottom-up spreadsheet-based model which allows estimation of the baseline final energy consumption and CO_2 emissions of the Hungarian residential buildings and individual and cumulative incremental assessment of mitigation options in terms of their potential for CO_2 emission reduction and associated costs in 2025.

The dissertation identifies a wide range of opportunities for cost-effective CO_2 mitigation available in all types of the Hungarian residential buildings studied. Its key conclusion is that the application of cost-effective measures result in a reduction of c. 29% of the sectoral baseline CO_2 emissions in 2025, whereas the total technical potential possible to achieve with the implementation of all investigated measures is c. 50% of these baseline emissions. The realization of the cost-effective potential requires a total investment of 9.6 billion EUR from 2008 to 2025, but results in energy cost savings of 17.1 billon EUR. Efficient lighting and heating and water-flow controls were identified as the most attractive measures in the Hungarian residences in terms of cost-effectiveness. A fuel switch to low-carbon heating solutions and the improvement of the thermal envelope in old buildings present the largest potential.

The results of the research suggest the technological options to be prioritized with national mitigation policies and present the investment required to realize the mitigation potential. The results may help to establish the national targets for greenhouse gas reduction in the climate binding commitments. If realized, the associated reduction in the energy consumption of households could help reduce the social tension in Hungary caused by the recent growth of energy bills. This effect would add to numerous environmental and economic co-benefits of CO_2 mitigation. Research results may be replicated for countries with similar climate and economic conditions.

Keywords:

Buildings, climate change, residential sector, carbon mitigation, energy efficiency, Hungary.

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ACH	Air Changes per Hour
BAU	Business-as-Usual
CO_2	Carbon Dioxide
CEE	Central and Eastern Europe
CGE	Computable General Equilibrium
CHP	Combined Heat and Power
DVD	Digital Video Disk
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GWh	Gigawatthour
FSU	Former Soviet Union
EU	European Union
kWh	Kilowatthour
LOPOMO	Low power mode
IPCC	Intergovernmental Panel on Climate Change
PC	Personal Computer
TV	Television
VAT	Value Added Tax
USA	United States of America

Chapter 1 INTRODUCTION

1.1 Energy efficiency and carbon neutrality for the sustainable future

The current unsustainable pattern of energy production and use is one of the greatest global challenges humanity has ever faced. The list of its direct and indirect impacts includes, but is not limited to, deforestation and desertification, land intrusion and destruction, indoor and outdoor air pollution, radioactive waste, radioactive emissions, water pollution, and numerous accidents such as oil spills, breaches of hydroelectrical dams, explosions or fires, leakage from radio-active waste storage sites, landslides, and explosions in coal mines (Laponche *et al.* 1997). Impacts of anthropogenic climate change, caused largely by energy production and use, such as sharp temperature fluctuations, sea level rises, changes of borders of climatic zones, threats to biodiversity and human health, and other problems, have pushed the global community to a threshold beyond which every subsequent step of economic development needs to be weighted with environmental consequences in the long term. Furthermore, tension among countries and world regions associated with scarcity of natural resources, security of energy supply, and migration of climate refugees is getting stronger every decade. Energy is a primary factor of economic development and presently it is impossible to decouple economic prosperity and the demand for energy. Furthermore, some experts argue that securing behaviour change towards the demand for amenities, and decreasing the use of energy is largely dependent on structural factors rather than personal choices (Vedantam 2008). However it is possible to use energy in a more efficient, smarter way.

For the last three decades a wide circle of experts have argued that the first step to sustainable energy development and the key to limiting the effect of climate change is the application of energy efficiency and low and zero carbon technologies[1] (for instance, see Meier *et al*. 1983; Vorsatz 1996; Lovins *et al*. 1989; Von Weizsäcker *et al*. 1997). The European Union Action Plan for Energy Efficiency (Commission of the European Communities 2006) demonstrates that the energy saved through improved energy efficiency (referred as "negajoules") is greater than the energy produced by any individual production technology, and can therefore be considered as a significant primary energy source (see Figure 1). Therefore, using mitigation technologies may potentially allow the growing demand for energy to be supplied from avoided energy use, staying at the same or even a lower level of consumed primary fossil energy resources. Such a shift would not only bring a wide array of co-benefits for society[2] but would rarely require extra costs (Harvey 2006; Öhliher 2006).

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[1] Hereafter referred as to the mitigation technologies.

[2] IPCC (2001) defined co-benefits as benefits of GHG mitigation policies which are not connected to climate mitigation but are incorporated into the initial creation of mitigation policies.

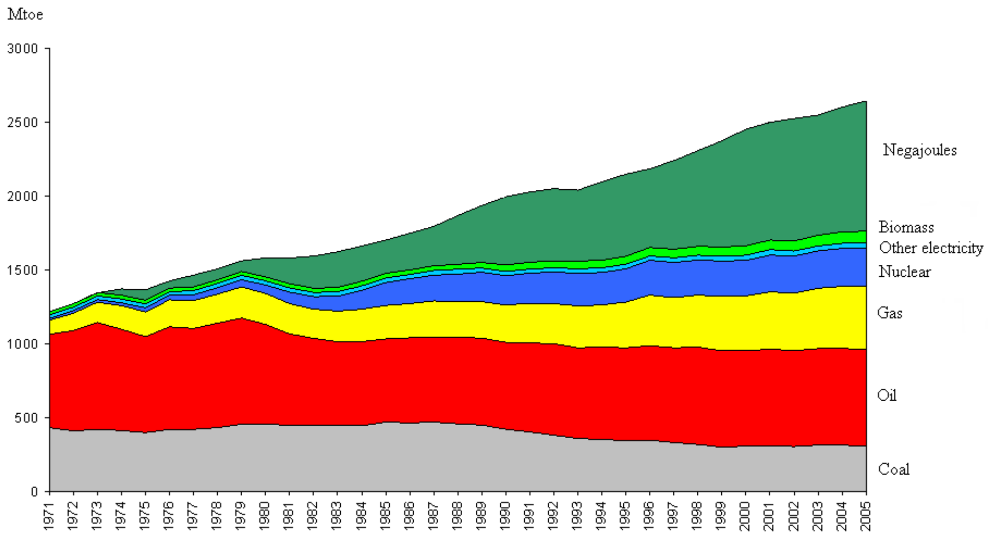

Figure 1 Dynamics of primary energy demand in the European Union-25

Note: “Negajoules” refers to energy savings calculated on the basis of energy intensity in 1971.

Source: Commission of the European Communities 2006.

1.2 The buildings sector for energy efficiency and climate change mitigation

In the light of this picture, the buildings sector plays an increasingly important role. This is due to two facts. First, buildings contribute significantly to growing global energy consumption and climbing greenhouse gas (GHG) emissions. Price *et al.* (2006) estimated that while GHG are expected to grow sharply over the next three decades, the contribution of the buildings sector will remain as high as 33% - 34%. Second, this sector provides abundant low cost opportunities for energy savings and GHG emission reductions. Research (Ürge-Vorsatz and Novikova 2008) implemented for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Levine *et al.* 2007) identified 29% of the global business-as-usual carbon dioxide (CO_2) emissions in 2020 available for cost-effective reduction in the buildings sector;

more than half of this potential is locked in residential buildings[3]. In absolute terms, this presents the largest potential for cost-effective CO_2 emission reduction among all sectors, both globally and specifically in economies in transition (see Figure 2).

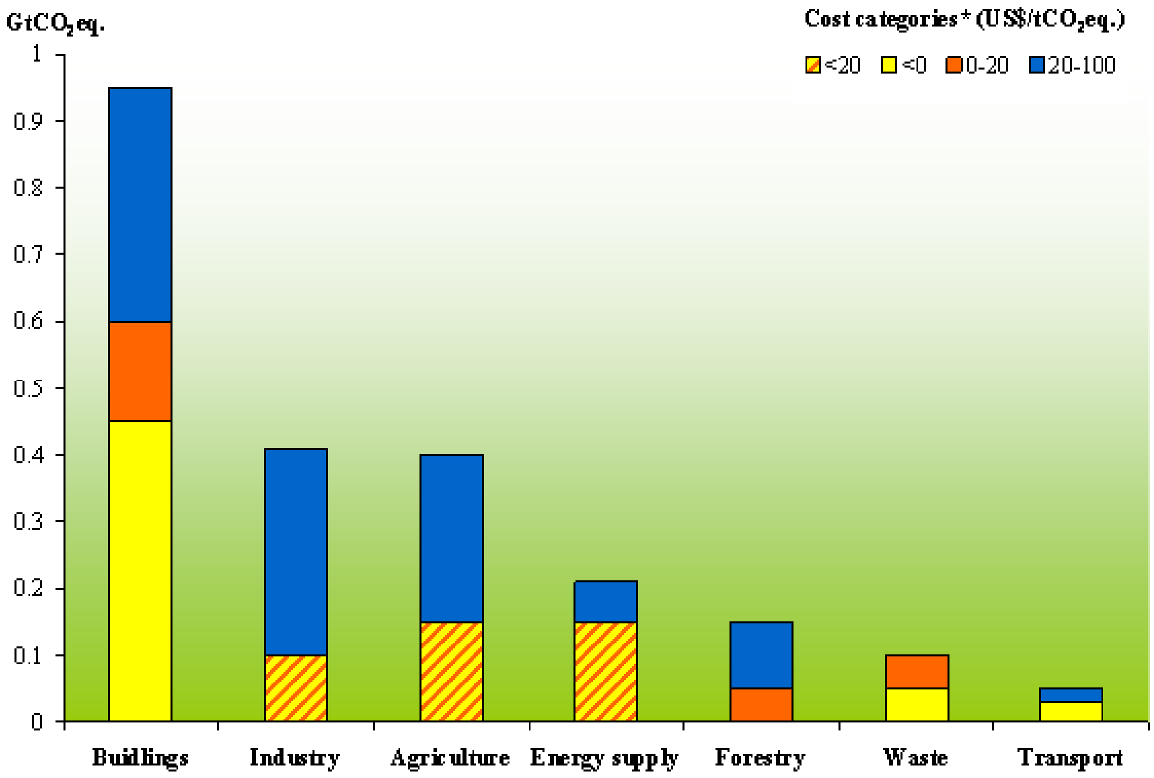

Figure 2 Potential for CO_2 mitigation in economies in transition at a sectoral level, 2030

Note: For the buildings, forestry, waste and transport sectors, the potential is split into three cost categories: at net negative costs, at 0-20 US\$/tCO_2, and 20-100 US\$/tCO_2. For the industrial, forestry, and energy supply sectors, the potential is split into two categories: at costs below 20 US\$/tCO_2 and at 20-100 US\$/tCO_2.

Source: constructed based on Baker *et al.* (2007)

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[3] The buildings sector is often split into residences and tertiary buildings. The latter category includes commercial

Nevertheless, many opportunities for energy efficiency improvement in the buildings sector are not covered well by existing policies (Lechtenböhmer and Thomas 2003). This is especially true for transition economies whose strategies for energy efficient development concentrate mainly on the efficiency of industry and the power supply sector. This is due to the fact that efficiency potential in buildings is spread among dwellings as separate units and fragmented among end-uses (Ürge-Vorsatz *et al*. 2007). Many policy designers simply do not have good enough information to develop a comprehensive strategy for this sector. While climate mitigation strategies are well investigated in developed countries and, sometimes, in developing countries[4], there is a lack of such research activities in transition economies. According to the best knowledge of the author, as of March 2008 there were only four case studies covering the buildings sector of countries of Central and Eastern Europe (CEE) and the Former Soviet Union (FSU) within the last ten years (see Petersdorff *et al*. 2005; Kallaste *et al.* 1999; Szlavik *et al.* 1999; Lechtenböhmer *et al*. 2005).

Therefore, there is ample evidence that, whereas the buildings sector can potentially play an important role for energy conservation and climate mitigation purposes, it is hardly possible to design buildings-related policies. This is due to the lack of knowledge of how large the potential for GHG mitigation is in this sector; what energy end-uses and technologies secure this mitigation; whether or not it is economically feasible; and which options should be promoted to easily ensure this mitigation.

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and public buildings.

[4] In some developing countries, the topic has been investigated well with the support of such organizations as United Nations Environmental Programme, the Asian Development Bank, and others.

1.3 The aim, the goal, the objectives, and the task of the research

The dissertation addresses this gap in knowledge placing a special focus on Hungary. The overall research aim is to assist the evidence-based design of the new policies targeted at CO_2 emission reductions in the Hungarian residential buildings sector with the necessary information. More specifically, the research goal is to estimate and to analyze CO_2 mitigation potential in the Hungarian residential sector and the associated costs resulting from the application of energy efficient technologies and practices as well as the use of fuel switch options at the point of energy demand.

Hence, the research objectives are:

- ⇒ To estimate the baseline CO_2 emissions of the Hungarian residential sector in the future
- ⇒ To identify the key mitigation technologies and practices applicable in the residential sector of the country
- ⇒ To estimate the CO_2 emission mitigation potential existing in the Hungarian residential sector from the application of identified individual options and associated mitigation costs
- ⇒ To estimate the total CO_2 mitigation potential of the Hungarian residential sector as a function of the costs of CO_2 mitigation technologies.

To achieve these objectives, the task of the dissertation research is to develop a bottom-up model[5] which allows estimation and analysis of CO_2 mitigation potential in the Hungarian residential sector and associated costs based on presently available data.

1.4 Theoretical and practical contribution

It is vitally important to have the solid background information to design an influential and targeted policy tool. Therefore, for the success of sustainable energy efficiency development and climate mitigation, evidence-based knowledge of the potential for energy efficiency and low and zero carbon opportunities is necessary. This dissertation research addresses this need and supplies the information regarding the most cost-effective and the most effective (in terms of reduction of CO_2) technological options available for the residential buildings sector of Hungary. It examines the total sectoral potential at different cost levels, the related investments required to realize the potential, and the associated saved energy costs. The research results have been used for preparation of the Hungarian Climate Strategy for 2008 – 2025 (KVVM 2008) and for the design of the Green Investment Scheme[6] in Hungary (the research run by the Budapest University of Technology and Economics). Therefore, the research results are already contributing from the practical point of view to a sustainable climate future on the national level.

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[5] Bottom-up model is a method of system analysis through combining estimates of its components.

[6] Green Investment Scheme is a scheme channeling the profits from sales of assigned amount units under the Kyoto Protocol Article 17 (International Emission Trading) to realization of projects which directly or indirectly generate GHG emission reductions.

Additionally to the practical application, the research contributes to the theoretical knowledge on CO_2 mitigation modelling in economies in transition. As described in the previous sections, there have been only four pieces of research in the CEE and FSU regions during the last ten years which assess the existing opportunities for CO_2 mitigation in the residential buildings sector. Each of these studies had their significant limitations; some of these studies do not cover many mitigation options, while the assumptions of others are outdated making it difficult to apply their results to the present conditions. One of the key reasons for the low research activities in this field in the CEE and FSU regions is the difficulty of collecting input data and then incorporating these limited and often uncertain data into the framework of highly detailed, bottom-up, technology-rich models. This dissertation research, therefore, is useful for methodological learning in order to conduct such research in the region. The modelling framework and the technological database developed in the dissertation research can serve as a basis for assessment of opportunities for CO_2 mitigation in the residential buildings sector of other CEE and FSU countries with similar economic and climate conditions, in particular Slovakia, the Czech Republic, and Poland. Furthermore, the modelling framework and the technological database can be partially used for similar assessments of the commercial buildings sector of Hungary or the other above-mentioned countries of the region.

1.5 Structure of the manuscript

The manuscript is structured in nine chapters. After justification of the importance and contribution of the research and stating its aim, goal, questions, and task in Chapter 1 (p. 1), Chapter 2 (p. 10) describes the present state of energy consumption and CO_2 emissions on the national and sectoral level in Hungary, identifies the best energy using practices, and states the research hypothesis. The methodological chapters, Chapter 3 (p. 23) and Chapter 4 (p. 49) provide an overview of existing energy system assessment approaches and models developed worldwide and in the region, and the description of the model developed in the present dissertation, including its main equations, assumptions, data sources used, and research uncertainties. Chapter 5 (p. 74) describes the main characteristics of households and details the results of modelling of the household stock by building types and space and water heating over the projection period. Chapter 6 (p. 98) reviews the most important thermal and electric options for CO_2 mitigation identified by the research which include the more efficient thermal envelope, advanced heating and water heating technologies, heating and water flow controls, and use of efficient appliances and lights. Chapter 7 (p. 129) describes modelling the baseline energy consumption and associated CO_2 emissions of the residential sector. Chapter 8 (p. 157) discusses the results of the assessment of the potential and costs of CO_2 mitigation from individual and then incremental installation of the options identified in Chapter 6. Chapter 8 also calculates the necessary investment costs for realization of these potentials. Chapter 9 (p. 189) summarizes the key messages of the dissertation.

Chapter 2 CO$_2$ EMISSIONS IN THE HUNGARIAN RESIDENTIAL SECTOR

2.1 Overall national final energy use and CO$_2$ emission trends

The buildings sector and especially residential buildings are the key targets for energy efficiency and climate mitigation policies in Hungary. As Figure 3 illustrates, the residential sector has been consistently the largest final energy consumer in the country since 1991.

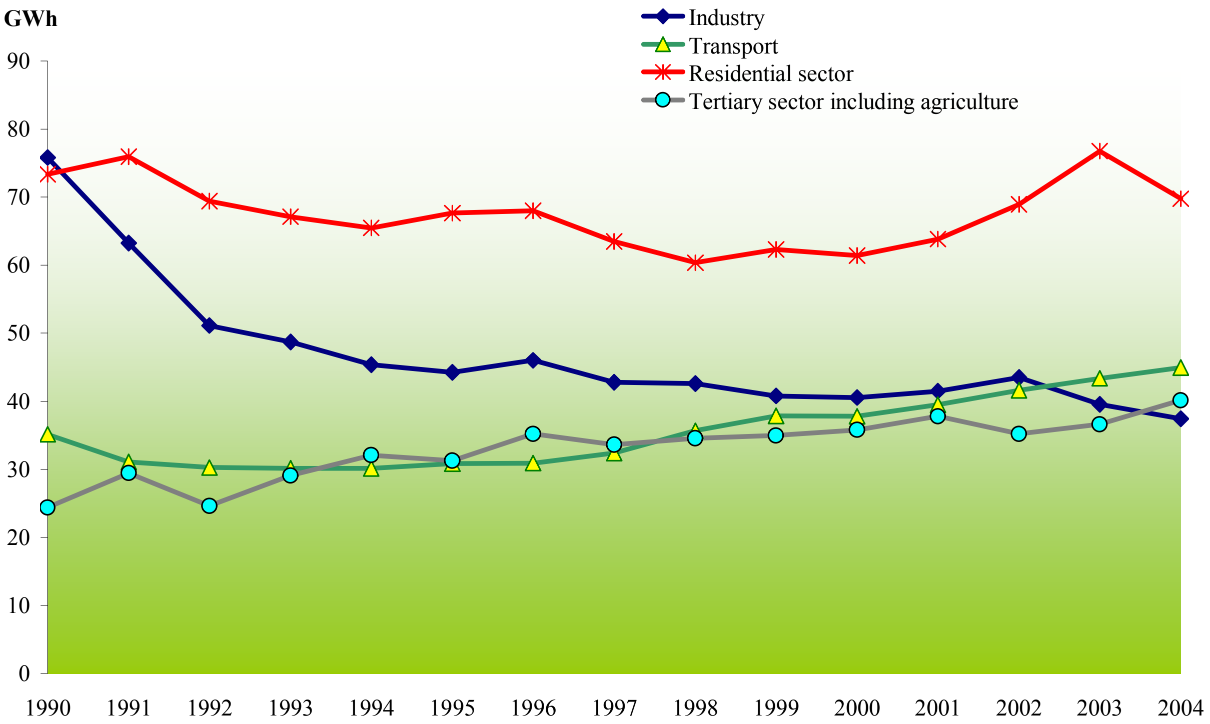

Figure 3 Final energy consumption of energy end-use sectors in 1990 - 2004, Hungary

Source: constructed based on ODYSSEE NMS (2007).

Due to this fact and the high carbon intensity of fuels used in the residential sector, it emits the largest share of CO_2 emissions as compared to other sectors. In 2004, as Figure 4 shows, this sector was responsible for 30% of total national CO_2 emissions (ODYSSEE NMS 2007).

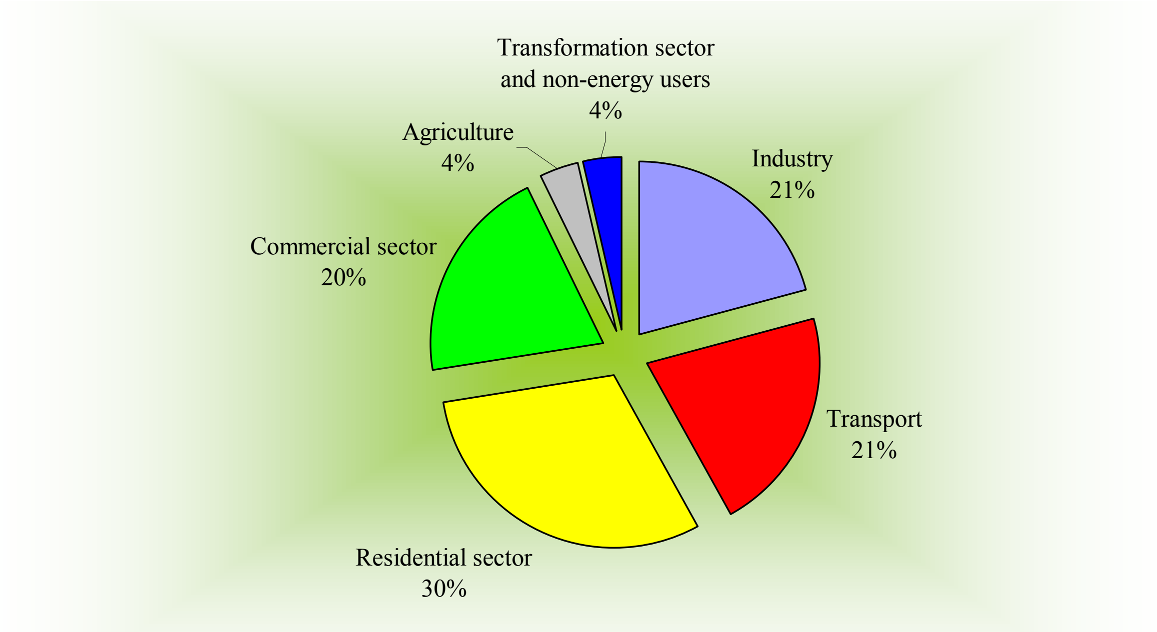

Figure 4 Direct and indirect CO_2 emissions of energy use sectors in Hungary, 2004

Note: Indirect CO_2 emissions include emissions associated with electricity consumed by the sectors.

Source: constructed based ODYSSEE NMS (2007).

The share of CO_2 emissions from the residential sector has stayed high despite the fuel switch presently occurring in the sector. This fuel switch is due to the expansion of the gas grid that allowed fuel a move away from oil and coal. Growing oil prices have also contributed to a limitation of oil for space heating in recent years (Kovacsics pers. comm.). The use of biomass for heat grew in the beginning of 2000s due to strong policy support, but it is unlikely that this trend will continue after this support ended (Kovacsics pers. comm.). The dynamics of energy consumption over time of each of the main energy commodities used in the residential sector of Hungary is presented in Figure 5.

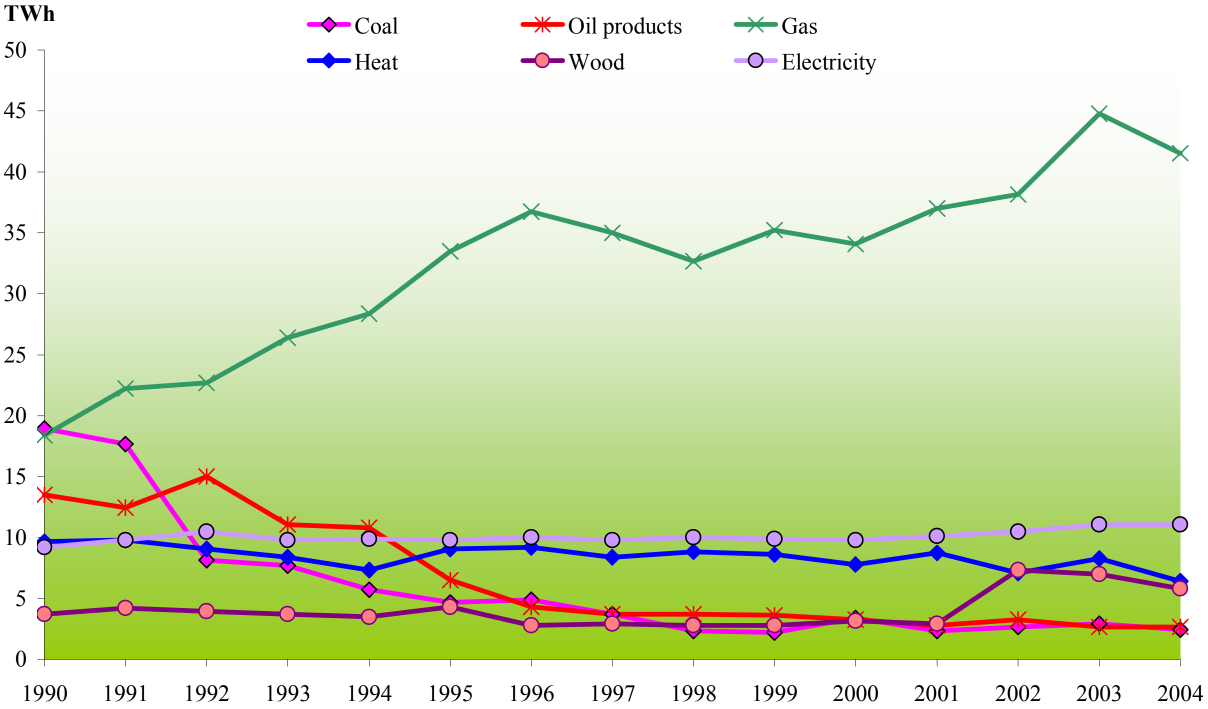

Figure 5 Dynamics of final energy use in the residential sector of Hungary, 1990 - 2004

Source: constructed based on NMS ODYSSEE (2007).

2.2 Energy use breakdown in the Hungarian residential sector

Before investigating the opportunities for CO_2 emission reductions, it is useful to understand the main uses of energy. There is a large uncertainty regarding energy end-use breakdown in the residential sector of Hungary. According to the best knowledge of the author, the latest assessment of this data was conducted in the frame of the national household survey in 1996 (KSH 1998). Figure 6, based on the results of this research, shows that the largest energy end-uses are space heating and cooking. They are followed by water heating and then all other energy uses.

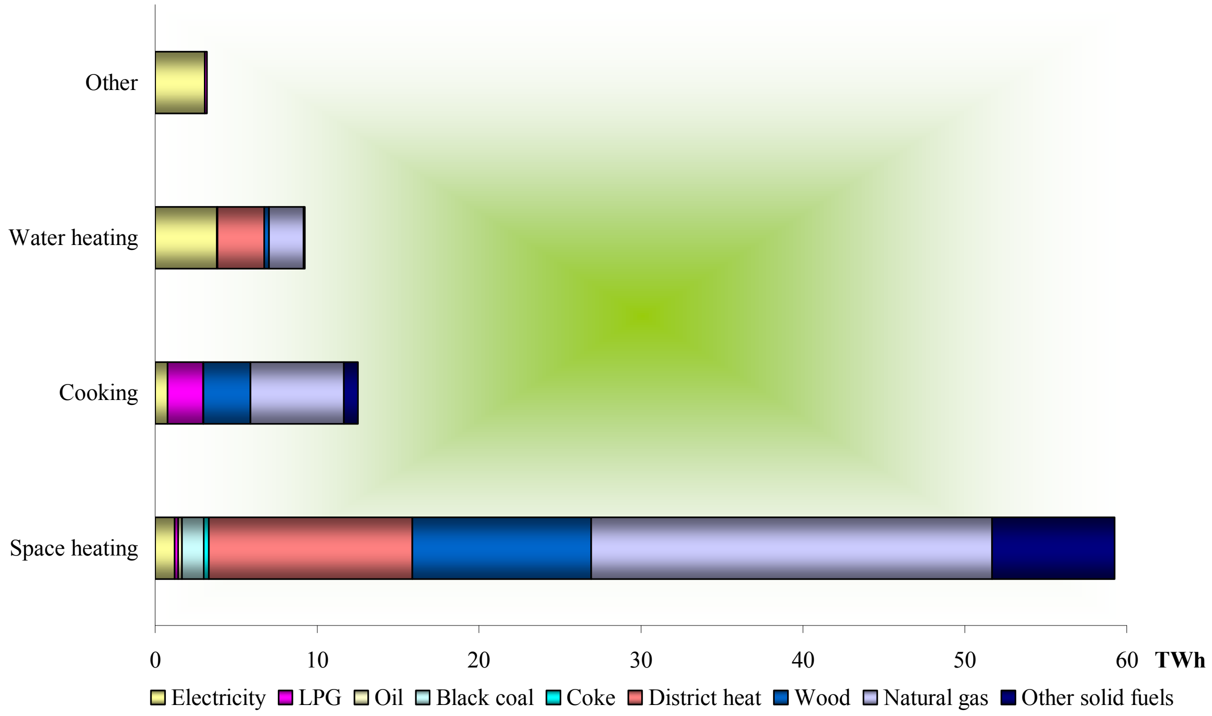

Figure 6 Energy use breakdown of the Hungarian residential sector, 1998

Source: KSH 1998.

The residential direct emissions[7] are mainly associated with combustion of fossil fuels for space and water heating and for cooking. In 2004, these emissions accounted for 29% of the total national CO_2 emissions. This was slightly lower than the emissions from the transportation sector

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[7] I.e. emissions from combustion of oil, gas, and coal

(Figure 7). The World Energy, Technology and Climate Policy Outlook 2030 (Directorate-General for Research Energy 2003) expects that the thermal energy use per household will decrease in the EU in the long-term. But still, as mentioned above, it is expected to stay the main energy end-use in the sector.

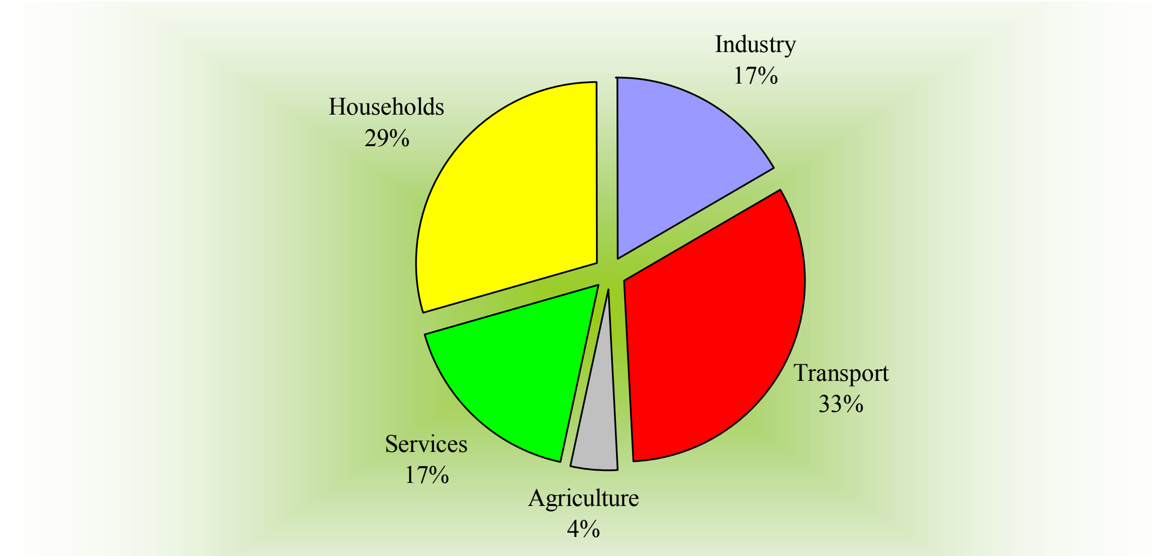

Figure 7 Breakdown of direct CO_2 emissions by final energy users in Hungary, 2004

Source: ODYSSEE NMS (2007).

Information about electricity use in the households of the country is more readily available than that about thermal energy use. Figure 8 illustrates the breakdown of electricity use in the Hungarian residential sector. The figure attests that water heating, lighting, and main appliances cover almost all household electricity use.

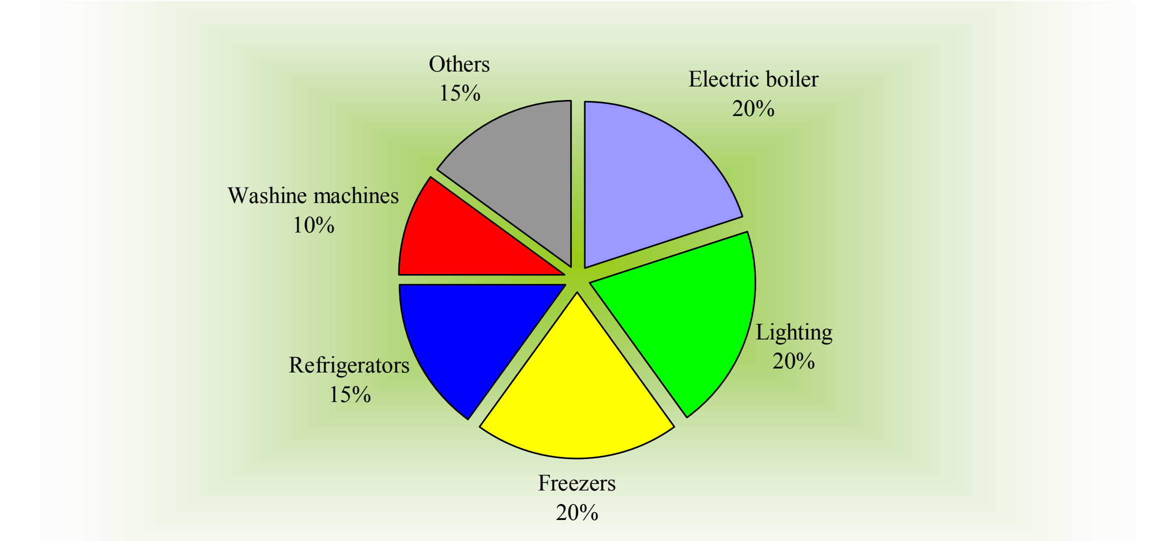

Figure 8 Breakdown of electricity consumption in the Hungarian residential sector, 2004

Source: GFK 2004.

Even though the structure of electricity consumption has changed during the period 1990 – 2004, as Figure 5 demonstrates, the sectoral electricity consumption has slightly grown. The World Energy, Technology and Climate Policy Outlook 2030 (Directorate-General for Research Energy 2003) explains this by arguing that the growing efficiency of domestic appliances and lights is outweighed by the increased energy demand from small electrical appliances. This is the result of the following trends (Bertoldi and Atanasiu 2007):

- ⇒ Higher penetration of “traditional” appliances (e.g. dishwashers, tumble driers, air-conditioners, and personal computers) which are all still far from saturation levels;
- ⇒ Introduction of new appliances and devices, especially consumer electronics and information and communication technology equipment (set-top boxes, digital video disk

players, broadband equipment, cordless telephones, etc.) with considerable standby power consumption;

⇒ Increased use of “traditional” equipment: more hours of television watching, more hours of use of personal computer (driven by increased use of the Internet), more washing and use of hot water;

⇒ The increased number of double or triple appliances, mainly television sets and refrigerators-freezers;

⇒ Larger single-family houses and apartments resulting in higher requirements for lighting, heating and cooling;

⇒ Aging population requiring higher indoor temperatures for all-day heating in winter and cooling in summer, and spending more time at home.

The statement about the trends of electricity consumption growth in the residential sector is supported by Figure 9. The figure illustrates that the residential and commercial buildings are the only two sectors which have increased electricity consumption steadily over the last 40 years; for the residential sector the average growth in electricity consumption was app. 1.1%/yr. during this period. CO_2 emissions associated with electricity consumption in the residential sector grew from 3.6 million tonnes/yr. in 1994 to 4.0 million tonnes/yr. in 2004.

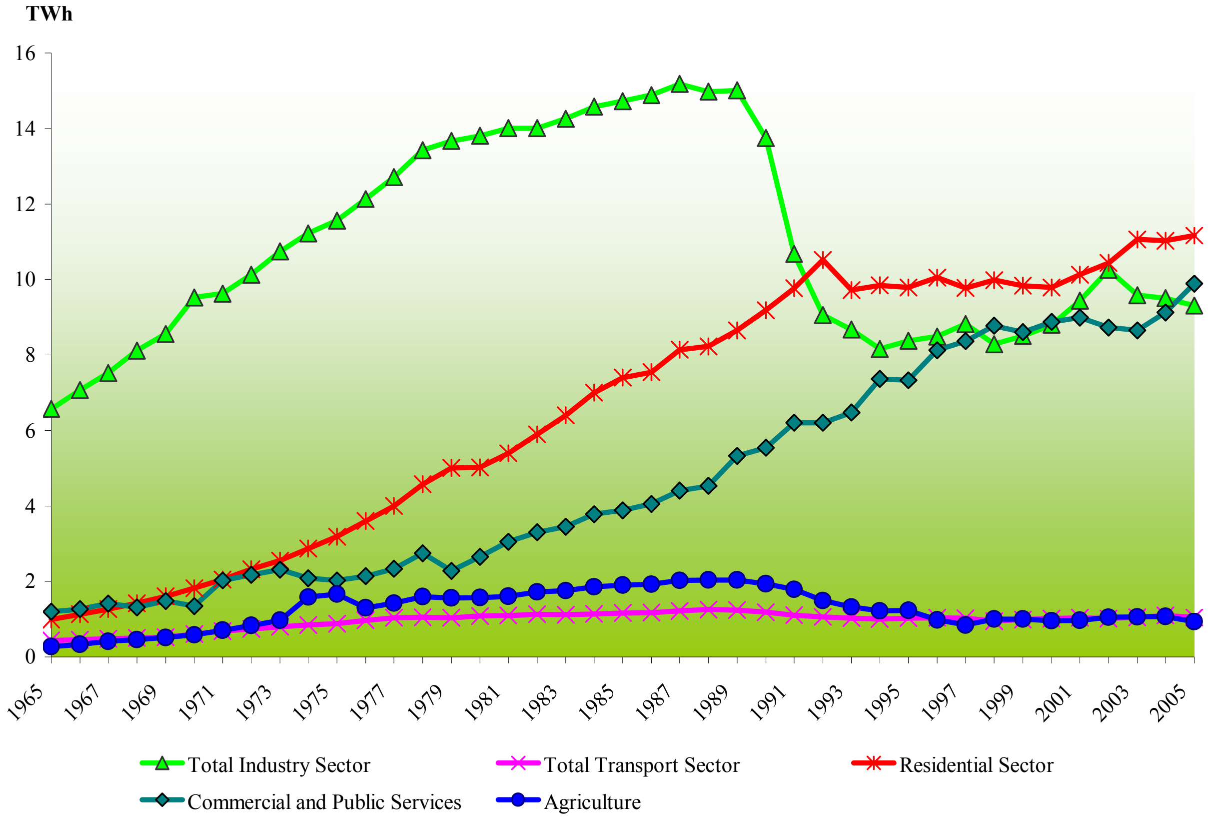

Figure 9 Dynamics of electricity consumption of end-use sectors in Hungary, 1965-2005

Source: constructed based on IEA (2004, 2006a, 2007).

2.3 Examples of energy savings in the Hungarian buildings

This section argues that there are outstanding examples of buildings renovation that are already taking place presently in Hungary. These examples show that using the mature technologies available on the Hungarian market, it is possible to reduce energy consumption and CO_2 emissions by a significant portion.

2.3.1 Renovation of a panel building in the frame of the SOLANOVA project

A panel building retrofitted in the frame of the SOLANOVA project is the first large residential panel building in Eastern Europe which almost corresponds to the passive house standards[8] (see Illustration 1). The heating requirement before refurbishment was 220 kWh/m^2-yr.; which is the average value for buildings constructed using industrialized technology (SOLANOVA 2008). A special feature of the panel buildings is a sandwich structure where the prefabricated panels consist of two reinforced concrete layers and 5-8 cm thermal insulation in between. Due to this structure, the major heat loss relates to the joints; furthermore, the thermal bridge losses are higher than the losses due to heat transmission. Under the project, to prevent this heat loss through thermal bridges and heat transmission though walls, 16 cm thermal insulation was applied on the building facades. Other measures targeted at the improvement of the thermal envelope included: insulation of the building cellar, covering the top of the building with a "green" roof, and window and door exchange. Additionally, the heating, ventilation, and district hot water systems were improved. Room radiators with heat controls were exchanged. Finally, a solar thermal system for domestic water heating was installed (Hermelink 2005). The building renovation resulted in energy savings of 200 kWh/m^2-yr. for space heating in the winters of 2005/06 and 2006/07 (SOLANOVA 2008). This figure does not include indirect electricity savings, for instance, due to a reduced load on the heating pump. Also, installation of electrical cooling (air-conditioning) can be avoided in the future even in case of higher temperatures (Hermelink pers. comm.).

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[8] Please see Section 6.1.5 (p. 2) for the definition of passive energy house.

Illustration 1 The "SOLANOVA" panel building before (left) and after (right) renovation

Source: Hermelink 2005.

The investment costs are estimated as 16,800 EUR/flat exclusive of the value added tax (VAT) (Hermelink per. comm.). This figure does not consider, however, that some of these costs would have occurred anyway in the near future for unavoidable refurbishment. Additionally, the costs of renovation include such options as the green roof and the solar system which are not necessarily important (see Table 1 for detailed description of the options and a breakdown of associated costs). The interesting fact is that households benefited not only in terms of saved energy but also in terms of the increased value of flats. The increased value of flats is estimated to be approximately 18,900 EUR/flat exclusive of the VAT (Hermelink per. comm.).

Table 1 Description of retrofit options in the SOLANOVA-building

Element	Option	Cost allocation
Ventilation	Decentral ventilation units with 82% real heat recovery	19%
Solar thermal	App. 75 m^2 solar thermal area	8%
Heating	Easy heating system solution with radiators	13%
Cellar insulation	10 cm insulation of cellar ceiling	1%
Roof insulation	Green roof of 30-40 cm	13%
Wall insulation	16 cm polystyrene	22%
Window/door exchange	Polyvinyl chloride (PVC) windows: three-glazing on the South and the west, two-glazing on the North and the East	24%

Source: Hermelink (2005) and Hermelink (per. comm.).

2.3.2 Retrofit of a 'Csombor utca' panel building

A second successful example of building retrofit in Hungary is a five-storey high-rise residential building, constructed in 1980, located in Csombor utca 5-7 (EUROACE 2005). The structure of the building envelope is similar to that of the 'SOLANOVA' building and represents the insulated pre-fabricated concrete panels with two layered 5 cm insulation. The building had wooden doors and double glazed, wood-framed windows in a poor and leaky condition. The building is heated with district heating.

Improvements of the building envelope included such measures as insulation of walls and the basement ceiling, pipe insulation, and fitting seals in windows and doors. Improvement of the heating system included fitting new consumption regulating devices to the main feed pipes in the basement, installation of thermostatic radiator valves, new loop circuits to staircase radiators, and the fitting of automatic valves to gas pipes. The building before and after renovation is presented in Illustration 2.

Illustration 2 The “Csombor utca” building before and after retrofit

Source: EUROACE 2005.

Thermal building improvement resulted in a reduction of space heating energy consumption from 246 kWh/m^2-yr. to 137 kWh/m^2-yr. (EUROACE 2005). This is not taking into account energy savings on hot water supply, which was not separately measured. The successful examples of renovation of the “SOLANOVA” and “Csombor utca” buildings attest that successful energy-saving opportunities do exist in Hungary and bring societal benefits beyond the value of energy saved such as increased comfort and real estate value.

2.4 Co-benefits of CO_2 emission mitigation in residential buildings

As the previous section concluded, successful examples of energy-efficiency retrofitting of the residential buildings do exist in Hungary. Investing in energy efficiency and CO_2 emission mitigation on a national scale would bring a number of co-benefits beyond the value of saved energy and reduced CO_2 emissions. Most importantly for Hungary, energy efficiency investments help households cope with the burden of paying increasing utility bills and, thus, improve social welfare (Ürge-Vorsatz *et al.* 2003). The saved energy costs could be spent by the population for other consumer goods, thus stimulating growth of the Gross Domestic product (GDP) (the so called multiplier effect). Additionally, inhabitants can enjoy higher comfort in their homes. Production, installation, and maintenance of better building shells and equipment open the window to new business opportunities and, thus, create jobs. For instance, Butson (1998) in Levine *et al.* (2007) estimated the value of the energy service market in Europe as between five and ten billion EUR. Another example (European Commission 2005 in Levine *et al.* 2007) is an estimate of one million new jobs in Europe if the EU aimed at 20% reduction of (Jeeninga *et al.* 1999; European Commission 2003). Finally, energy savings reduce the damage to public health, building materials, and agricultural crops in Hungary (Aunan *et al.* 2000). If the discussed and other co-benefits of energy efficiency improvement and CO_2 emission mitigation were identified and financially appraised, the value of efficiency and mitigation policies would probably be judged higher than it is presently.

Chapter 3 THEORETICAL FRAMEWORK

All models are wrong but some are useful

George Box

The previous chapters explained the importance of assessment of opportunities for CO_2 emission mitigation in Hungary. Whilst we may desire to do so, it is hardly possible to describe the world and its systems ideally and project its future state dependent on different conditions applied. For this reason, policymakers face the necessity of using applied scientific models as the tools to better understand the present and future processes (Boulanger and Bréchet 2005).

This chapter switches the discussion to consideration of how this problem can be addressed in practice. The chapter defines the main research approaches to energy system modelling. Then, it describes the method of energy conservation and CO_2 mitigation supply curves, which are often used in technology-rich bottom-up assessment. Furthermore, the chapter reviews a set of selected models and their assumptions developed recently worldwide and specifically in the CEE and FSU regions. The review of these models plays an important role in building and formulating the methodology of the dissertation research.

3.1 Approaches to energy system assessment

There are two key strategies to assessment of information. They are top-down (decomposition) and bottom-up (synthesis). Both approaches are applicable to assessment of an energy system.

3.1.1 Top-down models

For energy systems, the top-down models examine interactions between the energy sector and macroeconomic indicators on the national level; they typically do not detail concrete technological options. Such models search for economic equilibrium through linear or non-linear systems of equations using aggregate economic indicators as variables including fuel prices, income, investment and consumption, costs of production factors and others. The output of top-down modelling is typically a change of macroeconomic indicators such as GDP growth rates, GDP growth per capita, employment rate fluctuations, trade balance indicators, and others. The top-down approach is convenient to assist policy-makers with information on potential impacts of various policy tools on the national economy. This section continues by discussing the main types of top-down models applied to assessment of energy systems.

3.1.1.1 Input–output models.

The simplest among top-down models, input–output models, describe the complex interrelationships among economic sectors using sets of simultaneous linear equations with fixed coefficients. Input-output models assume aggregated demand as given and provide considerable sectoral details on how the demand is met. However, behavioural aspects related to climate change cannot be assessed. Usually such models are used to assess the sectoral consequences of mitigation or adaptation actions. Due to this high level of sectoral disaggregation, the validity of these models is restricted to five to ten years (IPCC 2001; UNEP 1998). Due to their limitations and simplicity, input-output models are not used so often.

3.1.1.2 Macroeconomic (Keynesian or effective demand) models

Macroeconomic models are used to describe investment and consumption patterns in various sectors of the economy. It is assumed that the final demand is the principal determinant of the size of the economy. The principal distinction of the top-down models, the equilibrating mechanism, is assumed to work through quantity adjustments, and sometimes via the price. The models consider temporary disequilibria of economy and this phenomenon results in underutilization of production capacity, unemployment, and current account imbalances and its adjustments to them (IPCC 2001). Macroeconomic models often use econometric techniques based on past behavioural data to drive the future market indicators. For this reason, macroeconomic models are better used to determine short and medium-run economic effects of GHG emission reduction policies. An example of this class of models is the New Econometric Model for Environmental and Sustainable Development and Implementation Strategies (NEMESIS). This model projects how the introduction of various environmental policies will impact on economic indicators such as economic growth, employment, welfare and others (NEMESIS 2006).

3.1.1.3 Computable General Equilibrium models

Computable General Equilibrium (CGE) models evaluate the behaviour of economic agents based on microeconomic principles. These models simulate markets for factors of production, products and foreign exchange, using equations that specify supply and demand behaviour and examine them in different states of equilibrium. The variables for which these models are solved are a set of wages, prices, and exchange rates in the equilibrium state (UNEP 1998). The main characteristic of CGE models is that they include a specification of the behaviour of all agents in the economy (IPCC 2001). In the mitigation applications they have usually adopted assumptions of optimizing rationality, free market pricing, constant returns to scale, many firms and suppliers of factors and perfect competition in order to provide equilibrium in all markets. An example of this class of model, a General Equilibrium Model for Energy – Economy - Environment interactions (GEM-E3), is applied to the EU Member States individually as well as together. The model describes the economy in macro- terms and monitors its interactions with the energy system and the environment. The model approach is a search for the equilibrium prices of goods, services, labour and capital under the Walras Law (Capros *et al.* 1997).

3.1.2 Bottom-up models

Bottom-up modelling typically implies merging individual system elements to larger elements and subsystems until a complete top-level system is formed. The bottom-up approach is based on detailed data collection and sectoral analysis. If applied to the assessment of energy systems, the main attention is paid to characteristics of energy system technologies; the intersectoral relations are typically not taken into account. This section discusses the main types of bottom-up models.

3.1.2.1 Partial forecasting models

A wide variety of relatively simple static and dynamic techniques are used to forecast energy supply and demand for varying degrees of feedback and other dynamics. The main content is data on the technical characteristics of the energy system and related financial or direct costs (IPCC 2001). Such models are often used as a supplement to main models.

3.1.2.2 Integrated energy-system simulation models

Integrated energy-system simulation models incorporate a representation of energy demand and supply technologies that include end-use, conversion, and production technologies. Demand and technology development are driven by exogenous assumptions often linked to technology models and econometric forecasts. The demand sectors are generally disaggregated to energy end-uses, which allows for the development of trends to be projected through technology development scenarios. Such models are best suited for short- to medium- term studies in which the detailed technological information helps explain a major part of energy needs (IPCC 2001). An example of a simulation model is the Integrated Resource and Market Transformation Analysis (IR/MTA) applied in assessment of EU-15 (Krause 2000). The study examines the entire EU electricity sector as part of an economy-wide analysis of carbon reduction scenarios (Krause 2000). In calculating economic impacts, the study incorporated such feedback effects as reductions in technology costs from economies of scale, reductions in the pre-tax or import prices of fossil fuels, reductions in the cost of electricity supplies, and other effects, and estimated the cost of carbon abatement.

3.1.2.3 Dynamic energy optimization models

Optimization models are useful to assess the dynamic aspects of GHG emission reduction potential and costs. Thus, dynamic energy optimization models aim to minimize the total costs of the energy system, including all end-use sectors, over a forty to fifty year horizon and to compute a partial equilibrium for the energy markets. Early versions of these models answered the question of how energy demand could be met at the least cost, whereas the recent versions include the demand response to prices, and links between aggregate macroeconomic demand and energy demand (IPCC 2001). A World and European optimization model from the family of MARKAL (MARKet Allocation) linear models is an example of this class of models. In MARKAL, the entire energy system is represented as a Reference Energy System, showing all possible flows of energy from resource extraction, through energy transformation and end-use devices, to demand for useful energy services. Each link in the Reference Energy System is characterized by a set of technical, emission and economic coefficients. MARKAL finds the best Reference Energy System for each period by selecting the set of options minimizing the cost of the total system over the entire planning horizon (Lee and Linky 1999).

3.1.3 Hybrid models

Work on narrowing the gap between economics-oriented top-down approaches and technology-oriented bottom-up models has resulted in a hybrid approach. There are two main types of hybrid models: moving from the top-down assessment to bottom-up and vice versa. The movement towards the adaptation of disaggregated bottom-up models to macroeconomic techniques is probably the most successful and frequently conducted. One of the well-known examples of hybrid models is the European energy model – PRIMES. PRIMES represents a modelling system that simulates a market equilibrium solution for energy supply and demand in the EU Member States depending on the energy price. As regards the residential sector, the model distinguishes five categories of dwelling split according to space heating technologies. The electrical appliances for non heating and cooling are considered as a special sub-sector, which is independent of the type of dwelling (Capros *et al*. 2001).

An overall characterization and comparison of top-down and bottom-up approaches are presented in Figure 10 and Table 2. Figure 10 describes a few examples of energy system models relative to two dimensions: the top-down versus the bottom-up modelling approach, and optimization versus simulation as a way of solving the model. Taking into account the aims and tasks of this dissertation research, the conclusion of the presented review and Table 2 is that the bottom-up simulation model is the most appropriate for the dissertation research. The model developed and used in the dissertation research is located relative to other models in Figure 10. Section 3.2 continues by reviewing the bottom-up models applied in a set of selected studies which assess the mitigation opportunities.

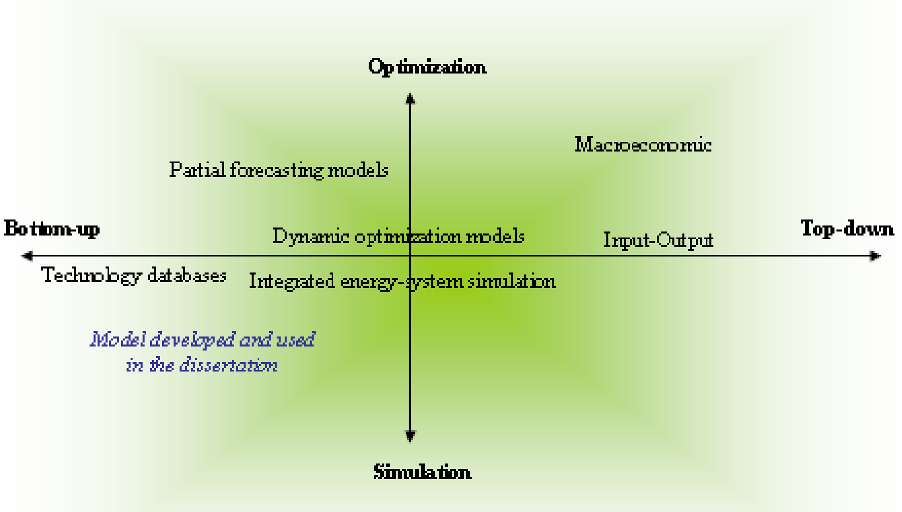

Figure 10 Characterization of a few energy system assessment models

Source: adapted from van Vuuren (2008).

Table 2 Comparison of top-down and bottom-up modelling approaches

Differences	Top-down models	Bottom-up models
Approach	(Historic) behaviour of economies and energy systems is studied using aggregated data in the long term. Economic feedback is studied.	Specific actions and technologies are modelled at the energy end-use level. Economic feedback is usually not included.
Subject of modelling	Impacts of policy tools and measures on macro-economic indicators are modelled.	Energy savings available from application of specific technological options and associated costs are modelled.
Deviations in cost estimates	Can overestimate the costs due to a failure to account realistically for consumer and producer behaviour relying too heavily on aggregate data.	Can underestimate the costs due to a failure to take into account all costs of actions associated with energy conservation in dynamics.
Consumer behaviour	Consumers act to maximize their utility or profit. If energy efficiency is less than it could be, it is because consumers do not see economic gain to make it more efficient.	Various market barriers prevent consumers from taking rational actions. Market barriers include lack of information, lack of access to capital to finance the efficiency investment, and others.
Technology understanding	Efficiencies of technologies are modelled through coefficients of production factors in aggregated production functions for each sector of the economy (elasticity of factors assume fuel switch).	Technology constitutes the basis of the bottom-up approach. A discrete shift from one technology to another assumes efficiency improvement. Price and factor elasticity are rarely studied.
Equilibrium versus Optimum	Models search for the state of equilibrium and initially assumed that the world without policy intervention was efficient.	Models search for optimization of energy systems in terms of allocation of the most cost-effective technological options.
Projection period	Applicable for the long-run assessment because econometric relationships among aggregated variables are usually more stable than among disaggregated components.	Bottom-up models are usually used for short- and medium-term analyses.

Source: Constructed on the basis of IPCC (2001), Sathaye and Mayers (1995), McFarland *et al.* (2002), Tol (2000), Krause (2000), Sathaye (2007), van Vuuren (2008).

3.2 Structure and assumptions of bottom-up models

In the light of sky-rocketing energy prices, energy security issues, and climate change consequences, growing attention is paid to research on opportunities for GHG emission mitigation and energy efficiency improvements. Recently dozens if not hundreds of studies have been developed worldwide to understand these potentials. These research activities differ across world regions, however. A considerable number of thorough reports have been prepared by research groups for developed countries (see Levine et al. 2007, Section 6.5.1, p. 122 on recent advances in potential estimations from around the world). In contrast, transition economies and developing countries are poorly covered by such climate mitigation research. Recently, the introduction of the Kyoto Flexibility Mechanisms gave a new stimulus to such research activities (for instance see Reddy and Balachandra 2006). Still, despite this and some local revivals, the question on the potential for energy conservation and GHG mitigation opportunities is poorly addressed in the CEE and FSU region, Latin America, Asia and Africa.

3.2.1 A ten-year worldwide review of selected bottom-up studies

Table 3 illustrates a set of selected bottom-up models (or hybrids based on the bottom-up approach) applied for estimation of GHG mitigation potentials or design of climate mitigation strategies. Only those studies which cover buildings are included in the review. The overview of these studies is important to understand and to learn how different studies develop their approaches and assumptions. Thus, models can be grounded on different baseline scenarios, various combinations of technological options, discount rates, and numerous other assumptions. Nine of sixteen reviewed in Table 3 bottom-up studies applied the method of supply curve of GHG mitigation (conserved energy) [9]. The convenience of this method in terms of easy-to-read research results and other advantages (discussed in Section 3.3.2, p. 41) explain why this method is also applied in the dissertation research.

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[9] Please see Section 3.3 for more the detailed description of the method.

Table 3 Bottom – up models applied in selected country studies and their main assumptions

Country/ region	Reference	Model type	Model-led unit	Baseline	Discount rate	Assumptions interesting from the point of view of dissertation research	Base/ Target years	Scenarios additionally to the baseline
EU-15	Joosen and Blok 2001	Bottom-Up, GENESIS	GHG	Frozen efficiency	4%	New and retrofit separately categorized	1990/ 2010	Mitigation scenario
Hungary	Szalvik *et al.* 1999	Bottom-Up, ENPEP[10]	Energy, CO_2	Business-as-usual	3% and 5%	New equipment and retrofitting. A wide range of supply side and demand side options.	2005/ 2030	Mitigation scenario
Hungary, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Poland, the Czech Republic	Petersdorff *et al*. 2005	Bottom-up and BEAM[11] model for the buildings stock	Energy and CO_2	Frozen efficiency	6%	The buildings stock is modelled based on climate regions, building type, size, and age, energy carrier, insulation level, and emission factor.	2006/ 2015	Three scenarios with the EU EPBD[12], extended EPBD to buildings > 200m^2, extended EPBD to all buildings.
	Lechtenbohmer *et al*. 2005	Bottom-up	Energy and CO_2	Business-as-usual	3% and 5%	A moratorium on new nuclear power plants and compliance with ongoing nuclear phase-out.	2005/ 2020	The Policies and Measures scenario ('Target 2020')
Greece	Mirasgedis *et al*. 2004	Bottom-Up, ENPEP	CO_2	Frozen efficiency	6%	Climatic zones, age of buildings and their size result in 24 categories of buildings. Based on CBA analysis (NPV).	2000/ 2010	Three scenarios based on different definitions of incremental cost of CO_2 abatement.
Estonia	Kallaste *et al.* 1999	Bottom-Up, MARKAL[13]-MACRO	Energy, CO_2, NO_2	Scenario with modest economic growth	6%	No limit for fuel import and investment, electricity import is restricted. Buildings-related options are insulation mostly.	1995/ 2025	Low CO_2 tax, high CO_2 tax, all high taxes, expensive oil shale.

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[10] Energy and Power Evaluation Program

[11] Building Environment Analysis Model

[12] The EU Directive on Energy Performance of Buildings.

[13] MARKet ALlocation model

Country/ region	Reference	Model type	Model-led unit	Baseline	Discount rate	Assumptions interesting from the point of view of dissertation research	Base/ Target years	Scenarios additionally to the baseline
Switzerland	Siller *et al.* 2006	Bottom-up	Energy and GHG	Business-as-usual	N/a	Modelling of technologies is based on standards (present Vs future). Renovation and new constructions. Only space and water heating/	2005/ 2050	Final energy consumption reduced by a factor of 3; CO_2 emission reduced by a factor of 5 by 2050.
UK	Johnston *et al.* 2005	Bottom-up, Advanced BREHOMES[14]	Energy and CO_2	Reference and business-as-usual	N/a	A “notional” dwelling type and efficiencies of its envelope and systems are modelled based on the present and expected standards.	1996/ 2050	‘Demand side’ scenario with the imposed target (60%)
UK	Boardman *et al.* 2005	Bottom-Up, UKDCM[15]	CO_2eq.	Reference: 1997 carbon emissions	N/a	Technologies are modelled in terms of fuel inputs, system efficiencies, and energy outputs assuming their take-over rates.	1996/ 2050	New scenario with 60% reduction of carbon emissions from 1997 levels by 2050(‘40% House’)
Brazil	Almeida *et al.* 2001	Bottom-Up	Electricity, CO_2	No-conservation scenario	0%, 15%, 35%, 70%	Residences are split into 15 sub sectors in 5 geographical regions and 3 household income classes	2000/ 2020	Scenarios considered for different types of potential
USA	Koomey *et al.* 2001	Bottom-Up, CEF-NEMS	Energy, carbon	Business-as-usual	7%	New energy-efficient technologies and new policies	1997/ 2020	Moderate and advanced scenario.
South Africa	De Villiers 2000; De Villiers and Matibe 2000	Bottom-Up	CO_2	Frozen efficiency	6%	New equipment and retrofit with improved technologies are modelled (only known technologies).	1990/ 2030	Mitigation scenario
Ecuador	FEDEMA 1999	Bottom-Up, LEAP[16]	Energy, CO_2	Expected efficiency scenario	10%	Rural and urban areas. Reduction in specific E- needs and intensities, fuel switch.	1995/ 2030	Mitigation scenarios for each sector

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[14] The Building Research Establishment’s Housing Model for Energy Studies

[15] UK Domestic Carbon Model

[16] Long-range Energy Alternative Planning System

Country/ region	**Reference**	**Model type**	**Model-led unit**	**Baseline**	**Discount rate**	**Assumptions interesting from the point of view of dissertation research**	**Base/ Target years**	**Scenarios additionally to the baseline**
India	ADB 1998	Bottom-Up, MARKAL and AHP[17] with imposed targets of GHG emission reductions by- 5,10,15,and 20%	Energy and GHG	Business-as-usual scenario and Baseline	6% and 12%	Business-as-usual is continuation of past trends whereas the Baseline is with the technologies likely to be used in the future	1990/ 2020	High efficiency scenario
Thailand	ADB 1998	Bottom-Up, EFOM-ENV[18]	Energy and GHG	Business-as-usual and baseline (see assumptions)	10%	The business-as-usual scenario is based on extension of present trends; the baseline is with policies but no special measures. Technological options are presented as programs targeted at efficiency improvement	1995/ 2020	1.Scenarios with CO_2 reduction by 10%, 20%, 25%, 30%, and 35% in 2020 as compared to Baseline 2.1st Scenario & 0.5% CO_2 reduction from 2010 compared to Baseline.
Viet Nam	ADB 1998	Bottom-Up, MEDEE/S-ENV[19] and EFOM-ENV	Energy and GHG	Business-as-usual as extension of past trends and the baseline	10%	Two modelling approaches applied: the first one is that CO_2 evolution depends on set targets, and the second – on growth rates of CO_2.	1993-94/ 2020	1.Imposed targets for GHG reductions are 5%, 10% and 15%; 2. CO_2 emission growth rates are 0.5%, 1% and 1.1% /yr.

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[17] Analytical Hierarchy Process

[18] Energy Flow Optimization Module-Environment

[19] Sectoral Energy Environmental Demand Analysis Model

3.2.2 Recent advances in research on mitigation targeted on CEE residential buildings

Ürge-Vorsatz *et al.* (2003) concluded that detailed and publicly available studies on end-use energy efficiency potential, especially ones that are still relevant and not outdated, are rare in the CEE region. The authors suggested that one of the key reasons for this is the lack of consistently collected energy end-use data. This lack makes such research difficult and imprecise. According to the author's best knowledge, as of March 2008 there have been four pieces of research developed during the last ten years and aimed at assessing mitigation opportunities in the buildings sector of the CEE and FSU region. Two case studies for Estonia and Hungary were developed in the frame of the UNEP series entitled "Economics of GHG Limitations" (Kallaste *et al.* 1999; Szlavik *et al.* 1999). The study commissioned by the European Association of Insulation Manufacturers (EURIMA) and conducted by Ecofys (Petersdorff *et al.* 2005) analyzed the buildings stock of the EU Member States joined the Union in 2004. Finally, Lechtenbohmer *et al.* (2005) assessed the impact of mitigation policies and measures in 2020 for the EU-15 and the EU Member States which joined the Union in 2004.

The Hungarian country study (Szlavik *et al.* 1999) considered the residential and public sectors and the forest sequestration potential as the main components of the national mitigation strategy. Two strategies were developed for the buildings sector; the first focused on retrofit of technologies and buildings while the second assumed technology replacement. The study learned both the demand- and supply- side impacts on electricity and heat use results from more than forty technological options and measures. The study concluded that up to 45% of the buildings-related baseline emissions can be mitigated through application of demand-side measures by 2030, and 31% of these baseline emissions can be avoided cost-effectively. Whereas the study considers a comprehensive number of options and is quite detailed, a Hungarian Ministry official (Szerdahelyi pers. comm.) in Ürge-Vorsatz *et al*. (2003) stated it should not be used any longer because since then the design of energy efficiency action plans and financial support allocations have been based on back-of-the-envelope style calculations, leaving no documentation behind.

The Estonian country study (Kallaste *et al*. 1999) considered more than thirty technically feasible mitigation measures for the industrial, the residential and commercial buildings, transportation, and non-energy uses of fuels. A number of scenarios such as low CO_2 tax, high CO_2 tax, all high taxes, and expensive oil shale were developed. The baseline scenario implied a modest economic growth forecast in combination with fulfilment of the present environmental agreements. For buildings, only eight energy conservation options in the short-term and four in the long-term were examined. All of them were targeted at heating and insulation improvement. Application of these options to the buildings sector resulted in a 3% reduction of the Estonian national CO_2 emissions in 2025.

The EURIMA report (Petersdorff *et al*. 2005) analyzed the impact of the EU Directive on Energy Performance of Buildings on thermal performance and associated CO_2 emissions in the buildings stock of the EU Member States which joined the Union in 2004 as compared to the frozen efficiency scenario[20]. The buildings stock was modelled using a bottom-up BEAM model depending on such input indicators as climate regions, building type and size, building age, insulation level, energy carrier, and emission factor. Scenarios used these input parameters to generate development of the buildings stock over time as a function of demolition rate, new

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[20] For the definition of the frozen-efficiency scenario please see Section 3.3.5

building activity, renovation and energy efficiency measures of retrofit. The estimate of the technical potential is made taking into account an assumption that all buildings are covered by the Directive and all buildings are retrofitted now according to insulation standards entered into force following the Directive. This potential for the assessed countries was estimated as 62 million tonnes CO_2 in 2015.

Finally, Lechtenbohmer *et al.* (2005) assessed the impact of mitigation policies and measures in 2020 for the EU-15 and the EU Member States which joined the Union in 2004, i.e. Hungary, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Poland and the Czech Republic. The mitigation and policies scenario considered both supply and demand side measures and implied higher energy efficiency measures for appliances and lighting, increased use of renewable energy, and reduced emissions from electricity generation. The estimate of the economic potential for CO_2 emission reduction in the residential sector for the mentioned eight EU Member States was 30% of the BAU emissions or 41 million tonnes CO_2 in 2020.

The summary of the assumptions and the results of the four pieces of research discussed are presented in Table 4. The overall conclusion of this section is that experience of modelling mitigation opportunities in the residential buildings of the CEE and FSU region is limited. The available studies argue that there is considerable potential for CO_2 mitigation in the buildings sector of these countries. Based on a review of the available studies, the most cost-effective options delivering large amount of potential are insulation options, exchange of building shell components, and exchange of lights and domestic appliances with more efficient ones. The review of assumptions and technological options applied in the available studies is a valuable contribution to framing the methodology of the dissertation research.

Table 4 Review of studies which assess mitigation potential in the CEE residential sector

Country/ region	Description of mitigation scenarios	Potential			Measures with lowest costs	Measures with highest potential	Notes
		Type	Million tCO_2	Baseline %			
Hungary (Szlavik *et al.* 1998)	Economic potential from 12 options and measures: building envelope, space heating, hot water supply, ventilation, awareness, and lighting.	Technical	22	45%	1. Hot water metering; 2. Flow controllers; 3. Programmable thermostats for heating.	1. Post insulation; 2. Window retrofit; 3. Appliance procurement.	Discount rate is 3%-5%; The business-as-usual baseline; The projection period is 2000-2030; Potential estimates are for public and residential buildings; ranking of measures is for residences.
		Economic	15	31%			
Estonia (Kallaste *et al.* 1999)	Market potential from 4 insulation measures: 3d window glass, new insulation into houses, renovation of roofs, additional attic insulation.	Market	0.4%	3% of the whole economy emissions	1. New insulation into houses; 2. Additional attic insulation; 3. Third pane for windows.	1. New insulation into houses; 2. Third pane for windows; 3. Additional attic insulation.	Discount rate is 6%; The business-as-usual baseline; The projection period is 1995 – 2025; The whole buildings stock is modelled.
Member States accessed the EU in 2004 (Petersdorff *et al*. 2005)	Technical potential from measures in building envelope esp. insulation of walls, roofs, cellar/ground floor, windows with lower U-value; and renewal of energy supply.	Technical	62	-	1. Roof insulation; 2. Wall insulation; 3. Floor Insulation.	1. Windows replacement; 2. Wall insulation; 3. Roof insulation.	Discount rate is 6%; The baseline is frozen efficiency scenario; The projection period is 2006 – 2015; The whole buildings stock is modelled.
Member States accessed the EU in 2004 (Lechtenbohmer *et al*. 2005)	Improvement in space and water heating, appliances and lighting, cooling/freezing, air-conditioning, cooking, motors, process heat, renewable energies, reduced emissions from electricity generation.	Economic	41	30%	Not listed in the study	1. Insulation; 2. Heating systems, fuel switch, district heating and combined heat and power.	Discount rate is 3-5%; The projection period is 2005 – 2020. Data is for the residential sector.

3.3 Bottom-up approach: a supply curve of CO_2 mitigation method

Section 3.1 (p. 23) reviewed the key approaches to energy system assessment and concluded that a bottom-up model is the most appropriate to address the research questions of this dissertation because it may better capture the technological details of the potential available for CO_2 mitigation, which is prioritized in the tasks of the research. As Section 3.2.1 (p. 31) concluded, many bottom-up models use the method of supply curves as a convenient tool to present and to analyze the complex results of assessment of opportunities for GHG emission mitigation. This section introduces and discusses the supply curve method in detail as the main methodological tool of the dissertation research.

3.3.1 Introduction of the supply curve method

A principal output of many bottom-up models is an energy conservation supply curve. The conservation supply curve approach was introduced by experts of the Lawrence Berkeley National Laboratory (Meier *et al.* 1983) in the 1980s and since then it has been widely used as a tool of economic analysis in dozens of case studies. The main advantage of the supply curve analysis is that it provides comprehensive, easy-to-read information on suggested efficiency technologies, their costs, their potential energy saving and the best schedule for their implementation (Laitner *et al*. 2003). In the last fifteen years, the energy efficiency supply curve framework has also been replicated for the analysis of the potential for GHG emission mitigation. Supply curves of mitigated GHG emissions are based on the analysis of low carbon options in addition to energy efficiency opportunities.

While there are several definitions of supply curves in the literature (see Vorsatz 1996), the author relies on the following definition as the most relevant for the dissertation aim: *the supply curve of CO_2 mitigation characterizes the potential CO_2 reductions from a sequence of mitigation technological options as a function of marginal costs per unit of mitigated CO_2*. A typical supply curve of CO_2 mitigation is presented in Figure 11 below. Each step on the curve represents a type of measure. A measure X can save as much emission reductions as ΔCO_2 at the indicated mitigation costs. Negative costs of conserved CO_2 mean that results of measures are greater than the cost of implementing the action, therefore society as a whole benefits from introducing this mitigation action instead of paying for it (Halsnaes *et al.* 1998).

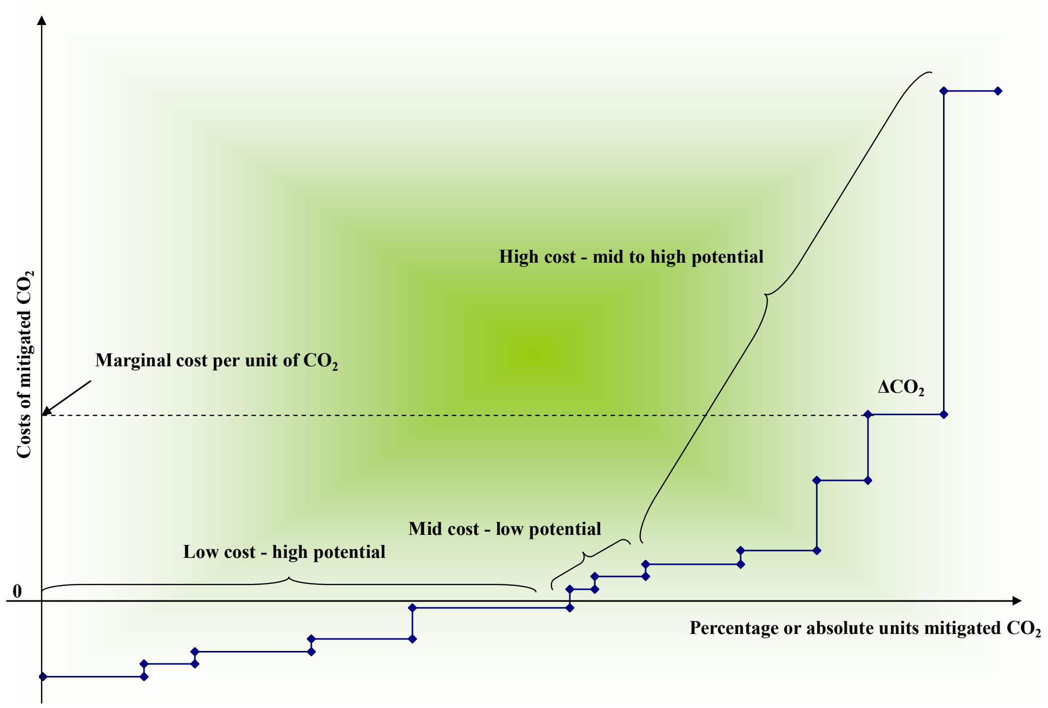

Figure 11 Example of a supply curve of CO_2 mitigation

Source: Constructed based on Rufo and Coito (2002).

3.3.2 Advantages and messages of supply curves

Probably the most useful advantage of the supply curves is that estimates of the potential for CO_2 emission reduction are already adjusted for the effects of overlapping options that are targeted at the same energy end-uses (see Section 3.3.4, p. 44 for further details). Due to this positive side of the curves, they are widely used to present results of analyses of complex systems such as buildings or industrial processes on the individual or national levels. Another advantage of the curves is that they represent often dozens and sometimes hundreds of individual technological options in a relatively simple graphical format (Rufo 2003) providing easy-to-read guidance on how CO_2 can be avoided cost-effectively by prioritizing technological options which should be promoted by environmentally sound policies. Also, the curve can be used to analyze future CO_2 emissions in a detailed breakdown and the baseline emissions if some of the options are realized. Finally, the curves supply the format of the results which can be often directly incorporated into follow-up research on modelling of mitigation policy tools.

To continue, the description of the key messages of the curves is given. The curves provide comprehensive information for making investment choices such as simple pay-back time, an internal rate of return, a cost-benefit ratio, and others (Vorsatz 1996). If the saved energy costs are higher than the total annualized costs, the area lying between the curve and the abscissa represent the ‘net benefit’ of realization of the cost-effective options (the yellow area on Figure 12). Under conditions of a carbon market, when someone producing CO_2 emission reductions from implementation of technological measures can sell these reductions, the net benefit is extended by the area between the abscissa and the CO_2 price level (the orange area on Figure 12). If the option is not cost-effective, the area between the curve and the CO_2 price level (zero if CO_2

is not priced) shows the amount of annualized investments that are not justified by saved energy costs and CO_2 sales (the blue area on Figure 12). It is important to note that energy saved costs may vary depending on the type of stakeholders considered. A residential customer calculates energy saved costs according to the energy prices for the residential end-users. By contrast, a utility may consider the costs of avoided electricity generation. The Government may have a broader understanding of types of costs which pay back investments besides saved energy costs, i.e. it can identify and monetize important co-benefits of CO_2 mitigation according to national priorities.

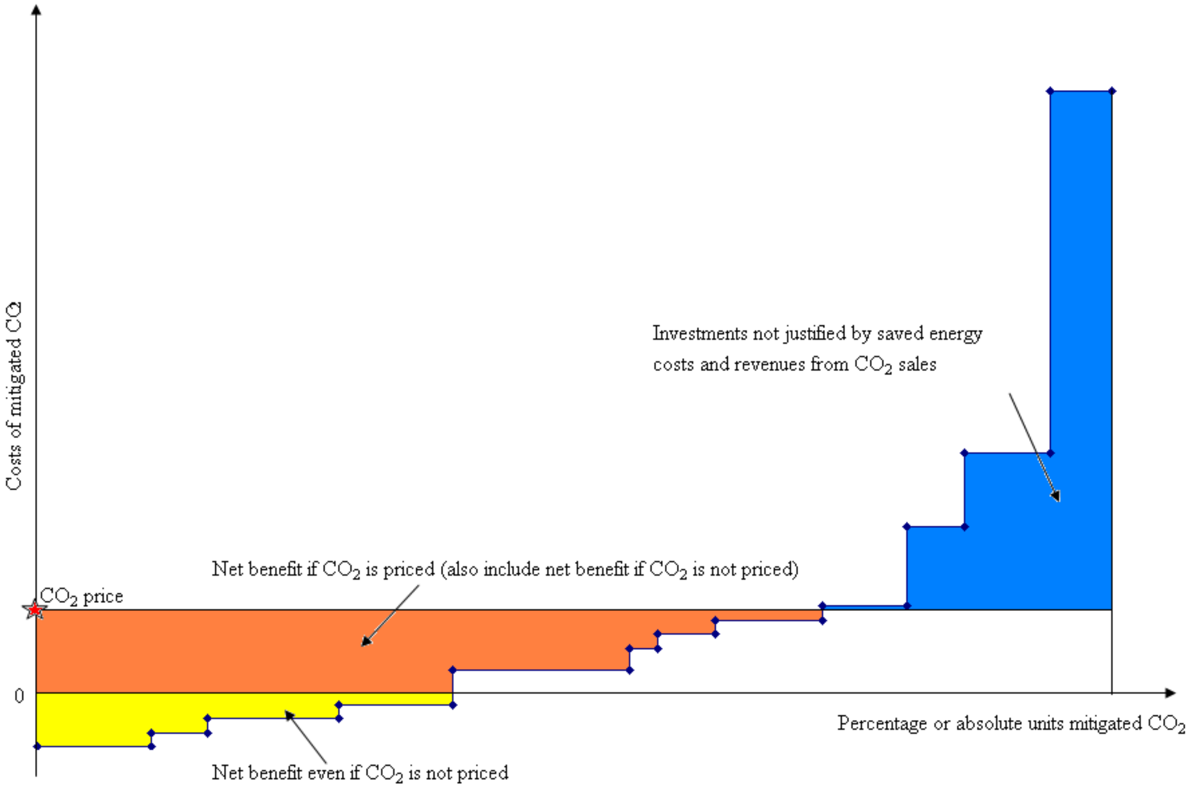

Figure 12 Messages of a CO_2 mitigation curve about its profitability of investments

3.3.3 Limitations of the supply curve analysis

The supply curve method has a number of limitations. One of them is that constructing supply curves requires a significant amount of input data, which are often difficult and time-consuming to measure, collect or obtain. Another limitation is that the identified potential is strictly linked to the identified list of measures for a specified point of time. Therefore, firstly, the potential is underestimated due to options which are missed out by the research; secondly, the cost and technical characteristics of some emerging technologies are presently hardly possible to identify, thus leading to the underestimation of the real potential savings. The third limitation that it is important to highlight is that modelling of the economic feedback to sectoral advances (such as the energy price feedback from the supply side) is challenging to include into the supply curve method. Furthermore, the supply curves capture only sequential and marginal technological opportunities and often miss the systematic and integrated opportunities. Finally, it is challenging to quantify and include non-technological options into the pool of the mitigation technologies assessed with the supply curve method.

Other disadvantages identified by Rufo (2003), Levine *et al.* (2007), Meier (pers. comm.) are that:

- ⇒ An understanding of the energy services does not change over time;
- ⇒ Costs in the supply curve are single point averages and, therefore, they do not capture the fact that the real costs vary among applications;
- ⇒ Non-energy costs and benefits are not included in the economic evaluation of technological options;

- ⇒ The least cost ordering of measures in supply curves implies that the technological options are applied purely on a rational least-cost basis. Whereas, application of technological options is a multi-attribute decision process;
- ⇒ Only one of mutually exclusive options can be presented on the curve.

3.3.4 Developing a supply curve: the main steps

The bottom-up analysis with the use of supply curves is a complex process. In general, the main stages of supply curve analysis are:

- ⇒ Creating a detailed database containing information on energy end-uses and conventional and energy saving technologies;
- ⇒ Recovery of the sectoral structures disaggregated per end-use and per energy form for the basis years;
- ⇒ Construction and calibration of the baseline of the demand for energy services and associated emissions;
- ⇒ Economic evaluation of selected technological options;
- ⇒ And amalgamation into the supply curve.

The potential delivered by a set of options can be determined from the potential of these individual options. However, a simple summing up leads to double counting of the potential that can be equally supplied by the different options. For instance, reduction of the demand for heating can be achieved by building shell insulation and improvement of a heating system as well as other options, thus the summing up of potentials of these two options will give an overestimate of the real potential. The supply curve method gives the key to calculate the potential, avoiding this double counting problem.

The key methodological principle of the supply curve method which helps solve the problem of "double-counting" is that the potential from application of mitigation options is not summed up directly but is stacked incrementally according to the order of their cost-effectiveness. In other words, the method includes the following steps. First, the potential and costs of mitigated CO_2 are estimated for each technological option individually. The second step is to pick up the measure characterized with the lowest costs of mitigated CO_2 and construct the new emission baseline scenario making an assumption that this measure is applied. For the rest of the options, new energy and CO_2 savings as well as costs of mitigated CO_2 are estimated based on this new baseline. The third step is to select the measure characterized by the lowest mitigation costs among the measures left, to construct again a new baseline assuming that this option is applied in its turn, and to estimate new energy and CO_2 reductions and associated costs for the remaining measures. The process keeps going until all measures are ranked and implemented according their cost-effectiveness. After this procedure, it is typical that the ranking of options differs from the one based on individual implementation of measures. The changing order is observed for interdependent measures such as insulation measures and other heating options, but this is not the case for independent options such as improvement of washing machines and lighting technologies.

3.3.5 Alternative definitions of baseline and potential types

This section aims to give an understanding of alternative definitions of emissions baselines and mitigation potential types used in the literature. This section helps to identify the best choice of these model elements for the dissertation research. According to the definition, the supply curves describe the potential for CO_2 reduction from the implementation of technological options (see Section 3.3.1, p. 39), therefore, it is necessary to identify the baseline emissions this potential is compared to, i.e. the information on what would happen without special energy efficiency and climate mitigation policy interventions.

There are different types of baselines considered by the literature. These are most often frozen efficiency, low efficiency/low carbon, and BAU baselines. A frozen efficiency baseline implies that no energy efficiency improvement and no reduction of specific energy consumption occur. A low efficiency/low carbon baseline typically assumes some (low) penetration level of energy efficiency/low carbon technologies. A BAU baseline assumes that no new energy efficiency and low carbon policies are implemented additionally to those which have been already realized and energy and carbon intensities change because of market forces. Koomey *et al.* (1996) compares emissions according to different baselines (see Figure 13).

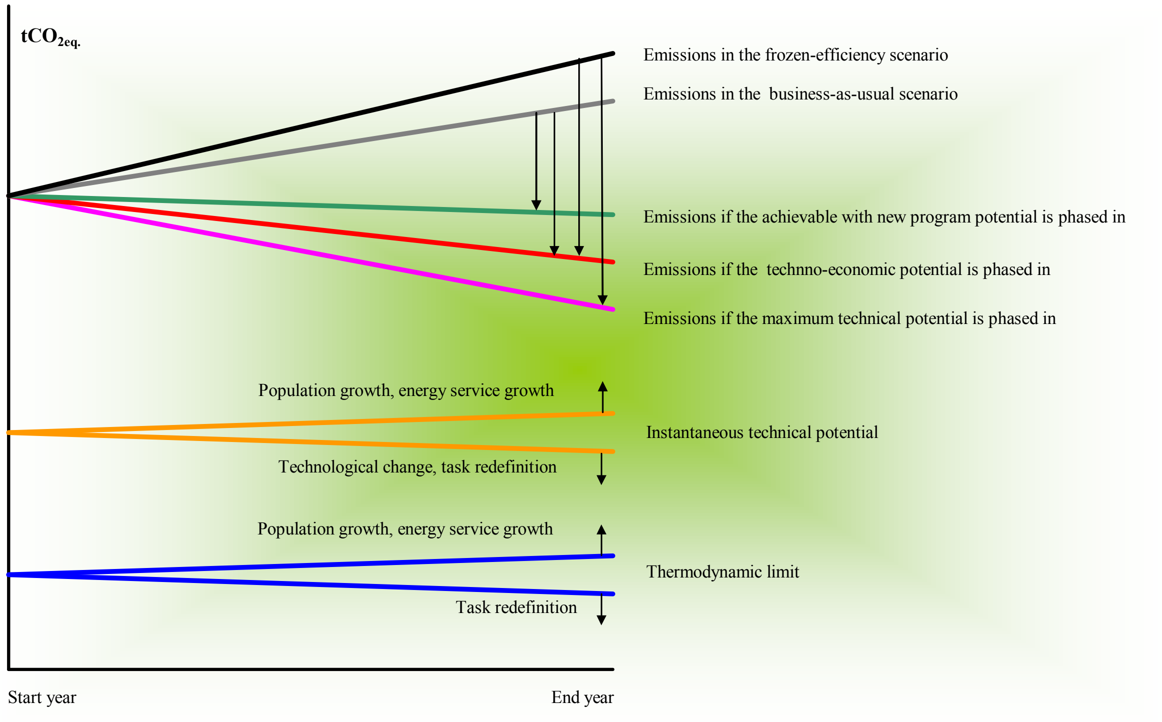

Figure 13 Alternative definitions of baselines and efficiency potentials

Source: adapted from Koomey *et al.* (1996) in Vorsatz (1996)

As a consequence of the second law of thermodynamics, there is a minimal energy required to provide a service. Therefore, there is a physical limit for efficiency improvement (Vorsatz 1996). The thermodynamic (theoretical) potential is rather uncertain and relies on the development of new technologies (Halsnæs *et al.* 2007); also this potential can be reduced through redefinition of the tasks when the understanding of a service changes (Vorsatz 1996). While definitions of different types of potentials vary in the literature, Rufo (2003) concluded that typically technical potential[21] options are those available with application of the current technologies. Among them,

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[21] Probably, the most appreciated presently source is the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Halsnæs *et al.* 2007] which determines the technical potential as the amount by which it is possible to reduce GHG emissions or improve energy efficiency by implementing a technology or practice that has

one can pick up economic potential[22] options that are also often referred to as cost-effective, i.e. those options associated with net negative costs (benefits from energy saved are higher than costs incurred). Market potential[23] options are economic potential options narrowed by the current market conditions without implementation of new policies, reforms or measures. The relative relation among different types of potentials is presented in Figure 13.

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already been demonstrated. There is no specific reference to costs here, only to 'practical constraints' although in some cases implicit economic considerations are taken into account.

[22] According to Halsnæs *et al*. [2007], the economic potential is cost-effective GHG mitigation when non-market social costs and benefits are included with market costs and benefits in assessing the options for particular levels of carbon prices in USD/tCO_2eq. and USD/tCeq. (as affected by mitigation policies), and when using social discount rates instead of private ones.

[23] According to Halsnæs *et al*. [2007], the market potential indicates the amount of GHG mitigation that might be expected to occur under forecast market conditions including policies and measures in place at the time. It is based on private unit costs and discount rates, as they appear in the base year and as they are expected to change in the absence of any additional policies and measures. The baseline is usually historical emissions or model projections assuming current social cost of carbon and no additional mitigation policies.

Chapter 4 RESEARCH DESIGN AND METHODOLOGY

Chapter 3 (p. 23) discussed the different approaches to energy system modelling. The last section concluded that the bottom-up simulation model using the supply curve method is the most appropriate for the dissertation research. The present chapter describes the research design, the equations used, the assumptions applied, and the research limitations.

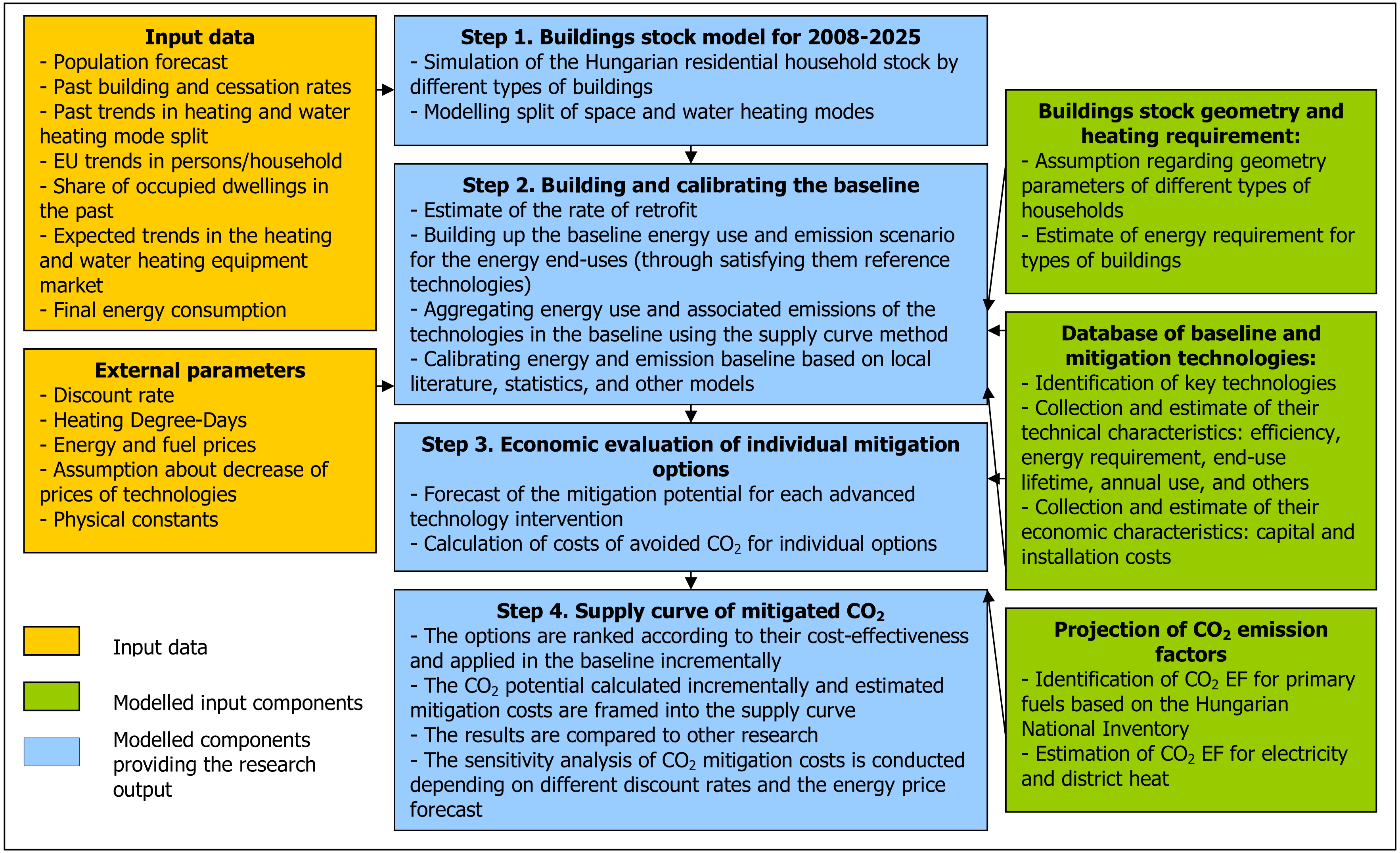
4.1 Dissertation research design

As mentioned in Chapter 3 (p. 23), modelling is currently the best known tool to evaluate the future. Ideal models do not exist and a number of approximations and assumptions are necessary to describe energy systems using modelling. Furthermore, the model should be relatively simple and transparent to balance between its complexity and the time required to collect and estimate the input parameters and assemble them together into the model. The last issue is especially important in the light of the finding of Koomey (2008) that both simpler and more complex models may provide results with similar magnitude of errors. The main fundamental assumption of the present research is that the understanding of the energy services does not change over time, i.e. cleaning clothes is done with the use of washing machines. It is also important to highlight that the present research focuses on the potential for CO_2 mitigation from technological options and does not consider the potential from non-technological options such as behavioural changes. The latter is disregarded due to a lack of worldwide knowledge and understanding of the impacts of behavioural options on GHG mitigation (this problem has been explicitly acknowledged by the recent IPCC Fourth Assessment Report, see Levine *et al*. 2007). Based on these key assumptions, the present section identifies the perspectives from which the buildings stock, energy services, and technologies satisfying them are modelled.

Illustration 3 presents the overall process of the dissertation research. Based on the data availability, the years 2004 - 2007 are set as the start for modelling of the input parameters and components of the sector. The introduction of mitigation options starts from the year 2008. Due to the uncertainty on which emerging energy end-use technologies will be used beyond a period longer than 15 - 20 years the model runs to the year 2025.

As for the first step, the overall number of households and their space/water heating mode split according to the main building types that were projected for 2008-2025 using a number of input parameters. For the purpose of modelling, the Hungarian residential buildings stock is divided into five main buildings types which possess different architectural and thermal characteristics. The building types are discussed in detail in Section 5.2 (p. 79). They are also outlined below for a better understanding of the modelling methodology. These building types are:

1. Traditional multi-family buildings constructed mainly at the end of the 19th century and during the inter-war years
2. Multi-family buildings constructed using industrialized technology until 1992
3. Single-family houses built until 1992 (referred to as old single-family houses)
4. Multi-residential and single-family buildings constructed during the last fifteen years (1993 – 2007)
5. Multi-residential and single-family buildings constructed after 2008.



Input data
- Population forecast
- Past building and cessation rates
- Past trends in heating and water heating mode split
- EU trends in persons/household
- Share of occupied dwellings in the past
- Expected trends in the heating and water heating equipment market
- Final energy consumption

External parameters
- Discount rate
- Heating Degree-Days
- Energy and fuel prices
- Assumption about decrease of prices of technologies
- Physical constants

Step 1. Buildings stock model for 2008-2025
- Simulation of the Hungarian residential household stock by different types of buildings
- Modelling split of space and water heating modes

Step 2. Building and calibrating the baseline
- Estimate of the rate of retrofit
- Building up the baseline energy use and emission scenario for the energy end-uses (through satisfying them reference technologies)
- Aggregating energy use and associated emissions of the technologies in the baseline using the supply curve method
- Calibrating energy and emission baseline based on local literature, statistics, and other models

Step 3. Economic evaluation of individual mitigation options
- Forecast of the mitigation potential for each advanced technology intervention
- Calculation of costs of avoided CO_2 for individual options

Step 4. Supply curve of mitigated CO_2
- The options are ranked according to their cost-effectiveness and applied in the baseline incrementally
- The CO_2 potential calculated incrementally and estimated mitigation costs are framed into the supply curve
- The results are compared to other research
- The sensitivity analysis of CO_2 mitigation costs is conducted depending on different discount rates and the energy price forecast

Buildings stock geometry and heating requirement:
- Assumption regarding geometry parameters of different types of households
- Estimate of energy requirement for types of buildings

Database of baseline and mitigation technologies:
- Identification of key technologies
- Collection and estimate of their technical characteristics: efficiency, energy requirement, end-use lifetime, annual use, and others
- Collection and estimate of their economic characteristics: capital and installation costs

Projection of CO_2 emission factors
- Identification of CO_2 EF for primary fuels based on the Hungarian National Inventory
- Estimation of CO_2 EF for electricity and district heat

🟨 Input data

🟩 Modelled input components

🟦 Modelled components providing the research output

Illustration 3 Design of the dissertation research

The second step was to model the baseline emission scenario using the created technological database, projected CO_2 emission factors for different energy carriers and external parameters as input data. The baseline emissions during 2008-2025 are estimated as emissions associated with final energy consumption of the reference technologies used to satisfy the demand for energy services. Aggregation of final energy consumption of the reference technologies and associated emissions was performed using the supply curve method.

The baseline scenario covers the current and projected emissions of all energy end-uses of the residential sector, namely space and water heating, lighting and appliances (including cooking). Modelling the baseline case of the thermal energy end-uses is based on the assumption that the technical progress of the thermal-related reference technologies happens quite slowly and these technologies in the future will be similar to those of today. In contrast, modelling of the baseline scenario for electricity technologies such as cold[24] and washing appliances and lighting (except water heating which is covered in the thermal component of modelling) assumes that their characteristics change quicker than the thermal options over the projection time. More details of the baseline scenario assumptions for space and water heating, cold and washing appliances and lighting, such as penetration rates and efficiency levels are described in the related sections (Chapter 6, p. 98 and Chapter 7, p. 129).

The best possible attempt was made to construct the baseline which is as close as possible to the business-as-usual scenario. However, due to the large number of uncertainties and data imperfection for some energy end-uses, the business-as-usual scenario is very challenging to

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[24] The category of cold appliances covers those appliances such as refrigerators and freezers.

construct. For instance, due to poor background data, efficiency improvement in energy use for cooking in the baseline was not considered. For this reason, in order to be more precise, the baseline developed in the frame of the present research is referred to as the ***reference scenario***.

As mentioned in Chapter 3 (p. 23), the modelling approach selected faced a number of challenges. Probably the most severe was the lack of the background data. Due to this reason, one of the key components of the model was the calibration of the baseline to the actual statistics such as the national energy and emission balance and to the results of other bottom-up models developed in the region and even worldwide. For more details of how this reality check was applied for the baseline emission forecast refer to Section 4.4 (p. 65).

Subsequently, the CO_2 mitigation potential was estimated individually for the most promising mitigation technologies selected from the technological database. The range of energy services is growing every year due to technological progress. It is hardly possible to cover estimate energy savings and associated emission reductions of all existing and emerging energy end-uses until 2025, therefore, the research investigates the potential of those energy services which currently have high penetration rates and consume large shares of the total energy used in the residential sector. These are space and water heating, refrigerating, freezing, clothes washing, lighting, and standby power for entertainment equipment.

As the final step, selected mitigation options were economically evaluated and stacked to the supply curve of conserved CO_2. The scenario which implies the realization of the technical potential[25] identified by the present research is referred to as ***the mitigation scenario***.

4.2 Calculation procedures

A number of existing models were considered to implement the research. However, using the existing software was difficult because usually such software requires input data which differs to the available data, and there are difficulties associated with adjusting this available data to the software requirements. Therefore, spreadsheet-based analysis was chosen as the most appropriate method because it allows variation of modelling methods dependant on the available data. This section reviews the mains steps and calculation procedures done with the use of spreadsheets.

To simplify the discussion, first, analysis of energy savings and CO_2 emission mitigation potential on the household level is described. After that, it is explained, how the household analysis is extrapolated to the national level. The calculation procedures are derived based on such sources as: Ürge-Vorsatz pers. comm., Mirasgedis pers. comm., Koomey pers. comm., Mirasgedis *et al.* (1996), Vorsatz (1996), Harvey (2006), Petersdorff *et al.* (2005), ADEME (2000), Fraunhofer IZM (2007), Kemna *et al.* (2007), SAVE (2001a, 2001b, 2002), and Thumann and Mehta (2001).

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[25] I.e. the total amount of the technical potential not regarding its costs found by the study.

4.2.1 Modelling household baseline energy consumption and CO_2 emissions

Final energy consumption of a household (FE_i, kilowatt-hours/household-yr.) in a year i (i=2008, 2009, …, 2025) was estimated as a sum of final energy consumed by this household for energy-use services such as space and water heating, lighting and other electric services, and cooking:

(1) $FE_i = \sum_i FE_{SpaceHeating_{m,j,i}} + \sum_i FE_{WaterHeating_{j,i}} + \sum_i FE_{Appliances\&Lights_{j,i}} + \sum_i FE_{Cooking_{j,i}}$, where

m a residential building type,

j an energy end-use technology.

CO_2 emissions ($CO_{2_{s,i}}$, gram CO_2/household-yr.) associated with household energy use of a service s were calculated as final energy consumption of this service ($FE_{s,i}$, kilowatt-hours/household-yr.) multiplied by the emission factor of the technology ($EF_{s,i}$, grams of CO_2/kiloWatt-hour) which delivers the service (see Equation 2). Analogously to Equation (1) CO_2 emissions associated with energy use of a household are calculated as a sum of emissions associated with household energy services.

(2) $CO_{2_{s,i}} = FE_{s,i} \times EF_{s,i}$

Final energy consumed for household space heating in year i is calculated as space heating requirement of a household of a building type m ($UE_{SpaceHeating_{m,i}}$, kilowatt-hours/household-yr.), divided by the efficiency of a space heating solution j ($\eta_{SpaceHeating_{j,i}}$, %) installed in the household:

$$(3)\, FE_{SpaceHeating_{m,j,i}} = \frac{UE_{SpaceHeating_{m,i}}}{\eta_{SpaceHeating_{j,i}}}$$

The accurate estimate of the space heating requirement of a household is based on the estimate of energy required to compensate heat loss due to its transmission and infiltration and the estimate of solar heat gains, internal heat gains from human bodies, appliances equipment and thermal mass gains. Due to complicated calculation procedure of all these factors, the research relies on the simplified procedure which takes into account only the currently dominant factor – the energy required to compensate heat loss due to its transmission ($EL_{Transmission_{m,i}}$ kilowatt-hours/household–yr.) and infiltration ($EL_{Infiltration_{m,i}}$, kilowatt-hours/household –yr.):

$$(4)\, UE_{SpaceHeating_{m,i}} = EL_{Transmission_{m,i}} + EL_{Infiltration_{m,i}}$$

Energy required to compensate heat loss due to its transmission is estimated as the heat transmitted through all components of the household cooling surface multiplied with demand for heating energy reflected in Heating Degree Hours[26] (HDH_i, Kelvin-hours/yr.). Heat transmission through a building component l is a product of the thermal transmittance coefficient, the U-value, of a building component l of a building type m ($U_{l,m}$, Watt/Kelvin per m^2) and the area of this component ($A_{l,m}$, m^2):

$$(5)\, EL_{Transmission_{m,i}} = HDH_i \times \sum_{l} U_{l,m} \times A_{l,m}$$

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[26] Heating degree hours is a quantitative index of demand for space heating calculated as a cumulative perennial difference between daily average air temperature and the reference temperature of 18°C (ODYSSEE NMS 2007). The index of heating degree hours considered does not include the cooling need.

The energy required to compensate heat loss of a household due to air infiltration is estimated as heat in air exchanged multiplied with demand for heating energy reflected in Heating Degree Hours. The heat in air exchanged is a product of the air change per hour rate in a building type m (ACH_m, times per hour), the volume of a household in a building type m (V_m, m^3), the air density (ρ_{air}, kilogram/m^3, the constant equalled c. 1.205) and the specific heat of air (c_{air}, kilowatt/kilogram-Kelvin, the constant equalled c. 0.00028):

$$(6)\ EL_{Infiltration_{m,i}} = HDH_i \times ACH_m \times V_m \times \rho_{air} \times c_{air}$$

Final energy consumed for water heating may be calculated similarly to that for space heating, i.e. as annual demand for hot water of a household in year i (V_i, litres) multiplied by energy requirement to heat one litre of water ($UE_{WaterHeating}$, kilowatt-hours) and corrected to the energy loss of water heating solution by diving the product by the efficiency of water heating and distribution ($\eta_{WaterHeating_{j,i}}$, %).

$$(7)\ FE_{WaterHeating_{j,i}} = \frac{V_i \times UE_{WaterHeating}}{\eta_{WaterHeating_{j,i}}}$$

Final energy consumption and associated emissions of appliances and lighting technologies was calculated separately for the cold and clothes washing appliances, miscellaneous appliances, lights, and cooking and then summed up. For cold appliances, the final energy consumption is found as the unit energy consumption ($UEC_{Reference}$, kilowatt-hours/yr.)[27] of a reference technology multiplied with Energy Efficiency Index[28] in year i according to Equation (8). The reference unit energy consumption (UEC) of cold appliances is the weighted average unit energy consumption of cold appliances sold in 1990-1992 in the EU-15. This reference for UEC serves as a benchmark for the Energy Efficiency Index (EEI) which indicates an appliance's energy consumption relative to it. For washing machines the final energy consumption is estimated as the product of the unit energy consumption of 1 kilogram washing load in year i (UEC_{Load_i}, kilowatt-hours/1 kilogram of clothes), the average washing load, and the number of washes per year according to Equation (9). Final energy consumption of lights is calculated as wattage of lighting technology multiplied by its time in use according to Equation (10).

$$(8)\ FE_{ColdAppliance_i} = UEC_{Reference} \times EEI_i$$

$$(9)\ FE_{ClothesWashingMachine_i} = UEC_{Load_i} \times Load \times Time$$

$$(10)\ FE_{Light_i} = Wattage_{Light_i} \times Time$$

The miscellaneous electricity use, i.e. electricity use of appliances others than refrigerators, freezers, clothes washing machines, electric water heaters, and lighting) is modelled based on the miscellaneous electricity use in 2004 (GFK 2004) and the assumption of its annual growth of 5%[29].

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[27] Unit Energy Consumption (UEC) is defined is average annual electricity/gas consumed for end-use.

[28] EEI indicates an appliance's energy consumption relative to a reference model. For domestic cold appliances the energy efficiency index (EEI) for a reference model was set at 102 for the average model on the market in year 1992.

[29] There is limited literature which projects the miscellaneous electricity use in Hungary and in Europe in general. The estimate of projected annual growth of miscellaneous electricity use is assumed based on Sanchez (1998) for the United States (in fact, this estimate is probably not that bad because many of the small electrical appliances and equipment items projected in the United States ten year ago are coming to Hungary only now).

Cooking energy use and related emissions are estimated based on the ODYSSEE NMS (2007) database. The database gives an estimate of the household annual final energy consumption for cooking in the EU Member States which joined the Union in 2004 at the level of c. 580 kWh/yr in 2004. Due to the lack of research on cooking, this value is assumed for cooking energy consumption in Hungary from 2008 to 2025. It was assumed that gas and electric cooking (electric cooking is considered in the miscellaneous electricity use) contribute equal shares to final energy use.

4.2.2 Estimation of energy saving and CO_2 mitigation potentials of individual options

The thermal improvement includes options to reduce the final energy required for space and water heating through improving the thermal envelope[30], through improving space and water heating efficiencies, switching to fuels with lower CO_2 emission factor, and improving space heating controls, water demand controls, and space heating metering systems. Estimating the impact of individual technological intervention requires changing parameters characterizing the technological improvement.

Thus, estimating the impact of insulation of a building component requires changing the heat transmittance coefficients in Equation (5) and calculating the difference between ex and ante final energy consumption and associated CO_2 emissions. Considering exchange of windows and weather stripping assumes decreasing the air change per hour value in Equation (6). In the case of exchange of space or water heating technologies, savings of final energy is estimated as the difference between energy consumption of the reference and advanced heating solutions to satisfy the space heating requirement of a household (the parameter to change in Equation (3) or Equation (7) is efficiency of space heating or hot water production and distribution). CO_2 emission reductions in this case are estimated as the difference between emissions associated with using ex and ante heating solutions (ex and ante final energy consumption is multiplied with emission factors of ex and ante heating solutions respectively according to Equation (2)). The effect of the installation of space heat controls is estimated with Equation (3) reducing the energy heating requirement. Analogously, the installation of water saving fixtures reflects in Equation (7) with the decrease of demand for hot water.

Improvement of electricity use includes exchange of main appliances (refrigerators, freezers, and clothes washing appliances) and lights with more efficient equipment and reduction of electricity consumption in low power mode (LOPOMO). Assessment of exchange of other appliances is omitted due to their lower significance (which is determined by contribution of these appliances to final energy consumption) and due to a lack of data. The saved final energy and associated CO_2 emission reduction of cold appliances, clothes washing appliances and lighting were estimated by changing the unit energy consumption of appliances or wattage of lighting technologies in Equations (8), (9), and (10). The impact of standby power reduction was estimated through changing the value of standby power of appliances according to Equation (11).

$$(11)\ FE_{Stansby_i} = Wattage_{Standby_i} \times Time_{InStansby}$$

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[30] Thermal envelope refers to the shell of the building as a barrier to unwanted heat or mass transfer between the interior of the building and the outside conditions (Levine *et al*. 2007).

4.2.3 Extrapolation of the estimates to the sectoral level

Baseline final energy consumption and associated CO_2 emissions are received by extrapolation of the household analysis to the country level through the following procedures:

⇒ Substituting household system efficiencies, household emission factors, and energy prices with country average system efficiencies, emission factors, and energy prices (weighted according to the final energy consumption) employed in the building types considered for space consumption assessment in Equations (3), (7), (8), (9), and (10).

⇒ Substituting in Equation (3) the space heating requirement with average space heating requirement weighted by the number of the households in a modelled type of buildings[31]

⇒ Substituting in Equation (5) and Equation (6) the heating degree days with the country average heating degree days[32] of households (weighted by the number of the households in a modelled type of buildings).

Calculating the country-wide energy saving potential and CO_2 emission mitigation potential is calculated by multiplying the stock of households with penetration rates of advanced technologies and their potential to save energy and CO_2 emissions as specified in the above equations.

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[31] The country average space heating requirement changes over time because as time passes the buildings are insulated better, requiring less energy for space heat.

[32] Lower heating temperature and shorter heating time will be required for increasingly insulated stock of households.

4.2.4 Economic evaluation of individual technological options

Costs of CO2 mitigated of a technology ($MCCO_{2i}$, EUR/gram of CO2) are estimated as the annualized investment costs of the technological intervention ($\Delta AIC_{j,i}$, EUR/yr.) deducting the sum of saved costs in year i ($EC_{j,i}$, EUR/yr.) per unit of CO2 mitigation in year i ($\Delta CO_{2_{j,i}}$, gram CO2/yr.) (see Equation (11)). Investment costs take into account only additional costs associated with advanced options, i.e. they exclude costs associated with the reference case (Equation (12)). Investment costs required for the technological intervention in year i consist of capital costs of the technology and associated installation costs. The annualized investment costs calculated as the product of investment costs into the technological intervention and the annuity factor of this option (a_j) as used and explained in Equations (13) and (14). Saved costs in year i due to the technological intervention imply only saved energy costs (Equation (15). The saved energy costs were calculated based on the fuel price for the residential end-users (including the value added tax and the energy tax) in year i (please see Section 8.2.2 on p. 162 for more assumptions about fuel prices).

$$(12)\, MCCO_{2j,i} = \frac{\Delta AIC_{j,i} - EC_{j,i}}{\Delta CO_{2j,i}}$$

$$(13)\, \Delta AIC_{j,i} = a_j \times AIC_{j,i} - a_{reference} \times AIC_{Reference,i}$$

$$(14)\ a_j = \frac{(1+DR)^{n_j} \times DR}{(1+DR)^{n_j} - 1}$$, where DR is a discount rate and n_j is the technology end-use time

$$(15)\, EC_{j,i} = \Delta FE_{j,i} \times \Pr ice_i$$

Additionally, to the cost of conserved CO$_2$ ($CCE_{j,i}$, EUR/kilowatt), the cost of conserved energy of a measure was calculated to facilitate an understanding of the magnitude of investments needed to save a unit of energy. This indicator was estimated as:

$$(16)\, CCE_{j,i} = \frac{\Delta AIC_{j,i}}{\Delta FE_{j,i}}$$

As Section 3.3.3 (p. 43) describes, the supply curve of CO$_2$ mitigation is built on the principle of the least marginal costs of technologies. Therefore, in the case of two or more competitive mitigation technologies (for example, the application of several space heating solutions to the specific building type), the cheaper option takes the full potential whereas the more expensive options are not implemented. This is not true in the real world – households install different heating solutions available on the market, not just the cheapest one. To overcome this limitation in case of two or more fully competitive mitigation technologies, the potential among these technologies could be split on the basis of their relative economic performance (Mirasgedis pers. comm.). More specifically, the potential was split according to Equation (17), which is originally used in top-down models to estimate the shares of the competitive technologies:

$$(17)\, MS_j = \frac{Q_j}{\sum_{j=1}^{k} Q_j} = \frac{\left(\frac{1}{PT_j}\right)^{\gamma}}{\sum_{j=1}^{k}\left(\frac{1}{PT_j}\right)^{\gamma}}, \text{ where}$$

MS_j, Q_j and PT_j, $j = \overline{1,k}$ the market share, the quantity, and the prices of technology j

γ the sensitivity of the market to prices of the technologies; the higher the price sensitivity, the higher the market share of the cheaper technology; this sensitivity indicator was assumed as 1.

4.3 Data sources used

The data used to reconstruct the present energy balance is collected from several sources. Regarding electric energy end-use, the data was collected from electricity use metering campaigns conducted by Central European University (REMODECE 2007), and such sources as the Status Report on Electricity Consumption and Efficiency Trends by Bertoldi and Atanasiu (2007), the task reports of the Ecostandby project (Fraunhofer IZM 2007) and other references. Regarding thermal energy end-use, the data was collected from the publications of the Hungarian Statistical Central Office, the task reports of the Ecohotwater project (Kemna *et al*. 2007), the EURIMA/ECOFYS report (Petersdorff *et al.* 2005), interviews with experts (Kovacsics pers.comm., Csoknyai pers. comm., and ‘Sigmond pers. comm.), and other references.

The database of efficiency and low carbon technologies is created based on:

- ⇒ Such comprehensive publications as Levine *et al*. (2007), Harvey (2006), IEA (2006);
- ⇒ Labelling and standardization programme reports (ADEME 2000; CECED 2001; SAVE 2001a, 2001b, 2002);
- ⇒ Equipment catalogues and pricelists (Danfoss 2007; Duplo-duplex 2007; Mega-öko Kazánfejlesztő-gyártó Kft. 2007; Megatherm 2007; ORIS Consulting 2007; Saunier Duval 2007; Szalontai and Sonnencraft 2007);
- ⇒ Reports, market reviews, and presentations of production associations and consultancies (Adam 2007; Trnka 2004; DBO 2007; EHPA 2007; Weiss *et al*. 2007);
- ⇒ Interviews with experts (Kovacsics pers.comm; Csoknyai pers. comm.; Sigmond pers. comm.; Hermelink email comm., Kocsis and Beleczki email comm.).

4.4 Calibration of the base year energy balance and reality check of the results received

As mentioned in Section 1.4 (p. 7), one of the major challenges of constructing the bottom-up model in the context of this dissertation was the use of highly uncertain background data. For instance, the data for thermal characteristics of buildings and the space heating requirement, which in theory directly correlate, were contradicting. Due to this reason, once the structure of the baseline energy consumption and associated emissions was filled with the available, estimated, and assumed data for the base years, the received data set for the base year was calibrated to the energy balance according to national official statistics and research. The most recent breakdown of energy consumption of the residential sector into energy-using services (space and water heating, cooking, appliances and lights) is available for the year 1996 (KSH 1998) and therefore is not able to serve as a reliable guide for calibration. Due to this reason, the energy consumption and emissions in the base years were compared to the total energy consumption and associated emissions of the sector according to the data from the ODYSSEE NMS database (2007), the Energy Efficiency Action Plan of Hungary (Ministry of Economy an Transport of Hungary 2008), and to the results of macro-economic modelling provided by the PRIMES model (Carpos *et al*. 2007). After this comparison, the disaggregated data were reviewed and adjusted to fit the available statistics in the best possible manner. The main adjustments are described in Section 7.3.1.1 (p. 151).

4.5 Limitations of the developed model

This section describes the opportunities for reduction of the limitations of the research and improvement of the quality of its results. Firstly, some of the limitations of the research are inherited from the modelling method. For example, see Section 3.3.3 (p. 43) for a description of the limitations of the supply curve method. Secondly, as SAFE (2002) mentioned, a model can only as be good as its input data. Due to this reason, many uncertainties are associated with the background data available. Finally, the research is limited by the time of the PhD Programme and the scope and tasks of the research were scaled and planned accordingly.

4.5.1 Limitations associated with the selected modelling approach

As mentioned, the fundamental assumption of the research is that the understanding of the energy services does not change over time. This might not be true because, as time goes by, new revolutionary technologies might be invented to satisfy unconstrained demands for luxury, comfort, entertainments, and other desires. It might happen that in fifteen years people will stop washing clothes in washing machines but will use some bacteria consuming dirt. Many other solutions which are hard to imagine today and are, therefore, difficult to model today may be invented tomorrow. Since more research is needed to identify future life styles and technological development, the present research does not go beyond the technological boundaries well described and known today.

As Section 3.3.3 (p. 43) highlights, development of a technology-rich bottom-up models requires a significant amount of background data. The background statistics for the residential sector and the market information about the Hungarian technological trends is scarce, contradictory, uncertain, and thus, difficult to trust. Moreover, if such information is available, it is often difficult and very expensive to obtain. In this context, the model can be improved significantly with better data support. The author found it especially difficult to obtain information for important energy end-use options, such as space heating consumption for more than half of the residential final energy. For better results, the author identifies the key data to collect as:

⇒ The age structure of the buildings stock by types of buildings over time

⇒ Better information about energy consumption of unoccupied dwelling stock

⇒ The average thermal properties of dwellings and building geometry, by building types

⇒ Energy heating requirement, by building types

⇒ The space and water heating mode split over time

⇒ Energy requirement, fuel mode split and installed efficiencies of cooking

⇒ Installed heating and water heating equipment efficiencies

⇒ Installed efficiencies of small household appliances and air-conditioners, review of market trends of these appliances for Hungary.

Other limitations due to the selected assessment method (Section 3.3.3, p. 43) include the omission of the economic feedback to sectoral advances, and the analysis of only sequential technological opportunities. In reality, the application of options is often integrated multi-attributive decision process.

4.5.2 Disregarding the co-benefits and barriers of CO_2 mitigation

The present research considers the private costs of residential end-users to improve energy efficiency and saved energy costs. At the same time, investments in building energy efficiency and fuel switch yields a wide range of benefits beyond the value of saved energy. These co-benefits of CO_2 mitigation can play a crucial role in making GHG emissions mitigation a higher priority. Thus, if co-benefits such as higher comfort, improved productivity, the avoided new power and heat producing capacities in the business-as-usual scenario, and others are identified and quantified, the mitigation costs might be lower than calculated otherwise (Levine *et al.* 2007). Even though the estimation of the societal costs of CO_2 mitigation is important, the choice of private costs of household was made for two reasons. First, the private costs are identified to be sufficient to meet the aims and address the objectives of the dissertation research. Second, the background data to monetize and account for the co-benefits are poor and for this reason, the decision was made to leave this issue to future research.

Similarly, another important issue for future research is the identification and monetization of transaction costs associated with overcoming barriers for efficiency penetration and fuel switch in the residential sector of Hungary. Certain characteristics of markets, technologies and end-users can hinder energy-saving behaviour and decisions (Levine *et al.* 2007) and they may severely limit the cost-effectiveness of efficiency investments. This is due to the fact that the efficiency upgrade must also address these barriers, offsetting most or all of the energy and cost savings associated with improved efficiency. Due to the lack of detailed research on the quantification of these barriers in Hungary, the research does not include them into the analysis of the mitigation costs.

4.5.3 Disregarding of non-technological and a few technological mitigation options

While the author tried to cover as many mitigation options as possible, their number was limited to only those which provide undoubtedly the largest potential for CO_2 mitigation. This does not mean, however, that other options are significantly less important. The energy end-uses and technological options not investigated in terms of their mitigation potential are discussed in the text that follows.

The improvement of the thermal envelope and exchange of space heating solutions in the buildings constructed from 1993 to 2008 is left out because these buildings are quite new and have lower potential for improvement than other types of buildings. Still this category of buildings might be important to cover in the future research because these buildings are criticized for their significantly higher energy use.

Similarly, the exchange of heating technologies in single-family and multi-residential buildings constructed after 2008 is not considered because heating solutions in these buildings are up to the market technologies. Therefore their exchange would be far less cost-effective than in other building types. Also, efficiency improvement of biomass heating systems presently installed in the family houses was not assessed due to the assumption than the biomass burnt is produced in a sustainable manner and therefore is a carbon-neutral fuel.

Those shares of space heating solutions that are not significant, such as non-gas heating in multi-family houses (0.3% of the total stock) and households heated with electricity (about 2.5% of the total household stock) are left out precisely due to their low significance. Options such as the exchange of doors and better insulation of pipes delivering district and central heat and water inside buildings are also omitted because these options are expected to result in significantly lower potential than that of other technological options assessed in the research.

The efficiency improvement of miscellaneous electrical appliances and equipment[33] is not assessed because they contribute cumulatively only c. 15% to the residential electricity consumption as Figure 8 (p. 15) attests (though standby power reduction of TV- and PC- related appliances is covered). For future research it would be important to study the dynamics of electricity consumption of miscellaneous appliances and equipment. Information technologies and communication are particularly important: their penetration and rates of energy consumption are the highest among all technologies (KSH 2004, 2006b,c; Bertoldi and Atanasiu 2007). Increasing demand for amenities and entertainments is expected to boost the electricity consumptions of small electrical appliances and, even though presently they occupy less than c. 20% of electricity demand (GFK 2004), they might become major contributors to future growing electricity consumption trends.

Due to a lack of data, efficiency options related to cooking and motors (lifts) are not studied. It is not yet clear how much these energy end-uses contribute presently to the final energy demand of the Hungarian residential sector and how high their present efficiencies are. As regards to lifts, the author has never even seen this energy end-use included in the Hungarian statistics, even though lifts should contribute significantly to the electricity demand in multi-floor buildings. It is

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[33] Other appliances than cold appliances (refrigerators and freezers), washing machines, and lights.

important to make more thorough research of these options for a better understanding of energy end-use and related CO_2 emissions in the residential sector.

Increasing demand for air-conditioning is the main driver for growing electricity use in the European southern countries due the fast penetration of small residential air-conditioners (Bertoldi and Atanasiu 2007); however, with a warming climate, air-conditioners can also be seen more frequently in Hungarian households as well. Although it is unlikely that Hungary will reach as a high a level of air-conditioning penetration as the US or the South of Europe, this energy use is believed to be the reason for the extremely high peak loads in recent summers (Capgemini 2006). Moreover, if the intensive building stock retrofit program is to be realized, reduced air infiltration will result in the need for more air ventilation and conditioning.

Very unusual options are likely sometimes to have considerable energy saving potential, but are not considered. An example is the construction of roofs under inner yards of traditional multi-family buildings. Such a development would allow increasing the yard temperature by several degrees, thus reducing the heat loss of the cooling surface of buildings and decreasing the heating requirement of households having common walls with yards.

There are also many ways to reduce uncertainties and clarify assumptions applied in the model. These include, but are not limited to:

⇒ The investigation of the expected decrease of heating degree hours and an expected increase of cooling degree hours for Hungary

⇒ Consideration of the heat released by domestic appliances and lights

⇒ Better research into energy price dynamics over 2008 – 2025

⇒ Investigation of the price dynamics of the reference and advanced technologies

⇒ Research on the market trends for space and water heating technologies in Hungary

⇒ Research on CO_2 emission factors for electricity and consumed heat in households

⇒ Other parameters.

Finally, non-technological options for CO_2 mitigation were not included into the pool of the mitigation technologies assessed in the research. The latest IPCC Assessment Report found (Levine *et al.* 2007) that the non-technological mitigation options are rarely included into mitigation models because there is a critical lack of understanding and characterisation of non-technological mitigation options. Omission of these options leads to underestimation of the overall potential. Therefore, more background research, data collection and metering are needed to include these options into the model developed in the present research.

4.5.4 Consideration of the rebound effect

Despite the growing efficiency of both thermal and electrical energy use is in the residential sector, the demand for energy services is growing. This is due, among other reasons, to structural changes and the growing demand for amenities coupled with new technological possibilities. Furthermore, saved energy costs due to energy efficiency improvement allow the consumption of higher amounts of amenities, including electric services, and the purchasing of more goods, some of which may consume energy. This phenomenon of an increasing energy efficiency accompanied by an increasing demand for energy services, and resulting in less energy savings than originally expected by researchers is called the rebound effect (Moezzi and Diamond 2006).

Including the energy price elasticity[34] into the model is perhaps one of the most prominent methods of accounting for the rebound effect in the forecast of opportunities to save energy (Mirasgedis pers. comm.). The author was not able to locate the research on energy price elasticity in Hungary and due to this reason consideration of the rebound effect was limited to the consideration of the energy consumption growth due to installation of advanced heating solutions. As described in Section 2.2 (p. 12), space heating is the largest residential energy service in Hungary and the rebound effect plays a significant role here (SAVE 2002). When switching to a better heating technology, very often a household exchanges its premise (room) heating with central dwelling heating (SAVE 2002; Kovacsics per. comm.). In this case, the heated area increases by a factor of 2-3 due to the switch from heating the main rooms to heating the whole house. Therefore the total energy consumed for heating increases, even though it is supplied with a technology of higher efficiency (SAVE 2002). Other rebound effects are not considered by the model.

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[34] The price elasticity is measure of estimating the effect of changing the price for goods or services on the demand for them. The energy price elasticity is respectively the percent change in energy demand due to 1% change in price.

Chapter 5 THE BUILDINGS STOCK MODEL

This section details the research aimed to describe and project the present and future building stock and its characteristics. Firstly, the section describes the modelling of the dwelling and household stock of Hungary. Secondly, the main building types and their thermal properties are described. Finally, overcoming a large uncertainty associated with the evolution of the building stock, this section presents the results of modelling the household stock and its split into different building types according to installed space and water heating solutions.

5.1 Modelling dwelling and household stock

5.1.1 Population dynamics and the dwelling stock

The historical dynamics and the forecast of population were taken from the Hungarian Statistical Central Office (KSH 2006a) and the EUROSTAT official population forecast (2007). The population dynamics based on these two sources is presented in Figure 14 . The historical data shows that despite the population decline since 1983 the total number of dwellings has been growing. During 1990 – 2004, the annual growth rate of the total number of dwellings was 0.7% which is the same as the average EU rate (calculated based on KSH 2006b). This is due to improved living standards and the phenomenon of "an independent home" described by Ball (2005). Many households have more than one dwelling – an independent home – which is not rented out in the private sector on a permanent basis. Another factor is a large share of low quality and, thus, unoccupied dwelling stock. Assuming that the annual growth rate of dwellings will stay the same until 2025, Table 5 describes the results of dwelling projections based on this indicator.

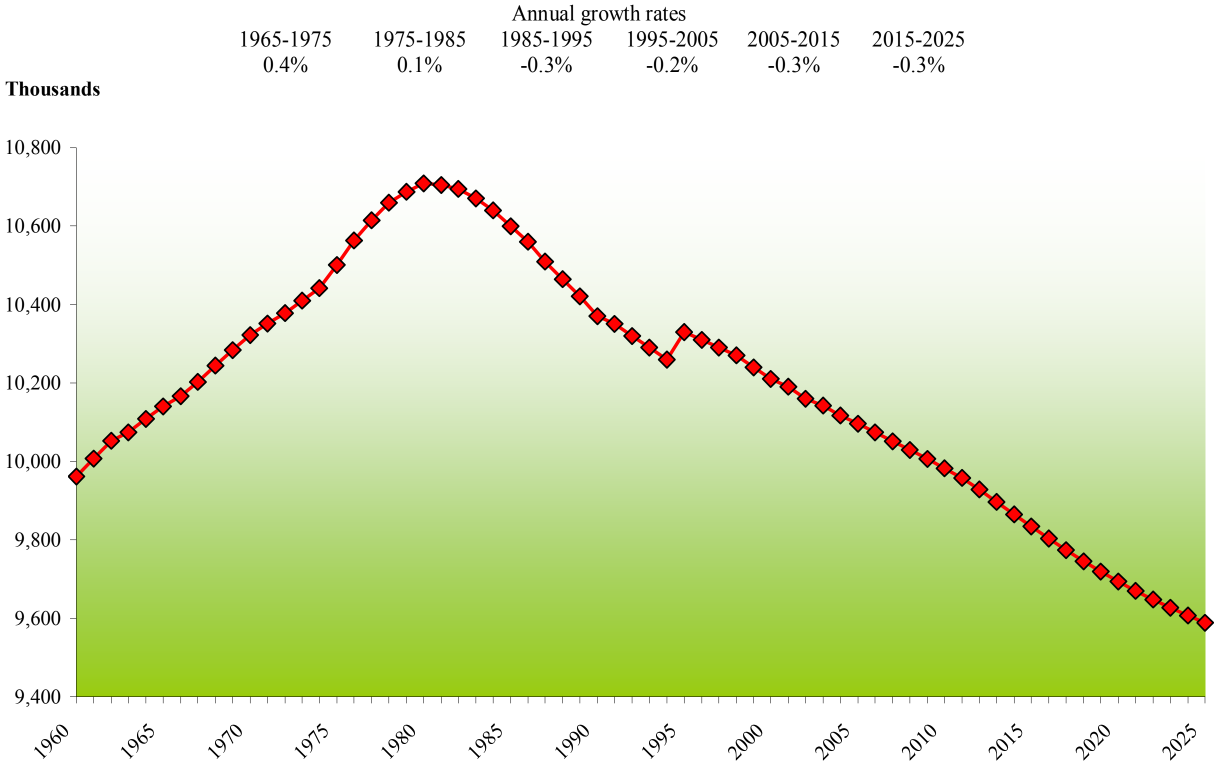

Figure 14 Population dynamics in Hungary, 1960 - 2025

Source: constructed based on KSH (2006a) and EUROSTAT (2007).

Table 5 Dynamics of the selected dwelling indicators, 1965 – 2025 (point data)

Indicator	Units	1965	1975	1985	1995	2005	2015	2025
Population, total	thousand persons	10,140	10,501	10,599	10,330	10,096	9,834	9,588
Persons per dwelling	persons/unit	4.23	3.56	2.93	2.60	2.42	2.24	2.08
Total number of dwellings	thousand dwellings	2,397	2,947	3,614	3,971	4,173	4,396	4,610

5.1.2 Projection of building and cessation dynamics

The projection of cessation of dwellings is based on the historical trends. Figure 15 illustrates the phenomenon that since 1988 the cessation of dwellings has dropped down to a level where dwellings are exchanged extremely slowly. Since it took approximately twenty years for the rate of cessation to drop down to such a low level, for the purposes of the research, it is assumed that by 2025 the average rate of cessation will reach its typical level estimated as an average during 1951 – 1988. This level of the dwelling turnover is approximately 200 years.

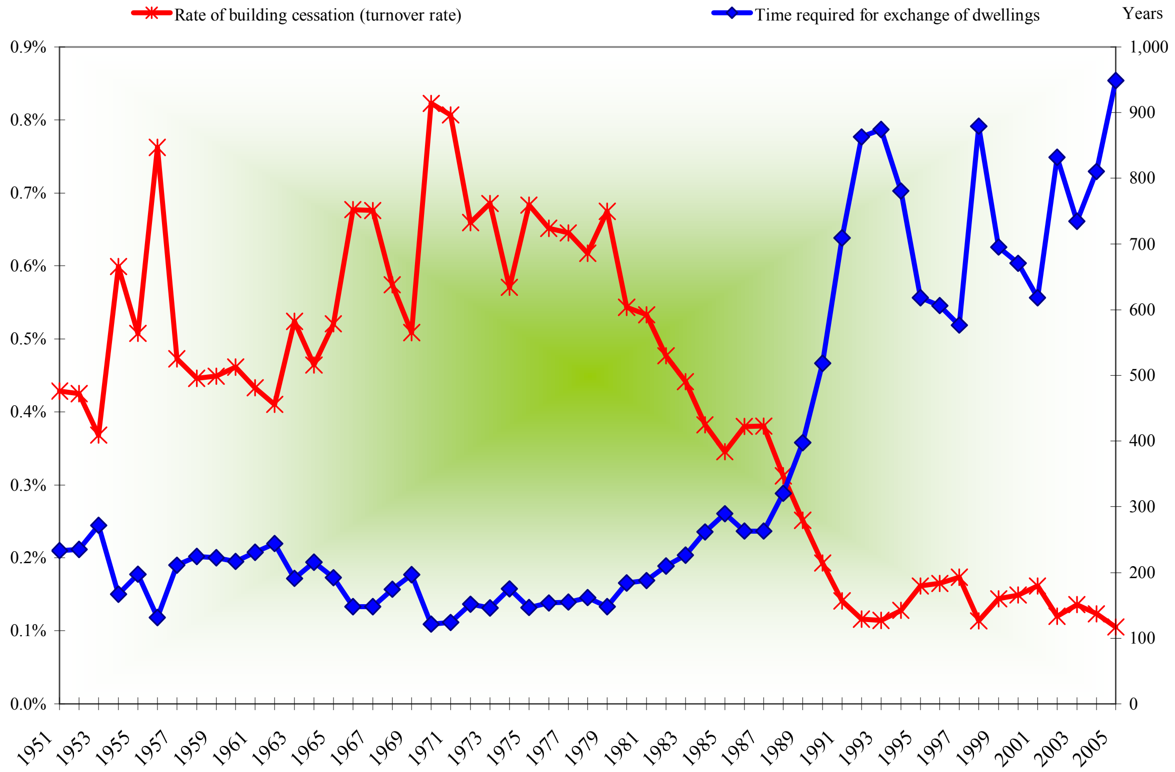

Figure 15 Rate of building cessation and time required for the buildings stock to exchange

Source: Constructed based on KSH (2006b)

The number of newly built dwellings is calculated as those which are required to cover the gap between the total expected number of dwellings and demolished dwellings. The results of these projections are presented in Table 6 .

Table 6 Dynamics of built and ceased dwellings in Hungary, 1965 - 2025

Indicators	Units	1965	1975	1985	1995	2005	2015	2025
Total number of dwellings	thousand dwellings	2,397	2,947	3,614	3,971	4,173	4,396	4,610
Dwellings built	thousand dwellings/yr.	55	100	73	25	41	29	48
Dwellings ceased	thousand dwellings/yr.	12	20	12	6	4	10	23
Dwelling replacement time[35]	years	192	146	289	618	949	434	198

Source: 1965 – 2005: KSH (2005); 2005 – 2025 – projections based on EUROSTAT (2007), KSH (2006a, b).

The analysis of Table 6 shows that the Hungarian dwelling stock is characterized by an extremely low turnover. As Ball (2005) explains one of the reasons behind this is the low level of people mobility. An average person in Hungary changes his/her living place 2.7 times in his/her life as compared to 6 or 7 times in Western Europe. The low level of people mobility slows down the process of moving from “worse” to “better” conditions (Ball 2005).

The low rate of dwelling replacement suggests that the partial or full reconstruction of dwellings might be one of the national priorities. According to Ball (2005) with the reference to the Central Statistical Office, only one quarter of dwellings does not require repair presently. At least one fifth needs full restoration and two fifths require partial restoration. With the remaining 13% of dwellings restoration is not economically viable and they must therefore be demolished. The quality of the thermal quality is illustrated in Figure 16.

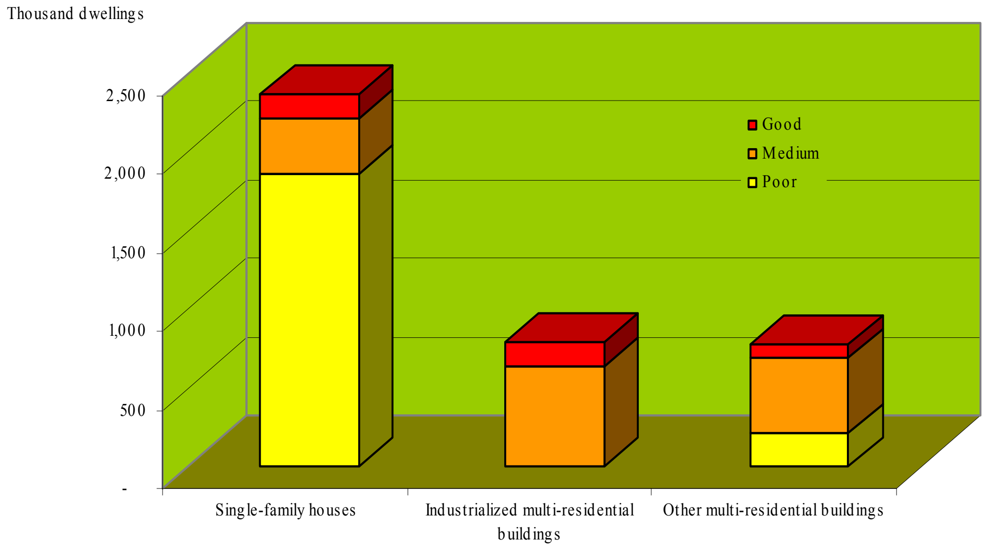

Figure 16 Thermal insulation levels of the existing dwelling stock in Hungary[36]

Source: Matolcsy *et al*. 2005.

5.1.3 Projection of the household stock

Due to the large share of buildings characterized by poor conditions and the phenomenon of "independent home" mentioned above a relatively high percentage of dwellings are unoccupied. Whereas before 1996, the share of non-occupied dwelling stock was about 4-5%, starting from 1997 this indicator amounted to 8% in average. For the future modelling purposes, it was

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[35] Estimated as the reverse of the dwelling cessation rate.

assumed that this share did not increase and, thus, the share of households (i.e. occupied dwellings) is 92% of the total dwelling number. Although unoccupied dwellings should be heated to some minimum degree to avoid structural damage of buildings, their energy consumption for space heating is considerably lower than that of occupied houses on average. It is reasonable to assume that non-occupied dwellings do not consume energy for other purposes. Due to these reasons, modelling of energy use for all end-uses is based on the number of occupied dwellings (households) rather than on the number of dwellings. Therefore, energy use and respectively CO_2 emissions of non-occupied low quality dwellings and "independent homes" are assumed to be zero.

5.2 Description and geometry of main building types

For the modelling purposes, the Hungarian housing stock is split into five buildings types, which possess different architectural and/or thermal characteristics. These are:

⇒ Multi-residential traditional buildings constructed mainly at the end of the 19th century and during the inter-war years

⇒ Multi-residential buildings constructed using industrialized technology (including panel, block, and cast buildings) built after the 2nd World War until 1992[37]

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[36] The authors of the figure (Matolcsy *et al*. 2005) make the difference between multi-storey terraced houses and multi-storied traditional houses, but the author does not do that in the dissertation.

[37] Buildings built between after the 2nd World War until c. 1965 and at the end of 1980s have a different building technology but their number is not very significant in the whole stock and they were included into the category of the multi-residential buildings built using industrialized technology.

- ⇒ Single-family houses in suburban and semi-urban areas constructed until 1992 (i.e. before the Buildings Standard of 1991 was applied)
- ⇒ Multi-residential buildings and single-family houses constructed during 1993 – 2007
- ⇒ Multi-residential buildings and single-family houses which will be constructed after 2008 until the end of the projection period, i.e. 2025.

The sections below describe the main types of buildings, their geometric characteristics and provide the projections of their space heating mode split. The geometrical characteristics are assumed based on observation of the Hungarian modelling stock, actual metering of selected representative dwellings, and the statistical publication (KSH 2006b).

5.2.1 Multi-residential traditional buildings

A significant number of urban multi-residential buildings were constructed within nearly 100 years from the middle of the 19th century to the middle of the 20th century and represents the architectural and historical heritage of the country. Due to the historic and aesthetic value of their exterior it is hardly possible to conduct an overall reconstruction of these buildings; however, improvement of some parts of the building shell is possible (Kovacsics pers. comm.). Added thermal insulation may change the appearance of the façade of these buildings and, therefore, options to improve the thermal performance of these buildings are focused on other building elements than walls, i.e. on improving characteristics of windows and roofs as well as on insulation of upper and ground floors (cellar ceilings or basements). The representative traditional multi-residential buildings are shown in Illustration 4.

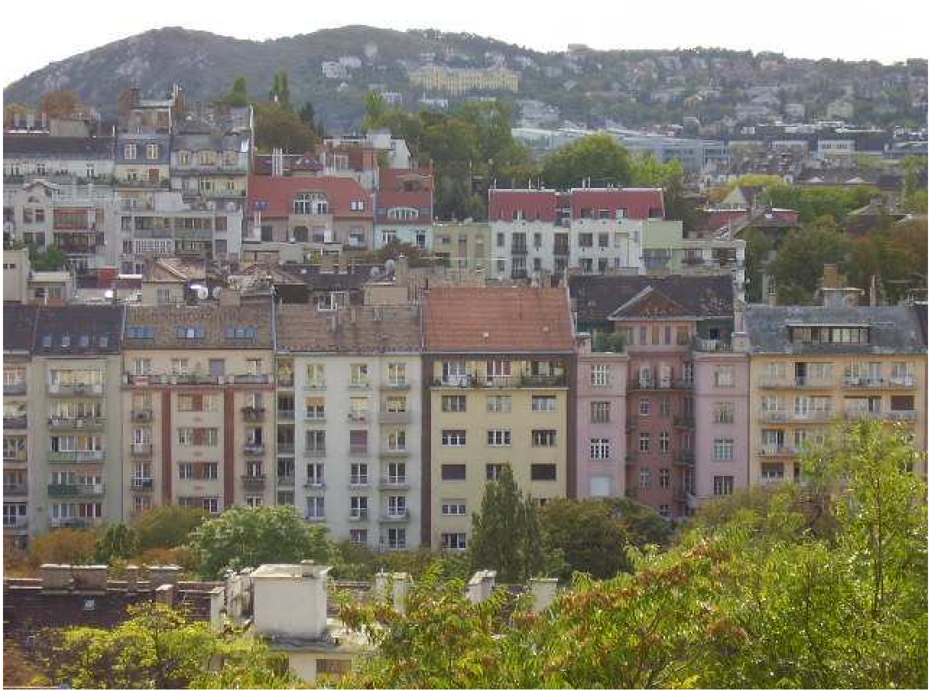

Illustration 4 Representative traditional multi-residential buildings (Budapest, Hungary)

The geometrical pattern of modelled traditional buildings is illustrated in Figure 17. It is assumed that a representative multi-residential traditional building has four floors and six flats per floor. An average floor area of a dwelling in a multi-residential traditional building is assumed to be 70 m^2 (KSH 2006b). This value was assumed as the heated area of households with centralized space heating (i.e. district, central building and central dwelling heating) and half this value was assumed for a premise heated household.

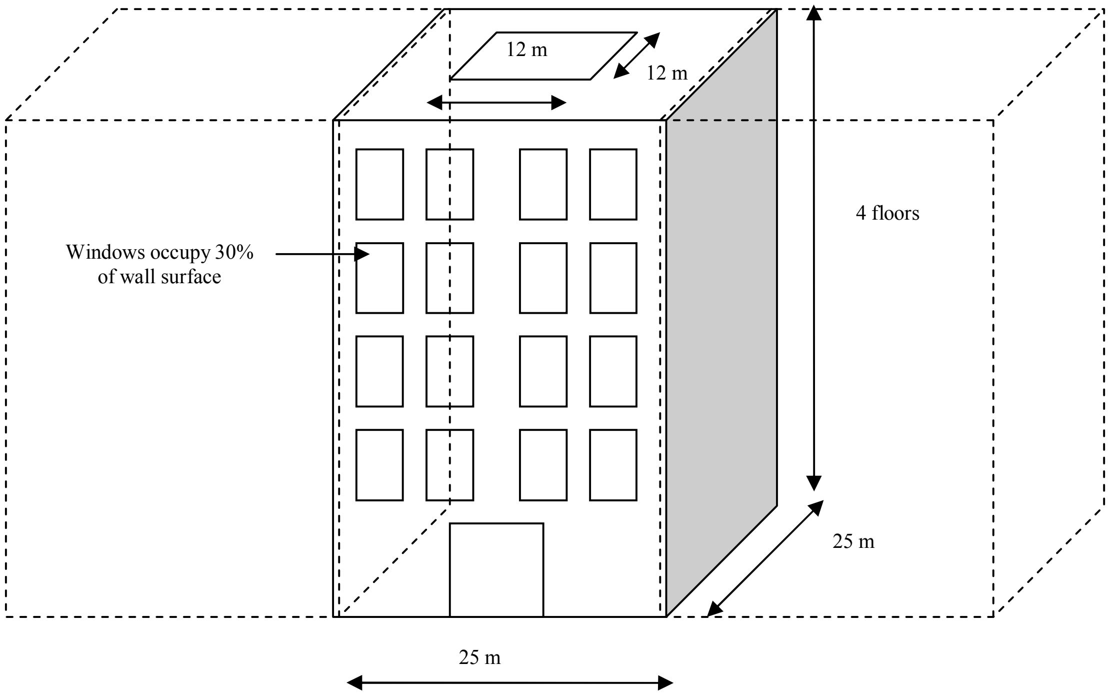

Figure 17 Pattern of a representative traditional building

Source: assumed based on observation of the Hungarian modelling stock, actual metering of selected representative dwellings, and the statistical publication (KSH 2006b).

5.2.2 Multi-residential buildings constructed using industrialized technology

The industrialized large panel and other concrete system building technologies were developed in Western Europe in the decades after World War II. Starting from the 1960s, they were applied to the majority of buildings in Europe and in the former Soviet Union. Western Europe quickly realized disadvantages of panel buildings whereas in the CEE and FSU regions such buildings were constructed until approximately 1990. The category of buildings constructed using industrialized technology comprises the so called “panel buildings”, but also those living-houses, which were constructed by other types of industrialized technology (e.g. block-, cast-, tunnel-shuttered-, ferro-concrete skeleton-houses). All these types of buildings are often referred to as "panel buildings" as they consist of about ¾ of the total industrialized buildings (Csoknyai 2005). The representative traditional multi-residential buildings are shown in Illustration 5.

Illustration 5 A building constructed using industrialized technology (Budapest, Hungary)

Panel-rehabilitation is one of the most acute questions of the CEE region because the expected lifetime of the holding structures is still around 50-100 years whereas the windows, building finishes and building service systems have reached the end of their physical lifetime (for instance the lifetime of windows, doors and insulation materials is typically about 30 years) (Csoknyai 2005). The panel buildings are criticized for their high heating energy consumption, uncontrollable heating systems, very poor thermal comfort especially in summer, low acoustic value, un-tight building envelope and physical building problems. Depreciation of panel buildings stock also causes social problems since the majority of inhabitants can only afford to live in flats with poor living conditions leading to the creation of “poverty islands” (Nagy 2007). This problem results in a vicious cycle as a growing concentration of low income people in deteriorated buildings will result in a lower ability to invest in renovation of their housing conditions. It is hardly possible to dissolve the concentration of poverty in such houses, therefore, it seems important to solve this problem before an exchange of inhabitants with the low income ones which have lower financial ability to retrofit the buildings they occupy.

This large stock of deteriorating panel buildings requires mass modernization. At the same time, the advantage of such buildings is that they can all undergo a complete, but very similar renovation of the building shell. In contrast to the traditional buildings, renovation of the industrialized buildings can embrace all building components. The example of the SOLANOVA project (Hermelink 2005; SOLANOVA 2007) shows that very significant energy savings are possible in panel buildings with significant co-benefits for their inhabitants. Zöld and Csoknyai (2005) highlight the importance of retrofitting the walls of panel buildings due to high thermal bridges between the joints of construction panels.

The building geometry of industrialized technology buildings is described in Figure 18. It is assumed that a representative building constructed using industrialized technology has three porches, five floors, and three flats per floor in a porch. An average floor area of a dwelling in a building constructed using industrialized technology is assumed to be 53 m^2 (KSH 2006b)

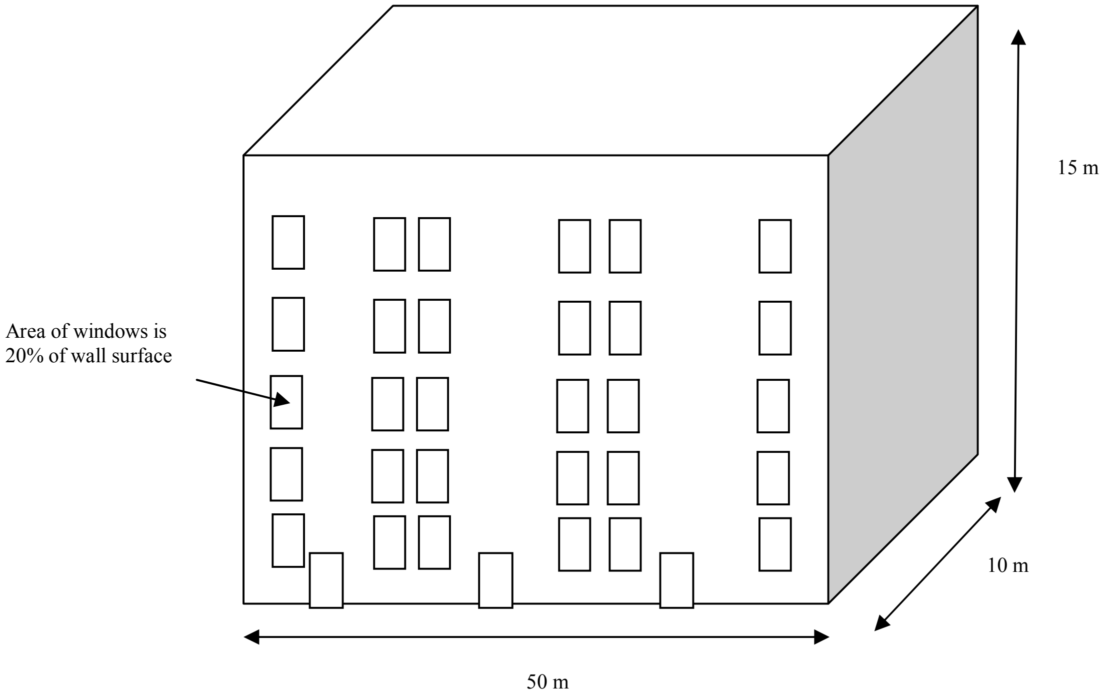

Figure 18 Pattern of a representative building constructed using industrialized technology

Source: assumed based on observation of the Hungarian modelling stock, actual metering of selected representative dwellings, and the statistical publication (KSH 2006b).

5.2.3 Old single-family houses (constructed before 1992)

Single-family houses dominate in the Hungarian household sector representing about 70% of the total number (Várfalvi and Zöld 1994; KSH 2004, 2005, 2006a, 2006b). The main advantage of single-family houses for our study is that many types of measures are available for them (Kovacsics pers. comm.). The representative traditional multi-residential buildings are shown in Illustration 6.

Illustration 6 A representative single-family house (Gödölő, Hungary)

Due to the large cooling surface, the complex reconstruction or improvement of insulation levels of walls, roofs and basements are very attractive. The geometrical pattern of a typical old Hungarian single-family house (constructed before 1992) is illustrated in Figure 19. An average floor area (heated in case of dwelling heating) of an old single-family house is assumed to be 80 m^2 (based on calibration to national statistics in KSH 2006b). In the case of premise heating, the heated area is assumed to be half that i.e. 40 m^2.

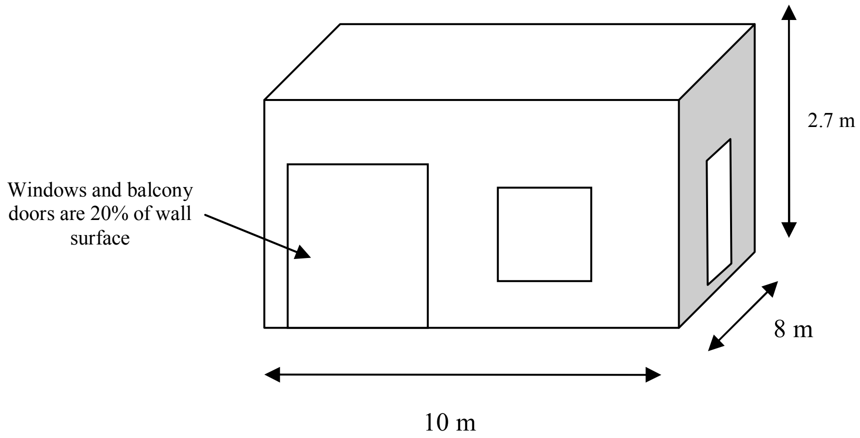

Figure 19 Pattern of an old (constructed before 1992) single-family house

Source: assumed based on observation of the Hungarian modelling stock, actual metering of selected representative dwellings, and the statistical publication (KSH 2006b).

5.2.4 Multi-residential and single-family buildings constructed during 1993 - 2007

The buildings constructed during the last fifteen years are already up to the more advanced standards. They are not the best in terms of performance, but extra insulation will not pay back as quickly as in other types of buildings. Systems are mostly either gas-fired or connected to central/district heating and not too much improvement is possible (Kovacsics pers. comm.). This is why improvement of the thermal envelope and heating efficiencies of single-family houses and multi-residential buildings constructed during 1993 – 2007 is not considered by the model and detailed consideration of patterns and characteristics of these buildings is out of the scope of the present research. For estimation of the baseline energy consumption of the residential buildings, it was assumed that the heated areas of a centrally-heated and premise-heated single-family houses were 105 m^2 (based on (KSH 2006b) and half less respectively. The heated area of households in multi-residential buildings (heated with the centralized systems) was assumed as 57 m^2 (KSH 2006b). The example of a modern multi-family building is shown in Illustration 7.

Illustration 7 A modern multi-family houses (Gödölő, Hungary)

5.2.5 Multi-residential buildings and single-family houses constructed after 2008

The new buildings will be designed according to the 2006 Building Code (unless revised), which is more advanced compared to the previous Building Standards, however, there are still significant opportunities for further heating requirement reduction. This opens the window for application of low (integrated) energy design to future homes (see Section 6.1.5, p. 104, for the description for this option). Among the building geometry characteristics, those important for modelling of the baseline energy consumption and associated emissions are the heated area of single-family houses and flats in multi-residential buildings which was assumed as 105 m2 and 57 m2 respectively (based on KSH 2006b).

5.3 Projection of the household stock by types of buildings

The projection of the household stock by types of buildings is based on such inputs as the estimated dynamics of the total household stock, the estimated construction and cessation rates of different types of buildings, and the information and statistics from such sources as Várfalvi and Zöld (1994), KSH (2006a, 2006b). The results are presented in Figure 20 below.

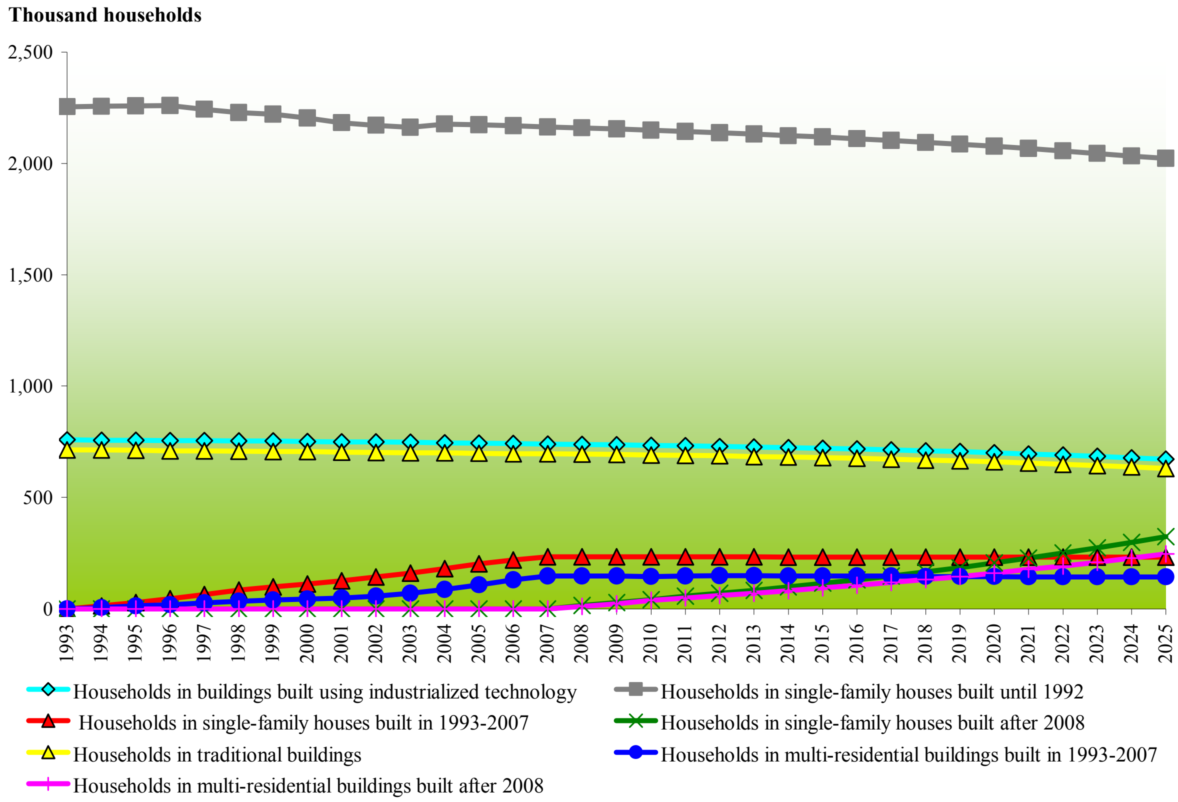

Figure 20 The projected household stock by building types

Source: research forecast based Table 5 (p. 75), Table 6 (p. 77), Várfalvi and Zöld (1994), KSH (2006a, 2006b).

5.4 Space heating split and related inefficiencies by building type

The projection of heating modes is constructed using reference to sources such as KSH (2004, 2005, 2006a, 2006b), GKM & KVVM (2007), Várfalvi and Zöld (1994), GFK (2004), and ODYSSEE NMS (2007). Below, the main assumptions behind the projections are detailed:

⇒ For industrialized buildings the main factor influencing the change of heating mode is the rate of building cessation.

⇒ For traditional buildings the dynamics of heating modes is determined by building cessation and by switch from premise gas heating to central dwelling heating. By 2025 premise gas heating will remain in c. 75% of households presently having this type of heating; a lower share is unlikely due to technical limitations, the size of dwellings, and high prices of dwelling central systems.

⇒ For old single-family houses (i.e. constructed before 1992) oil heating will be removed by 2008 (due to high oil prices), about half of presently installed premise gas, coal, and biomass systems will be replaced by central dwelling systems fired with the same fuel (i.e. no substitution among fuels). The factor of building cessation is also applicable to removal of old heating systems. It is assumed that new advanced systems are not installed in the reference scenario (advanced systems presenting in the stock are rather installed in new houses constructed during 1993 – 2007: from the beginning of 1990s, the new buildings were largely dominated by single-family houses constructed according to the individual design which is a luxury for an average income household. This leads to the assumption that new home owners may have financial resources to purchase new homes with advanced heating systems rather than owners of old houses).

⇒ The heating modes in buildings constructed from 2008 are projected based on the structure of presently installed heating solutions. Additionally, it is assumed that the growth of the number of pellet systems will be at least c. 10%/yr. and the growth of the number of solar thermal and pump systems will be about c. 5%/yr. for each type of these systems[38]. The increased number of all advanced heating systems is due to the newly constructed housing stock.

The remaining sections of the chapter provide details of the breakdown of space heating in each of the Hungarian building types and related inefficiencies, which will be further treated in Chapter 6 which is assessing the perspective efficiency and fuel switch options.

5.4.1 Multi-residential traditional buildings

A part of the traditional multi-residential buildings is connected to district heat and district hot water (Várfalvi and Zöld 1994; KSH 2004, 2005, 2006a, 2006b). This is why one of the major options is reduction of space and water heating demand through controls. Many of these buildings are located in urban areas and fuel switch is often not possible due to the necessity to transport and store such fuels as biomass. For a small share of buildings having a centralized natural gas boiler, installation of condensing boilers is feasible. However, more than half of these buildings still have premise heating limited to one or two rooms (Várfalvi and Zöld 1994; KSH

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[38] The assumed growth rates are based on the following consideration. The market review of solar heating (Weiss *et al*. 2007) estimated the growth rate of the technology penetration in Hungary as c. 5%/yr. before 2004 and this figure was also assumed until 2025 (from c. 6 to 15 thousand households over 2008 - 2025). The heating pumps have a comparable penetration rate to solar heating in Hungary and similar investment costs; and due to these reasons, it was assumed that the heating pump penetration will grow with the same rate as the solar heating, 5%/yr. (from c. 4 in 2008 to 10 thousand households in 2025). Pellet heating is a new technology in Hungary (only 2-3 years old) but it already accounts for a share of the heating solution stock twice as large than heating pumps; the stock of pellet heaters is assumed to grow at c. 10%/yr. (from c. 8 to 50 thousand households in the period 2008 - 2025).

2004, 2005, 2006a, 2006b). For these households, more efficient centralized dwelling heating systems would be an alternative (which, however, will result also in some increase of heating energy demand due to a larger heated area). The projected split of heating modes in households of traditional buildings is presented in Figure 21 .

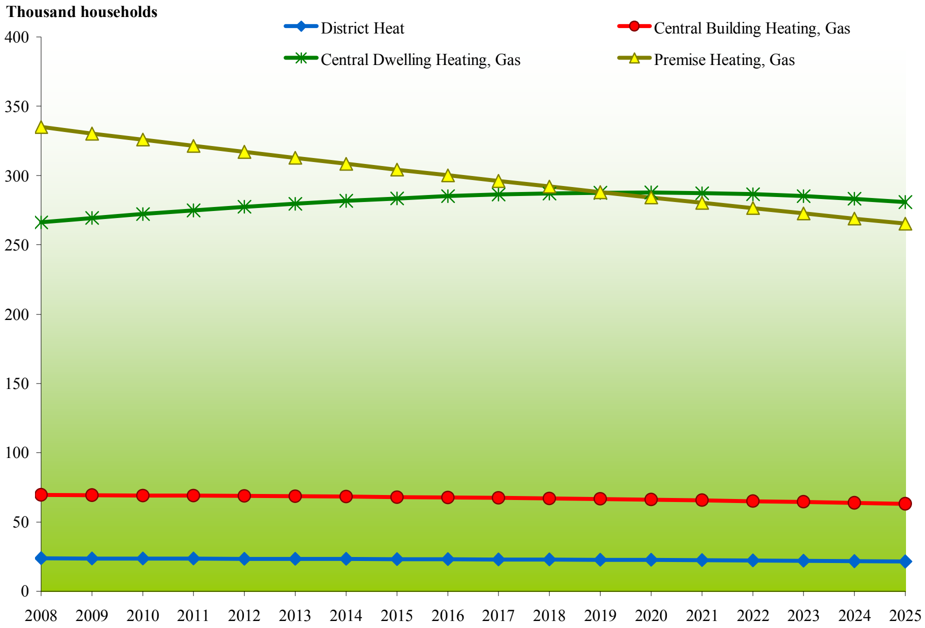

Figure 21 Space heating modes in households of the traditional buildings

Source: research forecast.

5.4.2 Buildings constructed using industrialized technology

Similar to traditional buildings, the majority of industrialized buildings are connected to district heat and district hot water while the rest of the buildings are connected to central building boilers (Várfalvi and Zöld 1994; KSH 2004, 2005, 2006a, 2006b). This is why retrofit options of the panel buildings are similar to those identified for traditional buildings, i.e. reduction of space and water heating demand with installation of controls and individual meters, and installation of more efficient centralized building boilers. The projected number of households in the panel buildings heated with different heating solutions is presented in Figure 22 .

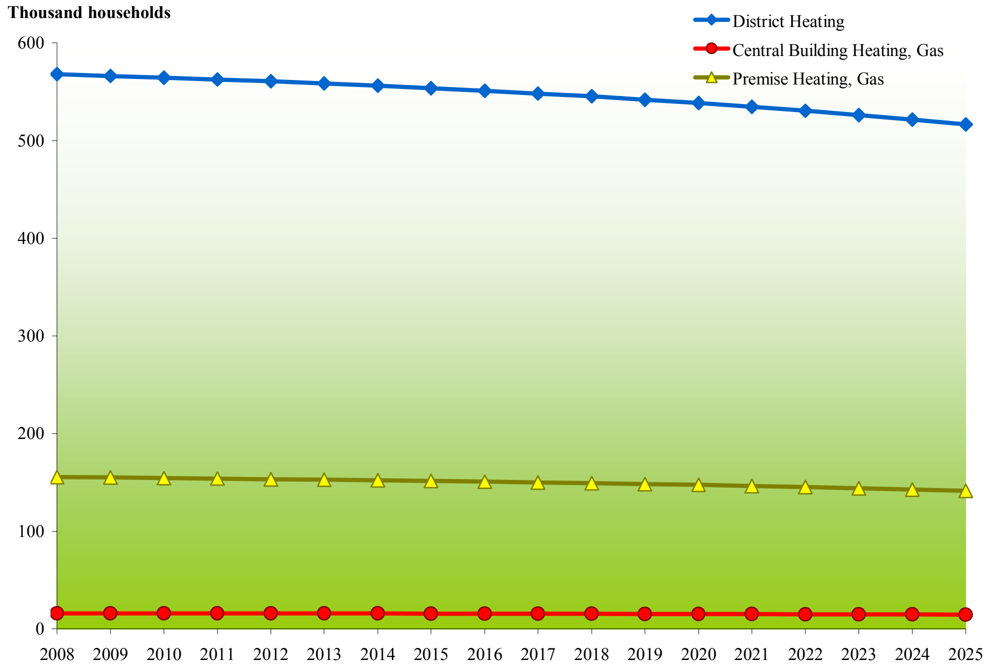

Figure 22 Space heating modes in households of the industrialized buildings

Source: research forecast.

5.4.3 Old single-family houses

The majority of single-family houses are located out of the city centres and there is no limitation of transportation and storage of fuels. Thus, a switch to biomass, for which the transportation and storage factor is important, is very attractive for these types of buildings. This option is especially important for climate mitigation policies if it is a complement for the solar thermal space and water heating systems. Since single-family houses usually have some space around their house, installation of ground, water, geothermal, or air pumps for space and water heating is also feasible. If both options are not welcome by households for any reasons, the vast majority of households, 94%[39] (KSH 2004), are gas-connected and therefore installation of high efficiency (condensing) gas boilers is almost always possible for them. Especially, substitution of highly polluting coal premise and central dwelling heating systems is important. The projected number of single-family houses heated with different heating solutions is presented in Figure 23 .

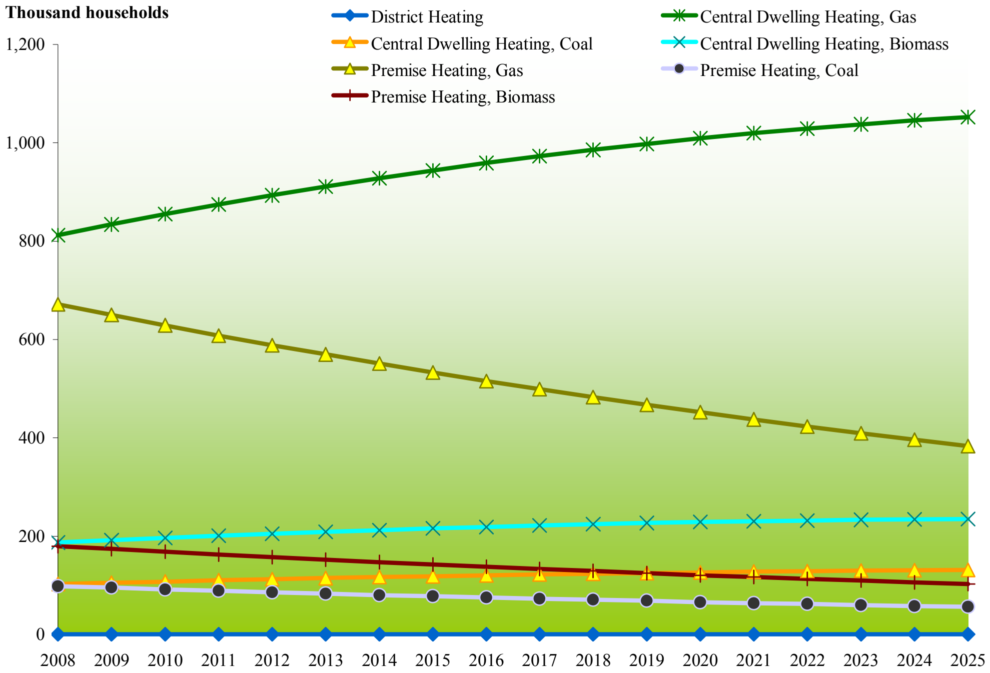

Figure 23 Space heating modes in old single-family houses

Source: research forecast.

5.4.4 Multi-residential and single-family buildings constructed during 1993 - 2007

As Section 5.2.4 (p. 87) described, the buildings constructed during the last 15 years are already up to the more advanced standards and extra insulation and advanced heating solutions will not

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[39] As of 2004.

pay back as quickly as in other types of buildings. Due to this reason, the assumed number of single-family houses heated with different heating solutions is assumed based on 2005 data as not changing during the projection period (the statistics for this year is from KSH 2006b).

5.4.5 New single-family houses and multi-residential buildings

The projected split of heating modes in the buildings constructed in 2008 – 2025 is presented in Figure 24 . The projections are made based on the heating mode spilt of the buildings constructed in 2005 (KSH 2006b).

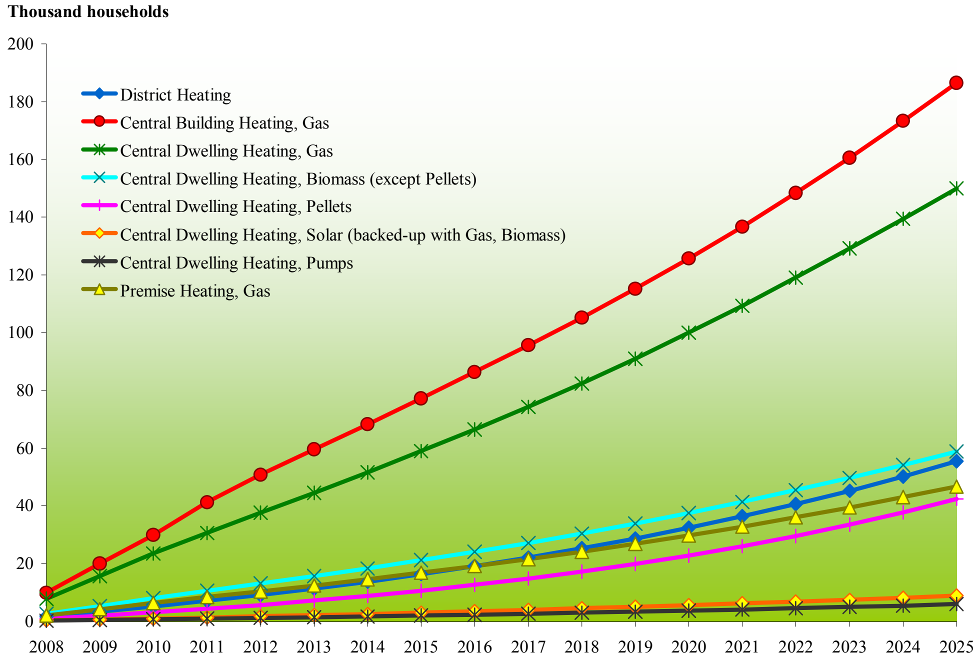

Figure 24 Space heating modes of households in new buildings

Source: research forecast.

5.5 Projection of water heating split of households

The projection of the stock of dedicated water heating appliances, water heating appliances linked to space heating systems, and the number of households with district and central building hot water is constructed based on KSH (2006a), Kemna *et al*. (2007), and the projection of combined space and water heating systems is described in sections 5.2 (p. 79) and 6.2 (p. 105). The projected stock is presented in Figure 25 and Figure 26 for the top three water heating options (in terms of the number of water heating appliances) and the rest of the water heating options respectively.

Hungary has a long tradition for using electric and gas storage[40] boilers produced by domestic companies. The share of primary electric instantaneous[41] water heaters (usually imported) is not significant; however, there is a small share of secondary instantaneous gas water heaters. As Figure 25 and Figure 26 show, it is expected that households will prefer to install combined space and water heating systems and the stock of these systems will be replacing the dedicated water heating appliances. Due to this trend, supplementary secondary water heating will not be needed by households. The projections are in line with the overall European trends which show decreasing sales of electric storage water heaters and gas instantaneous and storage water heaters and growing sales of combined systems for space and water heating (SAVE 2001a).

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[40] A storage water heater is a water tank which keeps a constant temperature by the burner which starts when the temperature in the tank becomes lower than the temperature required by the thermostat (MEEPH – Monitoring 2007).

[41] An instantaneous water heater is a water heater which starts the burner to heat the water when the user opens the tap (MEEPH – Monitoring 2007).

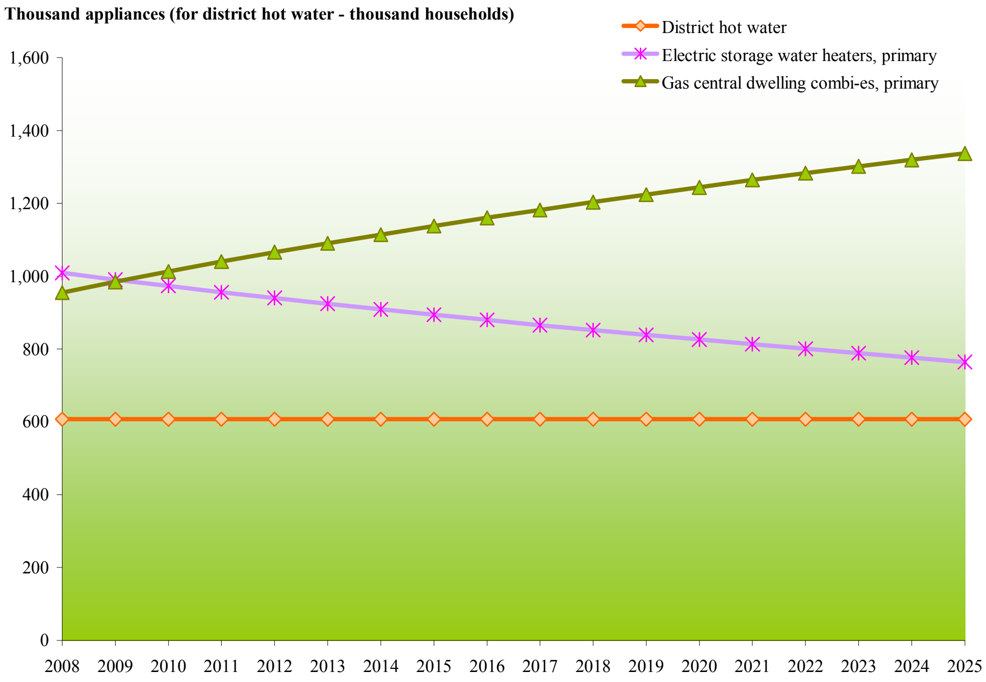

Figure 25 Water heating solutions – the number of systems, top three

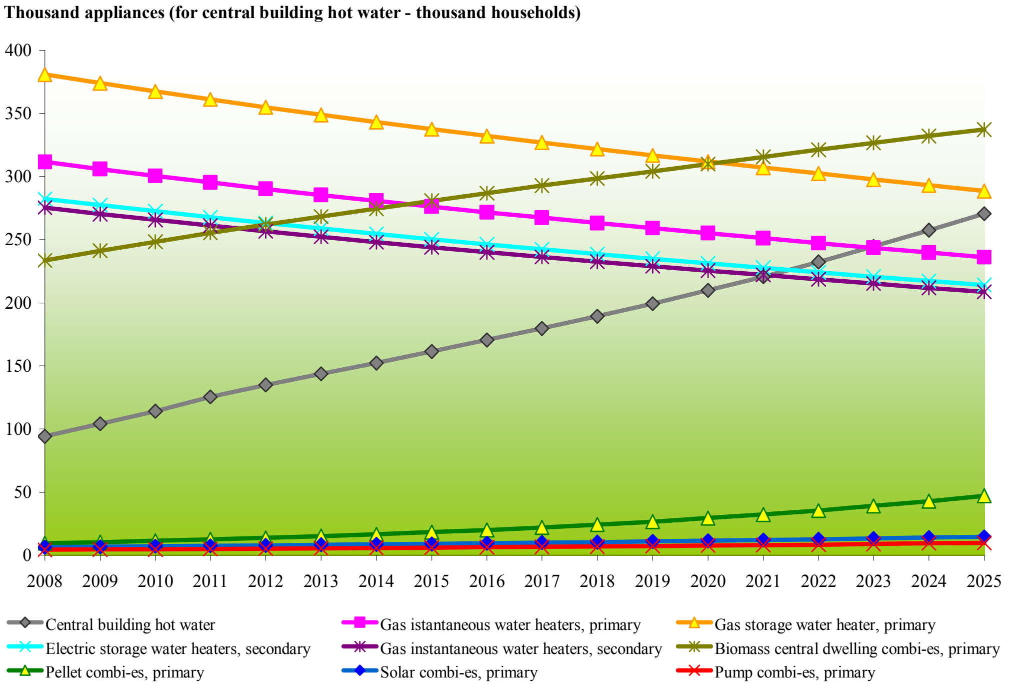

Figure 26 Water heating solutions – the number of systems, excluding top three

Source: research forecast.

Chapter 6 TECHNOLOGICAL OPTIONS CONSIDERED IN THE REFERENCE AND MITIGATION SCENARIOS

Levine *et al*. (2007) concluded that the key energy and CO_2 efficiency strategy for buildings is above all found by, reducing energy loads and selecting systems with the most effective use of ambient energy sources and heat sinks, followed by using efficient equipment and effective controls. The present research adopts these principles and starts the analysis of CO_2 mitigation opportunities by considering options to minimize the demand for space heating through thermal insulation. Subsequently, the renewable energy sources for space and water heating are assessed. The higher efficiency space and water heating solutions using conventional fuels and space heating and water flow controls concludes the discussion on thermal modernization. The review of electric efficiency options ends the assessment of opportunities to save energy.

6.1 Options aimed at improving the thermal envelope

The thermal envelope refers to the shell of the building as a barrier to the loss of interior heat (Harvey 2006). Insulation of the thermal envelope which refers to walls, windows, doors, roofs, and basements, can significantly reduce the energy demand for space heating.

6.1.1 External wall insulation

Petersdorff *et al*. (2005) describe the main insulation techniques applied in the CEE region, the thermal properties of insulation materials, and the investment costs associated with the application of thermal insulation. These data are complemented and revised based on the national literature (Csoknyai 2004; Szalay 2007) and personal communications with Hungarian experts (Csoknyai and Szalay pers. comm.).

According to Petersdorff *et al*. (2005), the most common method for external insulation in the CEE region is the attachment of the insulation material to the outer surface of external walls. This is typically done by attaching the insulation material to the wall and coating by a final layer. The capital and installation costs of insulation options are estimated as the average prices representing a mix of the most representative insulation materials usually used in retrofit projects in the CEE region (this statement also refers to cellar/basement and rooftop insulation). The main assumptions for technical and financial analysis of wall insulation are presented in Table 7 .

Table 7 Technical and financial parameters of external wall insulation

Types of dwellings	**U-values[42] before retrofit**	**U-values after retrofit**	**Investment costs**
	W/m^2K	W/m^2K	EUR/m^2 of insulated area
Old single-family houses (constructed before 1992)	1.25	0.35	37
Industrialized buildings	2.00	0.35	51
Traditional buildings	Not assessed	Not assessed	Not assessed

Source: estimated based on Csoknyai (2004, 2005), Csoknyai and Szalay (pers. comm.); Várfalvi and Zöld (1994), and Petersdorff *et al*. (2005).

6.1.2 Cellar/ground floor insulation

The method of insulating the ground floor depends on whether a building/house has a cellar. In buildings with a cellar, the insulation can be applied under the cellar ceiling or, with more complex technical implications, on top of the ground floor. The main assumptions for technical and financial analysis of this measure are presented in Table 8 .

Table 8 Technical and financial parameters of cellar surface insulation

Types of dwellings	**U-values before retrofit**[43]	**U-values after retrofit**	**Investment costs**
	W/m^2K	W/m^2K	EUR/m^2 of insulated area
Old single-family houses (constructed before 1992)	0.66	0.23	18
Traditional buildings	0.66	0.23	18
Industrialized buildings	0.50	0.23	18

Source: estimated based on Csoknyai (2005), Szalay (2007), Csoknyai and Szalay (pers. comm.), Várfalvi and Zöld (1994), and Petersdorff *et al.* (2005).

6.1.3 Roof insulation

For the analysis of roof insulation in the buildings constructed using industrialized technology, it is assumed that the insulation is applied to the exterior surface of the roof and is covered by a waterproof layer. For traditional houses and single-family houses, it is assumed that the

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[42] The thermal transmittance coefficient.

[43] The transmission co-efficient of the cellar surface (both before and after insulation) is multiplied by 50% to adjust to the fact that the temperature of the ground under the house is higher than that of the air (based on Csoknyai and Szalay pers. comm.).

insulation is applied to the attic floor. The main assumptions for the technical and financial analysis of roof insulation are presented in Table 9 .

Table 9 Technical and financial parameters of roof insulation

Types of dwellings	U-values before retrofit[44]	U-values after retrofit	Investment costs
	W/m^{2}K	W/m^{2}K	EUR/m^2 of insulated area
Old single-family (houses constructed before 1992)	0.89	0.225	27
Traditional buildings	0.89	0.225	27
Industrialized buildings	0.77	0.23	41

Source: estimated based on Csoknyai (2005); Szalay (2007); Csoknyai and Szalay (pers. comm.); Várfalvi and Zöld (1994); Petersdorff *et al*. (2005).

6.1.4 Weather stripping and exchange of windows

The heat flow through a window depends on the conduction of heat through glass, the frame and spaces between panels, and also on the transmission of solar radiation, and other factors (Harvey 2006). The rate of exchange of air depends on the air-tightness of the envelope, especially the quality of windows and doors, and on driving forces such as wind, inside-outside temperature differences, and air pressure differences due to mechanical ventilation systems or warm/cool air distribution (Harvey 2006). Nowadays, a broad range of window technologies can save up to 65-75% of the heat loss of standard non-coated double-glazed windows (Levine *et al*. 2007). This

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[44] Typically, single-family houses and multi-residential traditional buildings have the attic roof, i.e. the unheated loft under the pitched roof and insulation on the horizontal floor. Due to this reason, the heat transmission coefficient is decreased by 10% to adjust to the fact that the unheated loft is warmer than the external air (based on Csoknyai and Szalay pers.comm.).

includes the use of multiple glazing layers, low-conductivity gases between glazing layers, low-emissivity coatings on one or more glazing surfaces, and use of framing materials with very low conductivity. If the financial resources of households are limited, there are cheap, easily applicable and available technologies which can help to reduce air infiltration significantly. They include, for instance, filling up leaks with foams or weather stripping of windows and doors.

Regarding heat transmission, windows installed in Hungary before 1990s are characterized by an average a U-value of 3.5 W/m^{2}K whereas the presently installed double-glazed windows have this value of 1.3-1.5 W/m^{2}K (Csoknyai 2005). Gas-filled windows with three layers of glass, with a heat transmission value as low as 0.9-1.0 W/m^{2}K are available on the Hungarian market (Duplo-Duplex 2007). Capital investments for a window exchange start at 100 EUR/m^2 for a typical window and go up to c. 160 EUR/m^2 for an advanced window (Duplo-Duplex 2007).

Gas-filled triple-glazed windows with a low-emissivity coating and a U-value lower 0.7 W/m^{2}K are also present on the Hungarian market with investment costs above 300 EUR/m^2 (Duplo-Duplex 2007). Such high installation costs are explained by the immature market for such windows; even though they have existed for more than a decade, their market must be stimulated to achieve the size at which the competition will decrease the product prices. For this reason, windows with a U-value of 0.95 W/m^{2}K (an average between 0.9 and 1.0 W/m^{2}K) are assumed for replacement at the present installation costs of 160 EUR/m^2 per window based on the figures cited in the previous paragraph. Also, it is assumed that these costs go down until the year 2025 by c. 20% as the window market will develop further bringing down the price of the current technologies. The technical and financial characteristics assumed for window exchange are described in Table 10 .

Table 10 Technical and financial parameters of window exchange

Types of dwellings	U-values		Air change rate		Investment costs	
	Before retrofit	After retrofit	Before retrofit	After retrofit	2008	2025
	W/m^2K	W/m^2K	Times/ hour	Times/ hour	EUR/m^2	% of initial costs
Old single-family houses	2.50	0.95	0.8	0.5	190	80%
Traditional buildings	2.50	0.95	0.9	0.5	190	80%
Industrialized buildings	2.50	0.95	1.0	0.5	190	80%

Source: estimated based on Csoknyai (2005); Csoknyai (pers. comm.); Várfalvi and Zöld (1994); Duplo-Duplex (2007).

As mentioned, a household can also implement easier and cheaper measures such as weather stripping of windows and doors. Weather stripping is not, however, a preferable option for multi-floor buildings. This is due to the buoyancy effect in these types of buildings if they do not have individual heat controls[45] (Zöld pers. comm.). For this reason, weather stripping is considered only in single-family houses. Other advantages of window exchange above weather stripping include the possibility to avoid air-conditioning in summer due to higher air-tightness of the thermal envelope. Still, weather stripping might be a valuable option for low income households; therefore it is covered by the research. The technical and financial characteristics assumed for weather stripping are described in Table 11.

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[45] Spontaneous ventilation is a function of the difference of outside and inside temperatures and the difference between outside and inside pressure especially due to wind. The Buoyancy effect explains the circulation of the air in the high buildings as a function of the building height and the indoor-outdoor temperature difference. Due to this effect, if the building is not tight and if the building dwellings which are mostly affected to the effect do not have individual heat controls to react, the additional heating load for central building heating could be up to 30-35%. Due to this reason, the determining factor for choosing the technological option is not only decreased air change rate but also the variation of air infiltration rates in space and time (Zöld pers. comm.).

Table 11 Technical and financial parameters of weather stripping of windows

Types of dwellings	Air change rate		Investment costs
	Before retrofit	After retrofit	
	Times/ hour	Times/ hour	EUR/m^2
Old single-family houses	0.8	80% of the initial value	3.0
Traditional buildings	Not assessed	Not assessed	Not assessed
Industrialized buildings	Not assessed	Not assessed	Not assessed

Source: estimated based on Baumann *et al.* (2006) and Csoknyai and Szalay (pers. comm.).

6.1.5 Passive energy design versus current building practice

Passive energy design principles aim to use at maximum the passive energy emitted by the sun, people and appliances. They can generate savings of up to 90% of conventional design (Barta 2006). The currently constructed dwellings the energy requirement is c. 100-110 kWh/m^2 (Kocsis and Beleczki per. com.). The passive energy design considers southern orientation, strong insulation of building components (U-value not higher than 0.15 W/m^{2}K) and windows with low-emissivity coating, reduced air leakage and other features. Despite the common belief that low energy houses are expensive, in reality they could cost not much more than the conventional design buildings. For instance, Trnka (2007) estimated that the construction costs of passive energy housing in Austria are only 8% higher than those of the conventional design buildings, even though the incremental costs could range from 0 to 337 EUR/m^2. Based on consultation with Hungarian building experts (Csoknyai and Szalay pers. comm.), it is assumed that the additional construction costs of passive energy buildings with space heating requirement of 15 kWh/m^2 are 16% of the current construction cost in 2008. The current construction costs are estimated based on the "Yearbook of housing statistics of Hungary" (KSH 2006b) and communication with experts (Kocsis and Beleczki 2007 per. com.) as c. 700 EUR/m^2.

Experience from other countries shows that once the market is matures the passive energy construction costs decrease significantly. For this reason, it is assumed that during the projection period these additional costs decrease to half, i.e. they are expected to be mature by 2025 at the level of the Austrian practice.

Illustration 8 The example of a passive energy house

Source: Bauland 2007.

6.2 Options targeted at space heating efficiency and fuel switch

A number of high efficiency and fuel switch options are available for space heating (see Figure 27). Envelope measures combined with optimization of passive solar heating opportunities and other efficiency options are able to reduce heating levels from 250-400 kWh/m2-yr. to less than 15 kWh/m2-yr. in existing buildings in the CEE region (Levine *et al*. 2007).

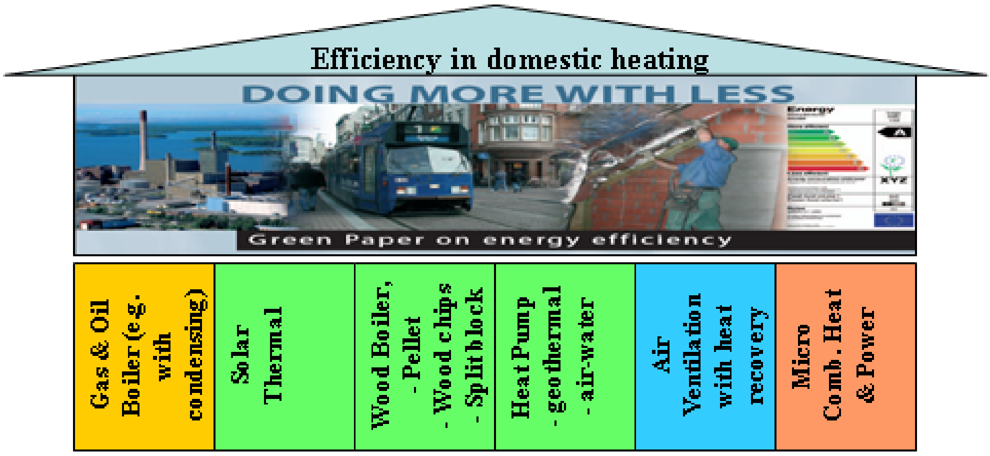

Figure 27 Technologies for efficiency improvement and fuel switch in domestic space and water heating

Source: Schild 2006.

In Hungary space heating is generally provided by district heating systems, central block (building) heating system, central dwelling and premise gas and coal heating. The current efficiencies for space heating systems[46] are estimated based on interviews with experts (Kovacsics pers. comm.; Csoknyai pers. comm.). These are 65% for premise and central dwelling non-gas conventional heating, 85% for premise and central dwelling gas heaters, and 80% for central building gas heaters. Efficiencies of all central and dwelling gas and biomass heating systems that are currently being installed (except district heating) are 85% (estimated based on Petersdorff *et al*. 2005; Mega-öko Kazánfejlesztő-gyártó Kft. 2007). Modelling of the reference efficiency of supplied district heat (at the building entrance) is described in Section 7.2.1.3 (p. 147. It increases from 78.2% in 2008 to 87.4% in 2025. The distribution losses of

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[46] The efficiency of heating solution included efficiency of heat production, distribution, and emission.

district and central heat inside the multi-residential buildings are estimated to decrease from 6.6% in 2008 to 5% in 2025 (Csoknyai 2004; Kovacsics pers. comm.).

Based on Mega-öko Kazánfejlesztő-gyártó Kft. (2007), DBO (2007), Petersdorff *et al.* (2005), Saunier Duval (2007), and Csoknyai and Szalay (pers. comm.) the investment costs of the heating solutions on the Hungarian market are estimated as:

⇒ c. 2450 EUR/system for a new standard gas dwelling central boiler,
⇒ c. 3100 EUR/system for a new gas-fired central dwelling boiler with instantaneous water heating,
⇒ c. 3850 EUR/system for a new biomass central dwelling boiler with storage water heating,
⇒ c. 2100 EUR/system for a new coal central dwelling boiler,
⇒ c. 15800 EUR/system for a new standard gas central boiler for multi-residential buildings.

In the case when a household switches from a direct heater or premise heating to central dwelling heating, additional costs for installation of radiators are estimated as c. 500 EUR/flat in multi-residential buildings and c. 700 EUR/house in single-family houses. The difference is due to the larger number of radiators in single-family houses as compared to flats in multi-residential buildings (Csoknyai pers. comm.).

The best strategy from a mitigation perspective is to maximize the use of heat supplied by renewable energy sources. Otherwise, high efficiency fossil technologies minimizing energy losses during production and distribution of heat could be used. Each of the advanced options has technical limitations on installation; however, for almost all types of household there is at least one advanced heating solution. Therefore, the discussion of advanced heating solutions starts with a description of renewable options.

6.2.1 Biomass for heating: pellets

Hungary has significant potential for biomass resources which can be utilized for heating purposes (ACCESS 2008). In the beginning of the 2000's the biomass-waste use for heating purposes jumped to c. 8% of the total final energy of the residential sector, however, it did not increase further (KSH 2006c). While considering the utilization of biomass, it should be highlighted that it is wiser to utilize biomass for heat rather than for electricity production (Kovacsics per. com.) since the efficiency of biomass burners for power production is about 30% while for heat production it is about 90%. The use of biomass for heat would save more gas for electricity production whose efficiency is at least 40% (Kovacsics per. comm.).

Biomass burners include burners fired with pellets, wood chips, woodcuts, corn, and with vegetable parts. Among these, agripellets from residuals of agricultural products can win a big niche in Hungary. Pellets from energy grass/crops are especially important because they can be a sound substitute for agricultural production. The potential for production of these two types of pellets is very significant (see Table 12). Some agripellets have a higher heating value and a lower price than those of woodpellets (DBO 2007). Another advantage of agripellet production is the possibility to produce the raw material for agripellets on an annual basis, while at least 15 years are needed for reproduction of a tree to produce woodpellets and woodcuts. Presently, woodpellets are not produced in Hungary. They are imported from factories located mainly in Transylvania, Slovakia, Poland and the Czech Republic and to a lesser extent in Austria and Italy.

However, there is a Hungarian firm that produces agripellets from a mixture of domestic raw material: straw, reed, and oily plants (DBO 2007).

Table 12 Biomass utilization potential and volumes in Hungary

N	Biomass type	Quantity of biomass, thousand tonnes/yr.	Energy potential, PJ/yr.
1	Straw	2400 – 2800	28 – 34
2	Corn-stalk	4000 – 5000	48 – 60
3	Crape-cane, fruiter scobs	350 – 400	5 – 6
4	Energy grass	500 – 600	6 – 7
5	Energy crops	1200 – 1800	25 – 30
6	Biogas substrat	8000 – 10000	7 – 9
7	Rape for biodiesel	220 – 250	3.5 – 3.8
8	Corn for bioethanol	2000 - 3000	24 – 27

Source: Gőrös (2005) in ACCESS (2007) .

Domestic pellet boilers were introduced in Austria in 1994 and have rapidly grown in popularity. Pellet burners appeared on the Hungarian market only two or three years ago (DBO 2007). The demand for them is growing, but it is constrained due to the high capital costs of burners. The price of a pellet burner capable of heating an average Hungarian single-family house (20-40W) ranges from c. 1500 EUR to 8000 EUR exclusive of VAT (DBO 2007). The costs of the additional equipment, a hot water-tank and the installation costs are not included in these prices. The high prices are due to the dominance of expensive imported equipment (mainly from Austria, Germany, Slovakia, Czech Republic, Poland and Italy) and low competition on the domestic market (DBO 2007). The Hungarian market has a great potential for production of pellet-burners, but more incentives and measures are needed to help the market grow.

One of the disadvantages of biomass for heat is the large storage need for biomass (2-7 tonnes for an average single-family house). In addition, it is difficult to transport biomass to central districts of cities due to heavy traffic and local air pollution issues. Therefore, biomass heat is difficult to use in multi-family buildings and single-family houses in the city centre area. The best prospective for renewable heat relates to the heating of single-family houses located outside of the city centres. Therefore, for modelling purposes it is assumed that only half of single-family houses can switch from the reference technologies to biomass heating by 2025.

Based on the review of the pellet market (DBO 2007) and the production catalogues (Szalontai and Sonnencraft 2007) the investment costs of pellet burners are estimated as c. 9550 EUR/system with an efficiency of 92%. Since the pellet boilers supply both space heating and hot water, the investment costs allocated to space heating are c. 8800 EUR/system (see Section 8.2.4, p. 165). Since the Hungarian market of pellet burners is not yet mature, in agreement with the local experts (Csoknyai and Szalay per. comm.) it is assumed that the investment costs go down to c. 70% of their initial amount in the target year 2025 in line with the development of the market.

6.2.2 Solar thermal energy

The use of solar collectors for space and water heating is a mature alternative to conventional technologies. The vast majority of installed solar systems in Hungary are "combi" systems producing hot water and space heating (Weiss *et al*. 2007). Solar systems sold in Hungary are designed to cover up to 80% of hot water demand and up to 30% of space heating demand of an average single-family house (see catalogues of Szalontai and Sonnencraft 2007). For this reason, a solar combi- system needs a conventional back-up system (a fossil-fuel boiler, a heat pump, or a wood boiler) which covers the rest of the heating requirement. Biomass heating systems can provide a zero carbon complement to solar heating systems.

Similar to biomass for heating purposes, it is assumed that only half of all single-family houses can switch from the reference technologies to solar heating, backed-up with pellet boilers by 2025. The capital and installation costs of a solar system including the back-up pellet system is estimated as c. EUR 16300 (Szalontai and Sonnencraft 2007). The efficiency of a pellet system is 92% while for solar it is 100% (i.e. no heat production and distribution losses). Since the solar systems supply both space heating and hot water, the investment costs allocated to space heating are estimated as c. 15 000 EUR /system (see Section 8.2.4, p. 165). The majority of renewable heating technologies are imported to Hungary and, therefore, presently the investment costs for solar thermal technologies combined with a pellet burner are high. In agreement with the local experts (Csoknyai and Szalay per. comm.) it is assumed that the investment costs go down to c. 70% of their initial amount in the target year 2025 along with the market development and the likely growth in the number of domestic equipment producers.

6.2.3 Heating pumps

Heat pumps can turn the direction of flow of heat from a lower to a higher temperature using a relatively small amount of energy. Electric heat pumps for heating buildings can supply 100 kWh of heat with c. 20-40 kWh of electricity (EURELECTRIC 2004). The heat sources can be the air, ground or water, as well as industrial or domestic wastes. Adam (2007) highlights there is significant potential to install geothermal heat pumps in Hungary. Theoretically, heat pumps can be installed in any building, but practically, there are some technical constrains such as a possibility to drill the ground near the building and space needed for the loop for ground- or water-source pumps and others. This is why a heating pump is a good opportunity for single-family houses, but probably not for multi-residential buildings. Considering the above mentioned constraints, it was assumed that it is possible to install heating pumps in c. 50% of single-family houses.

The bad news, however, is that heat pumps are very expensive to install in Hungary. Almost all heat pump systems are imported, mainly from Germany. For this reason, this opportunity is very difficult to implement for an average Hungarian household. The average investment costs of ground-source heat pump were estimated as c. EUR 12900/system (EHPA 2007), of which c. EUR 11865/system are allocated to space heating (see Section 8.2.4, p. 165). Still, the research is optimistic assuming that the capital costs of heating pumps decrease with time although the labour costs (installation of a heating pump requires significant expert assistance) might increase due to an overall salary growth in the country. For this reason, it is assumed that the investment costs for heating pumps decrease by 2025 to 80% of their initial amount in 2008. The coefficient of performance (the ratio of the heat produced to supplied work) is 5.0 (Ragwitz *et al.* 2005).

6.2.4 Condensing gas boilers

Achieving efficiency of gas boilers and gas furnaces for space heating higher than 88% requires a condensing operation (Harvey 2006). A condensing boiler is designed in a way to recover more waste heat, particularly the heat from water vapour produced during the combustion of fossil fuels. Despite their evident advantages over standard gas boilers, condensing boilers have a very low share on the market of Central Europe (Petersdorff *et al.* 2005). Installation of gas-fired heating systems is the most popular solution in Hungary and, therefore, stimulating sales of high efficiency condensing boilers will contribute to improved overall heating efficiency and, thus, the reduction of CO_2 emissions.

For the purposes of this research, two types of condensing gas boilers were considered. First, condensing boilers were suggested to substitute standard gas boilers for central building heating in multi-residential traditional and industrialized buildings according to the equipment stock turnover rate. Second, condensing boilers were proposed as an alternative for standard gas boilers for dwelling central heating in traditional buildings and single-family houses.

According to Petersdorff *et al.* (2005), the investment costs of a condensing central building boiler for space heating with efficiency of 97% were estimated as c.19000 EUR/system. Additionally c. 500 EUR/household were allocated for installation of larger radiators[47] (Csoknyai per. comm.). Based on production catalogues (Saunier Duval 2007) the investment costs of a 97%-efficiency condensing gas boiler for central dwelling heating in flats were estimated as c. 3000 EUR/system, additionally 500 EUR/flat is allocated for larger radiators (Csoknyai per. comm.).

Based on the same sources, the investment costs of a condensing gas boiler for central dwelling heating and for instantaneous water heating for a single-family house with 97% boiler efficiency are estimated as c. 3650 EUR/system, similarly c. 700 EUR/house is considered for the

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[47] Radiators connected to condensing gas boilers should be larger than those connected to conventional gas boilers because the temperature of circulated water in condensing system is lower.

installation of radiators. About c.3350 EUR/house is estimated for space heating and the rest for water heating (see section 8.2.4).

6.3 Control and metering of space heating

Harvey (2006) estimated that improved controls could reduce energy costs by over 20% for space heating. With regards to the CEE region in particular, Živkovi *et al.* (2006) described an experiment where heat flow meters and space heating controls were installed in Serbian standard panel buildings connected to district heat. The households of these buildings paid the same fixed tariff for space heating (based on the flat size) before and after installation of heat meters and controls. They were not stimulated financially and only adjusted the heating loads according to their comfort levels. Even though the buildings had relatively good insulation levels (U-values of 0.7-0.9 W/m^{2}K), the experiment showed a reduction in demand for heating energy of 10.5% - 15% depending on the building and the heating season.

6.3.1 Individual heat metering

The household stock connected to district heating is the largest consumer of heat in Hungary (see Figure 28 below). This is not only due to the high energy heating requirement of the buildings constructed using industrialized technology (which constitute the largest share of buildings connected to district heat) but also due to a lack of any possibility to regulate the desired heating levels, and the lack of possibility to pay according to the actual heat consumed[48].

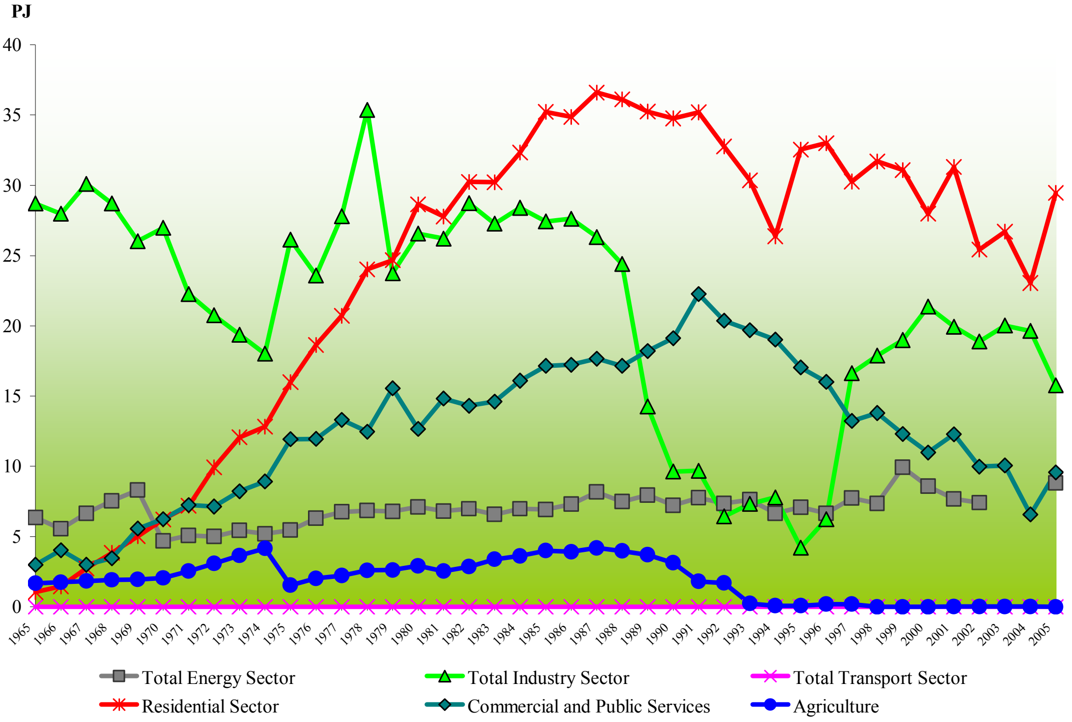

Figure 28 Dynamics of heat consumption in Hungary, 1965 – 2004 yr.

Source: constructed on the basis of IEA (2004, 2006a, 2007).

Installation of separate heat exchangers and heat meters in individual flats allows households to regulate their heat consumption according to the comfort level and according to their ability to pay. This is quite an expensive option which requires rearrangement of the hot water pipe system within the building, and the installation of some new pipes, individual heat exchangers and heat meters. Based on an interview with experts ('Sigmond per. comm.), the estimated useful energy

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[48] Typically, the heat consumed by a multi-residential building is metered at the entrance of the building and associated costs are distributed among households according to dwelling floor area. Half of the costs of district heat consumed by the building are fixed (capacity costs) and half of them vary depending on the heat consumption of a building (Sigmond pers. comm.).

savings could be as high as 20% whereas the total investments are up to c. 2000 EUR/household. The estimate of useful energy demand savings is based on consideration of the typical inhabitants of district heated flats. These are usually young families for whom the purchase of a flat in prefabricated building is an affordable option or elderly people who received such flats some 20-30 years ago. In both cases, households relate to the low or middle income class and are therefore concerned to economize on energy costs. In the first case, it is likely that young people leave their homes to work for at least eight hours and can switch off space heating for this period of time. This would save c. 30% of consumed energy for heating. Elderly people are mostly at home and, moreover, they request a higher heating temperature due to their physical preferences. They are very interested to save energy due to the high related costs for them, but probably would only be able to regulate the heating load to some extent, presumably by 10%. The average figure between the estimates of energy savings made for these two prevailing types of households is 20% of useful energy demand.

6.3.2 Programmable room thermostats

The installation of programmable room thermostats helps to keep the room temperature at set levels, for instance with lower and higher temperatures depending on the occupancy and life style of a household. Typically, a room thermostat is installed in the most representative room of the houses (Kovacsics per. comm.). In households where all family members are working, it is reasonable to lower space heating from 9 a.m. – 6 p.m. and to set the thermostat, for instance, to 18 °C from 11 p.m. – 6 a.m. The Project MEEPH – Monitoring (2007) estimates that a 1°C lowering of the overall room temperature enables a saving of 5% or more of the energy for heating.

For modelling purposes, it was assumed that the total capital and installation costs of a programmable thermostat are about c. 140 EUR/household (based on Saunier Duval catalogue 2007). The useful energy savings of thermostats are estimated as 5% of the total energy requirement for space heating based on the information provided by the website of MEEPH – Monitoring (2007).

6.3.3 Thermostatic radiator valves

While installation of room thermostats was modelled as the most suitable control option for dwelling heating systems, installation of thermostatic radiator valves (TRVs) is considered to be the convenient solution for controlling consumed heat supplied by district heating system or by central building (block) heating system. The TRVs regulate the heat flow through radiators and allow households to regulate the desired heating levels in different rooms.

The energy savings from installation of TRVs are estimated as 10% of the total energy requirement for heating, based on the experiment conducted by Živkovi *et al.* (2006) and described above (Section 6.3, p. 114). The similarity between the measures used in this experiment and installation of the TRVs is that both share the possibility to adjust dwelling heat loads in different rooms according to comfort feelings without the possibility of influencing the energy costs.

It is also assumed that installation of TRVs on c. five radiators per flat (an average estimated number) would cost c. 100 EUR/household if it can be realized without installation of bypass pipes into the radiator networks (possible in c. 50% of flats). It is estimated as twice this amount if dwellings need bypass lines (the remaining 50% of flats). The necessity of installing additional bypass lines is illustrated in Figure 29 below. According to a common design in many Hungarian multi-residential buildings, hot water is circulated through radiators installed sequentially (from the highest building floor to the lowest). Installation of TRVs which stop unwanted heat flow through a household will result also in stopping the flow of heat to subsequent households. The cost estimates are based on production catalogues (Megatherm 2007; Danfoss 2007) and personal interviews (‘Sigmond pers. comm.; Kovacsics pers. comm.).

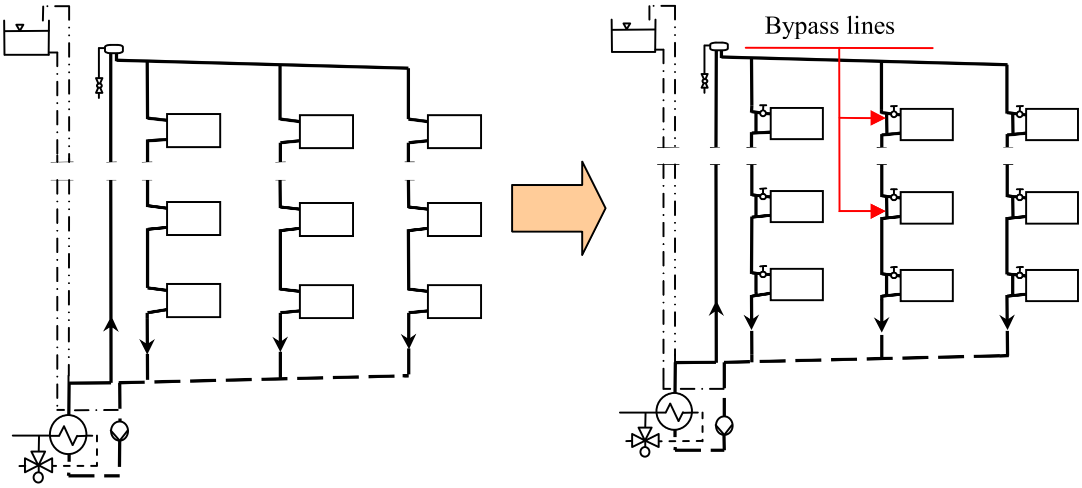

Figure 29 A hot water distribution system[49] before and after installation of TRVs

Source: Courtesy of ‘Sigmond (pers. comm.).

6.4 Options for emission mitigation in domestic water heating

After space heating, domestic water heating is the second largest energy consuming end-use in the residential sector. Water heating is characterized by lower efficiencies than space heating and

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[49] Scheme of a series-loop one-pipe down-feed hot water distribution system.

provides significant potential for energy savings. Typically, primary energy spent for production and supply of hot water for an average three person household is c. 3 to 5 times the actual energy content of the hot water consumed by household members (SAVE 2001a). These losses result from the water heating appliance/system, the distribution system, the type of faucets and other sources. SAVE (2001a) estimated that the economical and technical potential for domestic water heating appliances is in the range of c. 20%-35% taking into account the efficiency options with a pay-back period of less than 10 years, whereas the technical potential is about 50%.

There is a wide range of water heating and water saving technologies on the Hungarian market. The individual options considered for CO_2 reduction through water heating include an exchange of combined space and water heating systems with advanced combined space and water systems as described in Section 6.2 (p. 105), an exchange of dedicated water heaters with dedicated water heaters of higher efficiency, and the installation of water saving fixtures on the shower heads and sink facets.

6.4.1 Electric storage water boilers

An electric storage water heater is one of the most commonly installed solutions for water heating in Hungary. The overall system efficiency of the installed stock is estimated as 65% for both primary and secondary electric storage water heaters (Kemna *et al*. 2007).

Based on the Hungarian market data presented in Kemna *et al*. (2007) it is assumed that a typical primary electric boiler has a volume of 120 litres while a typical secondary boiler has a volume of 30 litres. Currently installed electric storage boilers are estimated as having heater efficiency of

100% and standing (on/off) losses of c. 548 kWh/yr. and c. 244 kWh/yr. for primary and secondary boilers respectively (estimate based on Kemna *et al*. 2007). For the mitigation case, it is assumed that households can switch to primary electric storage boilers of a lower volume, i.e. 80 litres. This volume is proposed based on the estimation that a household has on average 2.5 persons (EUROSTAT 2007) and an average person consumes 25litres/day, and therefore the daily household consumption of hot water is approximately 65 litres/day. The best available electric storage boilers on the market are of the same heater efficiency as of those purchased presently but with lower standby power losses of c. 288 kWh/yr. and c. 179 kWh/yr. for primary and secondary boilers respectively (estimate based on Kemna *et al*. 2007). The investment costs for primary and secondary boilers were estimated as c. 285 EUR (120 litres) and c. 155 EUR (30 litres) per appliance for the current practice and c. 245 EUR (80 litres) and c. 165 EUR (30 litres) per appliance for advanced technologies respectively (the estimates are based on the data adopted from Kemna *et al*. (2007)).

6.4.2 Gas storage and instantaneous water heaters

The overall system efficiency of the installed appliance stock was estimated as 55% for primary gas instantaneous water heaters, 45% for primary gas storage water heaters, and 50% for secondary gas instantaneous water heaters (Kemna *et al*. 2007). For gas-fired conventional and condensing storage boilers (the volume of both is 80 litres) the heater efficiencies are 85% and 97% and standing losses are c. 960 kWh/yr. and c. 471 kWh/yr. respectively (Kemna *et al*. 2007). The investment costs of conventional and condensing gas storage boilers are estimated as c. 440 and c. 595 EUR/system respectively (Kemna *et al*. 2007).

The efficiency of conventional gas-fired instantaneous water heaters purchased in the reference case is estimated as 78% against 97% for condensing water heaters in the mitigation case (based on Kemna *et al*. 2007). The investment costs are c. 355 EUR and c. 265 EUR for the primary and secondary reference instantaneous water heaters versus c. 520 EUR and c. 385 EUR for the condensing primary and secondary instantaneous water heaters (estimated based on Kemna *et al*. 2007).

6.4.3 Water heating linked to solar thermal, biomass boilers and heating pumps

The overall system efficiencies for water heating of the installed combined systems were estimated based on Kemna *et al*. (2007) as 50%-55% depending on whether it is a combined system or if water is heated in the indirect cylinder. The heater efficiencies of combined systems are described in the space heating Section 6.2 (p. 105). The additional standing and other energy losses of combined combi- boilers providing instantaneous water heating are c. 210 kWh/yr., whereas for systems with a storage tank (biomass boilers and solar thermal systems) they are c. 470 kWh/yr as estimated based on standing losses of similar hot water storages according to Kemna *et al*. (2007). For heating pumps the standing losses are estimated as 5% of energy input according to Kemna *et al*. (2007). The investment costs of combi- systems are described in Section 6.2 (p. 105) and, as detailed in Section 8.2.4 (p. 165), represent c. 13% of the total system investment costs.

6.4.4 Water saving fixtures

The same tasks and hygiene procedures can often be performed with a considerably smaller amount of hot water without sacrifice to comfort levels. Reducing hot water use for showering and washing by at least a factor of two is possible if efficient fixtures replace standard fixtures (Harvey 2006). According to Harvey (2006), installation of low-flow fixtures on showers would reduce water use from 10-20 litres/minute to 5-10 litres/minute, and on faucets such fixtures would reduce water use from 10-20 litres/minute to 2-8 litres/minute.

The author was unable to locate any experiments in the CEE region of water saving with saving fixtures and this is why the Canadian experience was used based on Harvey (2006). According to Harvey (2006), it was assumed that low-flow faucets and showerheads save about half of the water demand in households with district or central house water supply and in households with instantaneous water heating appliances. In storage water heaters, savings in hot water energy use are partially diluted because hot water is stored in tanks due to standby power losses (Harvey, 2006); for this reason it was assumed that water saving fixtures save about 25% of water in households with these appliances. Based on the product pricelist (ORIS Consulting 2007), the average investment cost of such a fixture is estimated as c. 30 EUR.

6.5 Electrical efficiency improvement of domestic appliances and lights

This section studies selected electric end-uses which have high penetration rates and consume large shares of the total electricity consumed by the residential sector. In contrast to thermal energy, it is expected that electricity consumption will rise due to the growing spending power of the Hungarian population, a growing demand for amenities, an increasingly busy lifestyle, the widening assortment of available appliances and other factors. A switch to higher efficiency appliances can enable CO_2 savings more quickly and easily than through the installation of many insulation and heating technologies. This is due to the fact that appliances are driven by electricity which has significant production and distribution losses. Also, such appliances have a shorter lifetime and therefore a higher exchange rate.

6.5.1 Efficient cold appliances (refrigerators and freezers)

Despite significant improvements in the past, the potential for efficiency improvement of cold appliances is far from exhausted and it is still believed to be one of the largest electricity saving opportunities. Bertoldi and Atanasiu (2007) estimated that there has already been a 27% net efficiency improvement of cold appliances sold after the introduction of minimum energy performance standards on the EU market compared with pre-labelling efficiency levels. This resulted in decreased electricity consumption of cold appliances from c. 450 kWh/year in 1990-92 to c. 264 kWh/year in 2005 in the EU-15. In addition to these savings, Bertoldi and Atanasiu (2007) surmise that the share of cost effective electricity savings of cold appliances may be at 40%-50% of the total existing potential in residential electricity consumption.

The average model sold in 2005 on the Hungarian market had an energy efficiency index[50] (EEI) of c. 0.62 for refrigerators and 0.80 for freezers (between A and B classes for both appliances),

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[50] For cold appliances the EEI was set at 102 for the average market model in 1992 (Bertoldi and Atanasiu 2007).

whereas the best models on the market were rated A++ with the EEI below 0.30 for both refrigerators and freezers (Bertoldi and Atanasiu 2007). The background document for the revision of the EU labelling and standardization program (ADEME 2000) estimates that the lowest technically achievable energy efficiency indices in the long term are 0.16 – 0.18 for refrigerators, 0.19 – 0.23 for refrigerator-freezers and 0.22 – 0.26 for freezers. These indices are set as potential targets for the mitigation scenario in 2025. The reference case EEI was estimated based on the scenario reported by ADEME (2000), which takes into account the EU labelling scheme, the minimum energy performance standard, and the fleet targets which are close to the present level[51]. Summaries of model input indicators for refrigerators and freezers are presented in Table 13 and Table 14 respectively.

Table 13 Technical and financial parameters of the stock of refrigerators in Hungary

Input parameters	Units	2008	2025	Sources and comments
Reference case EEI, sold appliances		0.59	0.40	Estimated based on Bertoldi and Atanasiu (2007), ADEME (2000)
Mitigation case EEI, sold appliances		0.38	0.17	Estimated based on Bertoldi and Atanasiu (2007), ADEME (2000)
Unit energy consumption (UEC) of the installed stock	kWh/yr.	366	366	REMODECE 2007
Reference scenario UEC, sold appliances	kWh/yr.	185	127	Estimated based on above indicators
Mitigation scenario UEC, sold appliances	kWh/yr.	120	54	Estimated based on above indicators
Price of the purchased appliance, reference case	EUR/piece	321	321	Estimated based on Bertoldi and Atanasiu (2007)
Price of the purchased appliance, mitigation case	EUR/piece	408	408	Estimated based on Bertoldi and Atanasiu (2007)

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[51] As of September 2007.

Table 14 Technical and financial parameters of the stock of freezers in Hungary

Input parameters	Units	2008	2025	Sources and comments
The reference case EEI, sold appliances		0.69	0.38	Estimated based on Bertoldi and Atanasiu (2007), ADEME (2000)
Mitigation case EEI, sold appliances		0.42	0.22	Estimated based on Bertoldi and Atanasiu (2007), ADEME (2000)
UEC of the installed stock	kWh/yr.	1075	1075	REMODECE 2007
The reference scenario UEC, sold appliances	kWh/yr.	297	161	Estimated based on above indicators
Mitigation scenario UEC, sold appliances	kWh/yr.	180	94	Estimated based on above indicators
Price of the purchased appliance, reference case	EUR/piece	318	318	Estimated based on Bertoldi and Atanasiu (2007)
Price of the purchased appliance, mitigation case	EUR/piece	403	403	Estimated based on Bertoldi and Atanasiu (2007)

6.5.2 Efficient clothes washing machines

For washing machines, the weighted average sold appliance had an EEI[52] of 0.24 kWh/kg (between classes A and B) in 2005 in Hungary (Bertoldi and Atanasiu 2007). The reference case EEI is estimated based on the scenario reported by the background document for the revision of the EU labelling programs and targets for washing machines SAVE (2001b), which takes into account the EU Labelling Directive and the CECED commitment on the fleet target as of 2004. With regards to the mitigation scenario, presently there is significant potential for efficiency improvement between the average model and the best model available on the market (A++). In the future, there is a large potential for electricity conservation from switching to lower washing temperatures due to better detergents and washing techniques. SAVE (2001b) estimates that the lowest technically achievable EEI in the long term is 0.085 for washing at 40°C. This was set as

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[52] For washing machines the EEI is expressed as the energy used per kg of washed cloths in a standard 60ºC cotton cycle (kWh/kg).

the potential target in 2025. A summary of estimated model input indicators for washing machines is presented in Table 15 .

Table 15 Technical and financial parameters of the stock of washing machines in Hungary

Input parameters	Units	2008	2025	Sources and comments
The reference scenario EEI, sold appliances	kWh/kg	0.20	0.19	Estimated based on Bertoldi and Atanasiu (2007), SAVE (2001b)
Mitigation scenario EEI, sold appliances	kWh/kg	0.16	0.09	Estimated based on Bertoldi and Atanasiu (2007), SAVE (2001b)
UEC installed stock	kWh/yr.	124	124	REMODECE (2007)
The reference scenario UEC, sold appliances	kWh/yr.	109	101	Estimated based on above indicators
Mitigation scenario UEC, sold appliances	kWh/yr.	84	46	Estimated based on above indicators
Price of the purchased appliance, reference case	EUR/piece	325	325	Estimated based on Bertoldi and Atanasiu (2007)
Price of the purchased appliance, mitigation case	EUR/piece	386	386	Estimated based on Bertoldi and Atanasiu (2007)

6.5.3 Efficient lighting

Lighting constituted 25% of the total residential electricity consumption in Hungary in 2004 (Bertoldi and Atanasiu 2007). The major trends of the growing lighting market are determined by larger houses and apartments, decorative aspects and fashion, among other factors (Slek 2004). The efficiency of the tungsten filament lamp in the form of visible light is about 5 % of the input energy; still, this technology is the most popular in Hungary. Incandescent lamps with halogen-gas-filling are 1.5 to 3 times more efficient than classic incandescent lamps and are also widely used in the Hungarian households. The compact fluorescent lamp (CFL) emits 28% of input energy in the form of visible light. Light-Emitting Diode (LED) lamps which produce more lumens per watt than any other known artificial lighting alternatives today have just appeared on the Hungarian market a couple of years ago, and as yet are not a commercially attractive technology in Hungary. Therefore, the best currently economically feasible lighting technology available on the Hungarian market is the CFL lamp. The most widely used incandescent lamp found is 60W (REMODECE 2007); it is typically well substituted with a 17W CFL. The capital investments in lights of these wattages were assumed as 0.7 EUR/incandescent lamp and 7 EUR/CFL. As EURELECTRIC (2004) reports there are still many ways to improve CFLs such as reducing the voltage distortion, improving the colour rendering, increasing the speed of start-up, reducing the sensitivity to the number of lightings, and improving other characteristics.

6.5.4 Low standby power consumption

There are several definitions of standby power consumption of electrical appliances in literature. In the present dissertation, the standby power definition is assumed as consumption of appliances and equipment in passive and off (often referred as low) power modes (LOPOMO). Based on the survey of ninety five households in Hungary, Valentova (2007) estimates their average LOPOMO power as c. 30W and the average LOPOMO electricity consumption as c. 236kWh/yr. This is 8% of the electricity consumption of Hungarian households on average.

Bertoldi and Atanasiu (2007) report that consumer electronic and information and communication equipment is the fastest growing electricity end-use in the residential sector and the largest standby power consumption is attributed to them. Due to the uncertainty with input parameters for the full range of LOPOMO consuming domestic appliances and equipment, this dissertation focuses only on the reduction of electricity consumption from standby power in personal computers and TVs as well as their related peripheries (listed in Table 16).

According to the methodology of the Ecostandy project (Fraunhofer IZM 2007), efficiency improvement of installed equipment stock in the reference scenario is assumed as 1%/yr. In the same publication, Fraunhofer IZM (2007) estimates the LOPOMO electricity consumption of selected appliances in the mitigation scenario and the related additional capital investments to produce the low LOPOMO appliances. The summary of the input parameters is presented in Table 16 .

Table 16 Modelling parameters of PC- and TV- related equipment in LOPOMO

Indicator/ Assumption	**Time in passive and off-mode**	**LOPOMO consumption of installed equipment, the reference case**		**LOPOMO consumption of new equipment, the mitigation scenario**		**Additional capital investment**
Units	**Hours/ day**	**Watt**		**Watt**		**EUR/piece**
Year		**2008**	**2025**	**2008**	**2025**	**2008-2025**
TV	18	6.3	5.3	1.0	1.0	1
VCR[53]	21	6.0	6.0			
DVD	19	3.3	2.8	1.0	1.0	1
Antenna/Satellite	23	6.0	5.0	3.0	1.0	3
Desktop	15	5.2	4.3	1.0	1.0	1
Monitor	18	1.5	1.3	1.0	1.0	1
Printer	20	3.7	3.1	1.0	1.0	1
Modem/router	22	5.3	4.4	3.0	1.0	3

Sources: research forecast based on REMODECE (2007) and Fraunhofer IZM (2007).

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[53] VCRs are not produced any more and are therefore not included in the mitigation scenario.

Chapter 7 PROJECTIONS OF BASELINE ENERGY CONSUPTION AND ASSOCIATED CO_2 EMISSIONS OF THE RESIDENTIAL SECTOR

The estimates of the potential available for CO_2 emissions mitigation is most useful if it is compared to a baseline scenario, i.e. the information on what would happen without special energy efficiency and climate mitigation policy interventions. There are different types of baselines considered by the analytical literature and discussed in detail in Section 3.3.5 (p. 46). As Section 4.1 explained, for the purposes of the research ***a reference scenario*** as close as possible close to the business-as-usual case is considered. Developing a baseline scenario that describes social and technological development over twenty years is one of the most challenging aspects of the mitigation analysis (Sathaye and Meyers 1995). The present section describes the main assumptions applied to develop the reference energy consumption and associated CO_2 emissions and results of the baseline modelling.

7.1 Assumptions concerning modelling of the reference technologies

When constructing the baseline scenario, it is of utmost importance to make careful assumptions regarding the growing (or decreasing) demand for energy services, technologies which satisfy these services, and penetration rates of these technologies. Overestimated baseline efficiency and fuel switch would yield lower baseline emissions and ultimately lower mitigation potential. Similarly, underestimated baseline efficiency would yield an overestimate of mitigation potential. Sections 7.1.1 - 7.1.2 below document in details the assumptions used.

7.1.1 Space and water heating

Theoretically, it is enough to heat a building only once if the heat loss is fully eliminated. In reality, heat is constantly lost due different factors; and a heating system has to supply heat to compensate this loss. The subsection below provides assumptions for the estimate of the space heating requirement based on this consideration.

7.1.1.1 Estimate of space heating requirement

The methodological Section 4.2.1 (p. 55) explained that the space heating requirement of a household is determined by the amount of energy required to compensate for heat loss due to its transmission and infiltration, and by the gains from solar heat, internal heat from human bodies, appliances, equipment and thermal mass gains. Due to the complicated calculation procedure of all these factors, the research estimates the approximate energy heating requirement based on two dominant parameters only; namely the energy required to compensate for heat loss due to its transmission and infiltration.

The amount of heat lost due to its transmission is usually defined through the thermal transmission co-efficient (the U-value) which shows how a building component transmits the heat. The U-values are either metered or estimated based on physical characteristics of building materials. There is a wide range of U-values for the same building types provided by the literature, however, there is no average value calculated on the national basis. For the purposes of the dissertation research, the U-values of building components of the main buildings types are assumed based on Várfalvi and Zöld (1994), Csoknyai and Szalay (pers.

comm.), Petersdorff *et al*. (2005), Csoknyai (2004, 2005), Harvey (2006). They are listed in Table 17 below.

The amount of heat lost due to infiltration is defined by the air change per hour rate (ACH). That is, the total volume of air in a home turned over in one hour. The level of air infiltration depends on the tightness of the building envelope. Air exchange rates of different types of buildings are estimated based on Baumann *et al*. (2006) and Csoknyai and Szalay (pers. comm.). They are provided in Table 17.

Table 17 Assumed present thermal characteristics of the thermal envelope

Building component	**Single-family houses constructed before 1992**	**Multi-residential traditional buildings**	**Buildings constructed using industrialized technology**
Heat transmission coefficients (U-values), W/m^{2}K			
External wall	1.25	1.00	2.00
Roof surface[54]	0.89	0.89	0.77
Cellar surface[55]	0.66	0.66	0.50
External windows	2.50	2.50	2.50
Door	2.60	2.60	2.60
Air infiltration rates (times of air change per hour)			
Air change per hour	0.8	0.9	1.0

Source: estimated based on Várfalvi and Zöld (1994), Baumann *et al*. (2006), Csoknyai and Szalay (pers. comm.), Petersdorff *et al*. (2005), Csoknyai (2004, 2005), Harvey (2006).

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[54] Typically, single-family houses and multi-residential traditional buildings have an attic roof, i.e. the unheated loft under the pitched roof and insulation on the horizontal floor. For this reason, the heat transmission coefficient is decreased by 10% to adjust to the fact that the unheated loft is warmer than the external air.

[55] The transmission co-efficient of the cellar surface is multiplied by 50% to adjust to the fact that the temperature of the ground under the house is higher than that of the air.

As Section 4.2.1 (p. 55) defined, the demand for space heating is characterized by the heating degree hours[56]. The current heating degree-hours are estimated, based on the climatic conditions during 1990-2004, as 70 kiloKelvin/day and are assumed by the model to be constant over the projection period 2008 - 2025. In reality, the heating degree hours are expected to go down due to the global warming effect. If this happens, the total costs of heating will drop along with the heating degree hours resulting in slower pay back of investments into thermal technologies and thus, a higher cost of avoided CO_2. However, more research is needed to identify this effect for Hungary and this is why the issue is left for future research

Based on the equations detailed in Section 4.2.1 (p. 55) and Table 17, it is possible to estimate the space heating requirement of households in multi-residential traditional buildings, buildings constructed using industrialized technology, and old single-family houses (constructed before 1992). The space heating requirement of households in buildings and houses constructed during the period 1993 – 2007 and new buildings are assumed based on Csoknyai (pers. comm.), Istvan Kovacsics (pers. comm.) and Kocsis and Beleczki (pers. comm.). The results of these calculations and assumptions are presented in Table 18.

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[56] The index of heating degree hours considered does not include the cooling need.

Table 18 Space heating requirement in different building types

Types of buildings	**Type of heating**	**Energy heating requirement, kWh/m^2**
Old single-family houses (constructed before 1992)	Central dwelling	230
	Premise	299
Households in traditional buildings	Central dwelling	180
	Premise	234
Households in buildings constructed using industrialized technology	Central dwelling	200
	Premise	260
Multi-residential buildings and single-family houses constructed during the last fifteen years	Central dwelling	125
	Premise	163
New multi-residential buildings and single-family houses	Central dwelling	105
	Premise	137

Source: research results based on Table 17 (p. 131) and assumptions based on Csoknyai (pers. comm.), Istvan Kovacsics (pers. comm.) and Kocsis and Beleczki (pers. comm.).

Note: the space heating requirement of premise heating is assumed as the space heating of central dwelling heating multiplied by a factor of 1.3. This is due to the fact that the space heating area of premise heating is c. half of that in the case of the central dwelling heating, whereas some heat is transferred from the heated rooms to the non-heated area.

7.1.1.2 Renovation of the thermal envelope and space heating solutions

Modelling the reference scenario for the thermal energy end-uses assumes that evolution of thermal technologies occurs quite slowly and that their characteristics in the future will be approximately those of today. Details of the reference thermal technologies such as efficiency levels and their costs are described in Sections 6.2 - 6.4 (p. 105). The present section outlines the assumptions about penetration rates of the reference thermal technologies and other related specific assumptions.

The reference scenario assumes that the retrofit of the thermal envelope is undertaken for multi-residential traditional buildings, multi-residential buildings constructed using industrialized technology, and old single-family houses (constructed before 1992). The reference rate of insulation of roofs, basements, and external walls, window exchange and weather stripping is assumed to be constant and on the level of that in 2003 – 2004, i.e. c. 1% of the household stock/yr. (based on KSH 2005). It should be noted that weather stripping is applied only to old single-family houses (constructed before 1992) due to the buoyancy effect (see Section 6.1.4, p. 101). Additionally, insulation of external walls is not applied to multi-residential traditional buildings due to the historic and aesthetic value of their exterior view and also because the thermal properties of walls in this type of buildings are relatively good (see Section 5.2.1, p. 80, and Table 17, p. 131). As detailed in Section 4.5.3 (p. 69) and Section 5.2.4 (p. 87), the improvement of the thermal envelope is not applied to the multi-residential and single-family buildings constructed during from 1993 to 2007. With regards to the household stock constructed from 2008 to 2025, it is assumed that this is constructed according to the present technology and is not renovated until 2025.

Technological and financial characteristics of the space heating solutions installed in the reference case are described at the beginning of Section 6.2 (p. 105). The forecast of the stock of space heating solutions is presented in Sections 5.4.1 - 5.4.5 (p. 91). The exchange of space heating solutions in the reference case occurs due to the expired lifetimes of these solutions (according to Table 19) according to the trends forecasted and presented in Sections 5.4.1 - 5.4.5 (p. 91).

Table 19 Lifetime of building components, household equipment and appliances

Equipment and materials	Lifespan
Insulation materials	30 years
Windows and doors	30 years
New constructed buildings	100 years
Space heating systems, combined space and water systems, dedicated water heating appliances	20 years
Heating controls and water savings fixtures	20 years
Refrigerators	20 years
Freezers	25 years
Washing machines	25 years
Television sets, video-recorders, antennas/satellites	10 years
Digital video disk players	9 years
Desktop, monitor, router	6 years
Printer	4 years
Incandescent lamps	1 000 hours
Compact fluorescent lamps	6 000 hours

Sources: Petersdorff *et al*. 2005; Ragwitz *et al*. 2005; Bertoldi 2005; Meli 2004; Fraunhofer IZM 2007; IEA 2006b.

With regards to space heating controls, it is common that they are already installed in relatively new homes with the newer heating systems available on the market; however these controls are not installed in dwellings of relatively old buildings. The reference scenario assumes zero penetration rates for heating controls and individual heat meters in relatively old buildings, i.e. traditional and industrialized buildings as well as single-family houses constructed before the 1990s.

7.1.1.3 Water heating energy requirement and renewal of water heating solutions

Based on Kemna *et al*. (2007), the demand for sanitary hot water in Hungary was estimated as 25 litres/person/day of 60°C water. The energy requirement to heat water to 60°C is 0.06 kWh/litre (Kemna *et al*. 2007). Based on these figures, the net energy demand for water heating is approximately 548 kWh/person per annum. Based on Kemna *et al*. (2007), it was estimated that if a household has two water heaters, the average water consumption from the secondary heater is about a third of the total water consumption. It is important to note that while this requirement is assumed to be constant per person, the hot water requirement for a household changes over time because the number of persons per households is decreasing.

In the reference case, the water heating technologies are exchanged if their lifetime expires (see Table 19) according to the forecast of the stock of water heating solutions modelled and described in Section 5.5 (p. 96). The reference scenario assumes that the retired technologies are either exchanged with solutions of the same class (for example, a retiring storage water boiler with a more efficient new storage water boiler) or with standard gas and biomass boilers for space and water heating.

With regards to water saving fixtures, it is assumed that they are not installed in the reference case. Although this important and simple option has been known about for many years (for instance, see the estimates in Szlavik *et al*. (1998)), it is not a very common retrofit measure for Hungarian households.

7.1.2 Exchange of main electric appliances and lights

The reference scenario models the turnover of main electrical appliances such as refrigerators, freezers, clothes washing machines. The principal difference in modelling the electrical and thermal technologies was that the technical characteristics of the electrical options change quicker than that of the thermal options. Thus, if the efficiency of standard space and water heating solutions was assumed as constant from 2008 to 2025, the efficiency of electrical appliances driven by the EU labelling and standardization programs was changing during the modelling period . With regards to the financial characteristics, it was assumed that the costs in real terms of the reference and the best available appliances do not change over time. In other words, the presently efficient appliances are becoming cheaper in the future and the newer, more efficient appliances are taking over their price. The details of the reference efficiency levels and costs of the main electrical appliances as opposed to their more advanced analogues are described in the Sections 6.5.1 - 6.5.4 (p. 123). The saturation rates of these appliances are presented in Table 20.

Table 20 Saturation rates[57] of the main electrical appliances, 2008 - 2025

Input parameters	2008	2025
Refrigerators	96%	107%
Freezers	70%	70%
Clothes washing machines	77%	100%
TV	156%	238%
VCR[58]	38%	0%
DVD	34%	228%
Antenna/Satellite	70%	107%
Desktop	44%	105%
Monitor	44%	105%
Printer	21%	66%
Modem/router	20%	93%

Source: research forecast based on ODYSSEE NMS (2007), CECED (2001), KSH (2004, 2006a), Fraunhofer IZM (2007).

The reference scenario also models the exchange of lights due to their retirement according to the lifetime listed in Table 19. Taking into account that the CFLs are present in 47% of households (REMODECE 2007), it is assumed that the structure of the stock does not

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[57] The number of appliances per 100 households.

[58] VCRs are not produced any more.

improve further in this regard without additional incentives[59]. There are several reasons behind this, the colour of emitted light, and the shape of CFLs; according to EURELECTRIC (2004) the latter factor influences the market of CFLs significantly because CFLs do not look nice in conventional luminaries typically designed for incandescent lights. The EURECO (2002) cited in IEA (2006b) concluded that, if the lamps would be exchanged in order of use (most used first), replacing six lamps would produce about 85% of the total energy savings associated with lighting in households. This is why the six most consuming lamps were assessed and modelled in detail. The structure of the six most consuming lamps installed in households of Hungary[60] in 2007 is presented in Figure 30 The technical characteristics of the six most consuming lamps such as their wattage and usage were framed by the results of the REMODECE project (2007).

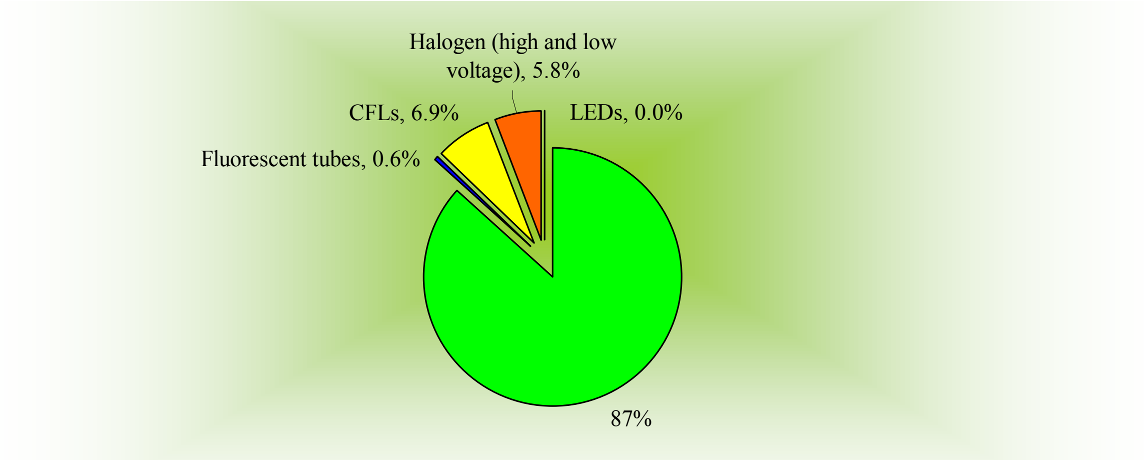

Figure 30 Structure of the installed lamp stock in Hungarian households, 2007

Source: constructed based on preliminary data of REMODECE (2007).

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[59] The ongoing product-specific preparatory studies being run in the frame of the EU Directive 2005/32/EC on Eco-design requirements for energy-using products plan to set-up the minimum energy efficiency to lamp technologies that will cause incandescent lamp technology to be non-compliant (Consultation Forum 2008). However, this requirement has not yet been set up and is therefore not considered in the reference scenario.

[60] In total, an average Hungarian household has 18 lighting points (Bertoldi and Atanasiu 2006).

Table 21 Technical characteristics of six lighting points mostly used in households

Ranking of lighting points according to the use	Usage	Share in the installed lamp stock, %			Typical wattage, Watt	
	Hours per day	Incandescent lights	CFLs	Other types of lights	Incandescent lights	CFLs
Point 1	4.0	70%	20%	10%	60	13
Point 2	3.0	55%	25%	20%	60	15
Point 3	2.5	55%	25%	20%	60	18
Point 4	2.3	50%	20%	30%	60	17
Point 5	2.1	50%	25%	25%	60	14
Point 6	1.9	70%	10%	20%	60	15

Source: estimated based on REMODECE (2007)

7.1.3 Modelling miscellaneous electricity use and cooking

Reference energy consumption other than that for space and water heating, refrigeration, freezing, clothes washing, and lighting was modelled in aggregate terms due to the limited background data. The detailed methodology and assumptions for modelling reference cooking and miscellaneous electricity use is described in Section 4.2.1 (p. 55).

7.2 Emission factors of fuels and energy

Generally, CO_2 emissions are estimated as a product of final energy consumption and respective emission factors of energy commodities. The present section discusses the model block which provides the estimate and the projection of CO_2 emission factors for primary fuels and final electricity and heat.

7.2.1 Emissions associated with the operation phase versus life-cycle emissions

The research considers only emissions emitted during the operation stage of the employed technologies. The research, therefore does not consider the life-cycle emissions which include those during manufacture of technological solutions, mining of raw materials used in their production and distribution, possible re-use or recycling, and disposal. This is due to two reasons. First, the research considers emissions according to the principle of associated final energy use. In this approach, emissions associated with production and replacement of building materials and equipment are allocated to the other energy end-use sectors (mainly industry and transportation). Second, energy use in buildings and associated emissions are dominant during the operation phase as compared to manufacturing and maintenance phases (see Figure 31). As Levine *et al*. (2007) concluded, it is common that the technological alternative which minimizes the operating energy use also minimizes lifecycle energy use. However, with the increase of operational energy efficiency the share of energy embodied in materials and construction will rise (WBCSD 2007).

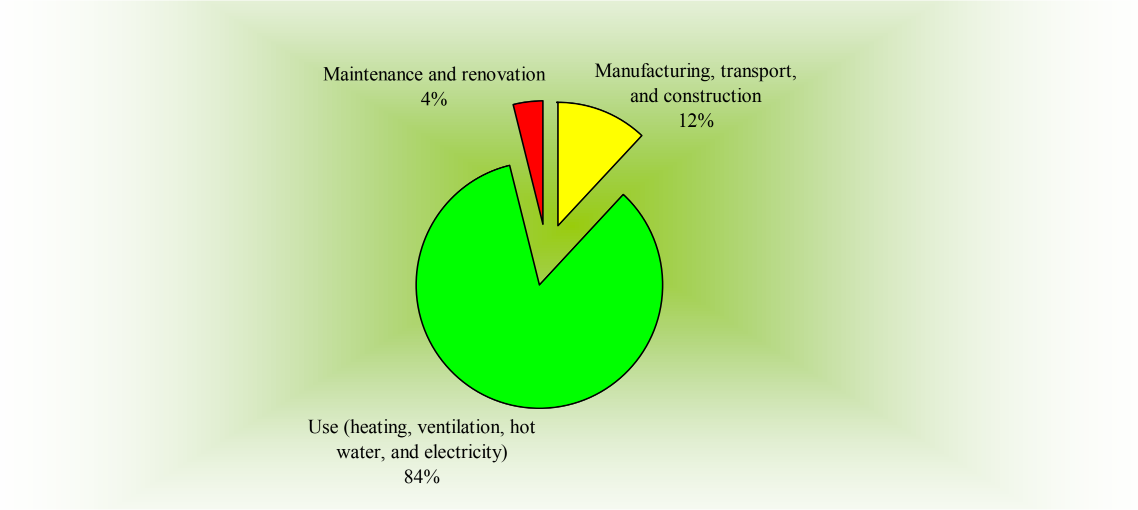

Figure 31 Life-cycle energy use of buildings

Source: Adalberth 1997.

7.2.1.1 Emission factors of primary fuels

Emission factors of primary fuels, namely natural gas, fuel oil, lignite, brown coal, and hard coal are taken from the Hungarian National Inventory (Hungarian Ministry of Environment and Water 2007). According to the same source, amounts of biomass used as fuel should be included in the national energy consumption, but the corresponding CO_2 emissions are not included in the national total (even though they are significant) as it is assumed that the biomass is produced in a sustainable manner. Emission factors of primary fuels (Table 22) do not change significantly over time (see the Hungarian National Inventories, 1987 – 2005) and for this reason they are assumed to be constant over the projection period.

Table 22 Emission factors of primary fuels

Primary fuel	Emission factor, gCO_2/kWh
Natural gas	202
Gas/diesel oil	267
Fuel oil	279
Lignite	392
Coking coal	356
Other bituminous coal	346

Source: Hungarian Ministry of Environment and Water (2007).

7.2.1.2 Emission factor of electricity

The emission factor of electricity production and distribution depends on the structure of the projected capacity of power production in the country, expected combustion technologies available on the market, improvement of distribution lines, and other factors. The author has not been able to locate any estimates of the emission factor of electricity production and distribution in Hungary over 2008 - 2025. For this reason, the author relied on her own analysis based on the MAVIR capacity plan during 2005 – 2020 (MAVIR 2005). This plan contains a forecast of the future fuel mix of power generation and heat production at national power plants, a forecast of an expected share of cogeneration in power and heat production, and estimates of efficiencies of future power and heat production technologies for the years 2005, 2010, 2015 and 2020. The key indicators taken from the MAVIR capacity plan and used to derive the projections of the emission factor of electricity are described in Table 23, Table 24, Table 25, and Table 26.

Table 23 Power and heat production at the Hungarian power plants, 2005

Power plants	**Electricity, GWh**		**Heat, TJ**	**Fuel consumption for electricity and heat production, TJ**							**Fuel for, TJ**		**Efficiency**	
	Total	**Incl. Cogen.**		**Lignite**	**Brown coal**	**Hard coal**	**Oil**	**Gas**	**Nuclear**	**Renewable**	**Electricity**	**Heat**	**Electricity**	**Heat**
Dunament	4,800	1,100	5,200				275	44,700			34,227	10,748	37%	12%
Paks Nuclear	12,300	80	600						134,182		133,383	799	31%	0%
Tisza II	1,800						3,000	14,300			17,300		35%	0%
Mátrai	5,500	25	300	60,500			1,000				60,461	1,039	28%	0%
Csepel	1,700	300	1,100					13,700			11,559	2,141	43%	8%
Oroszlány	1,100	50	350		13,500		100				12,337	1,263	25%	3%
Tiszapakunyal	400	50	550		4,000	1,000		300		1,200	4,525	1,975	19%	8%
Kelenföld	600	600	3,000				100	6,700			2,762	4,038	30%	44%
Lőrinc	5						60				60		30%	0%
Borsod	300	100	1,000			3,500		500		500	2,531	1,969	20%	16%
Pécs	250	250	2,500				300	4,000			1,060	3,240	17%	51%
Litér	3						40				40		27%	0%
Sajószöged	2						25				25		29%	0%
Újpest	500	400	3,000					6,000			2,193	3,807	29%	50%
Kispest	500	400	3,000					6,000			2,193	3,807	29%	50%
Ajka	150	80	2,800		4,000	1,000		100		300	560	4,840	6%	52%
DKCE	640	640	1,100					5,000			3,366	1,634	45%	22%
EMA Power	150	150	5,000				600	7,000			604	6,995	6%	66%
Big power plants	**30,700**	**4,225**	**29,500**	**60,500**	**21,500**	**5,500**	**5,500**	**108,300**	**134,182**	**2,000**	**289,186**	**48,295**	**30%**	**8%**
DÉDÁSZ	500	350	1,700				50	4,500		2,500				
DEMASZ	200	200	500					1,450		50				
EDASZ	1,000	700	7,300				600	12,900		3,000				
ELMU	600	500	6,500				550	9,850		1,600				
EMASZ	1,200	900	4,000				600	9,000		1,250				
TITASZ	500	450	6,400				1,200	7,000		1,600				
Small power plants	**4,000**	**3,100**	**26,400**				**3,000**	**44,700**		**10,000**	**46,879**	**10,821**	**23%**	**41%**
Total power plants	**34,700**	**7,325**	**55,900**	**60,500**	**21,500**	**5,500**	**8,500**	**153,000**	**134,182**	**12,000**	**336,065**	**59,116**	**29%**	**13%**
Import	7,000										25,200			
Total	**41,700**	**7,325**	**55,900**								**361,265**	**59,116**	**34%**	**12%**

Table 24 Power and heat production at the Hungarian power plants, 2010

Power plants	**Electricity, GWh**		**Heat, TJ**	**Fuel consumption for electricity and heat production, TJ**							**Fuel for, TJ**		**Efficiency**	
	Total	**Incl. cogen.**		**Lignite**	**Brown coal**	**Hard coal**	**Oil**	**Gas**	**Nuclear**	**Renew able**	**Elect-ricity**	**Heat**	**Elect-ricity**	**Heat**
Dunament	5,000	1,000	6,000				500	45,000			33,719	11,781	53%	51%
Paks Nuclear	14,000	100	650						152,727		151,928	799	33%	81%
Tisza II	2,700						1,000	24,500			25,500		38%	0%
Mátrai	6,100	30	300	58,000			500	1,500			59,096	904	37%	33%
Csepel	2,000	450	1,500					15,500			12,712	2,788	57%	54%
Oroszlány	1,000	50	350		13,000		100				11,755	1,345	31%	26%
Tiszapakunyal	350	50	550		4,000		20	300		2,500	4,519	2,301	28%	24%
Kelenföld	800	600	3,000				100	7,000			3,363	3,737	86%	80%
Lőrinc	800		50				15	5,500			5,415	100	53%	0%
Borsod	300	100	1,000			3,000	200	400		2,500	3,431	2,669	31%	37%
Pécs	260	230	2,700				300	4,000			992	3,308	94%	82%
Litér	3						40				40		27%	0%
Sajószöged	2						25				25		29%	0%
Újpest	600	570	3,000					7,000			2,873	4,127	75%	73%
Kispest	600	570	3,000					7,000			2,873	4,127	75%	73%
Ajka	145	70	2,800		2,000			300		3,000	566	4,734	92%	59%
Debrecen	640	640	1,100					5,000			3,366	1,634	68%	67%
EMA	140	140	5,000				600	7,000			510	7,089	99%	71%
Big power plants	**35,440**	**4,600**	**31,000**	**58,000**	**19,000**	**3,000**	**3,400**	**130,000**	**152,727**	**8,000**	**322,683**	**51,443**	**32%**	**8%**
Gas-turbine	1,200	950	16,000				3,000	14,000		7,000				
Gas turbine, combined cycle gas turbine	950	750	5,800					10,000						
Gas-motor	1,700	1,700	8,000				600	13,000		3,000				
Others	750									3,000				
Small power plants	**4,600**	**3,400**	**29,800**				**3,600**	**37,000**		**13,000**	**44,932**	**8,668**	**29%**	**50%**
Total power plants	**40,040**	**8,000**	**60,800**	**58,000**	**19,000**	**3,000**	**7,000**	**167,000**	**152,727**	**21,000**	**367,615**	**60,111**	**31%**	**13%**
Import	6,000										21,600			
Total	**46,040**		**60,800**								**389,215**	**60,111**	**35%**	**13%**

Table 25 Power and heat production at the Hungarian power plants, 2015

Power plants	**Electricity, GWh**		**Heat, TJ**	**Fuel consumption for electricity and heat production, TJ**							**Fuel for, TJ**		**Efficiency**	
	Total	**Incl. cogen.**		**Lignite**	**Brown coal**	**Hard coal**	**Oil**	**Gas**	**Nuclear**	**Renew able**	**Electri-city**	**Heat**	**Elect-ricity**	**Heat**
Dunament	4,800	1,000	5,800				500	44,000			32,882	11,618	37%	13%
Paks Nuclear	14,770	100	650						161,127		160,326	801	31%	0%
Tisza II	2,400							23,000			23,000		36%	0%
Mátrai	7,600	30	250	60,000			100	2,500		1,500	63,447	653	38%	0%
Csepel	2,000	530	1,500					15,500			12,712	2,788	43%	10%
Kelenföld	1,100	600	3,000					8,500			4,636	3,864	42%	35%
Lőrinc	1,000						50	6,700			6,750		51%	0%
Pécs	800	500	2,700				300	5,000		3,000	4,167	4,133	15%	15%
Litér	5		0				75				75		24%	0%
Sajószöged	5		0				75				75		24%	0%
Újpest	650	550	3,000					7,600			3,242	4,358	29%	39%
Kispest	650	550	3,000					7,600			3,242	4,358	29%	39%
Debrecen	700	640	1,100					5,200			3,588	1,612	47%	21%
New industrial	350	300	4,500				2,900	7,300			1,601	5,699	16%	56%
New heating	400	300	3,000					6,700			2,098	4,602	20%	45%
New condensational	2,100						1,000	13,700			13,700	0	54%	0%
Big power plants	**39,330**	**5,100**	**28,500**	**60,000**			**5,000**	**153,300**	**161,127**	**4,500**	**335,541**	**44,486**	**35%**	**7%**
Gas-turbine	1,000	1,000	17,000				2,900	7,000		15,000				
Gas turbine, combined cycle gas turbine	1,200	1,200	8,300					14,500						
Gas-motor	2,100	2,000	11,000				1,000	14,200		6,000				
Others	1,400									6,500				
Small power plants	**5,700**	**4,200**	**36,300**				**3,900**	**35,700**		**27,500**	**58,257**	**8,843**	**29%**	**50%**
Total power plants	**45,030**	**9,300**	**64,800**	**60,000**			**8,900**	**189,000**	**161,127**	**32,000**	**393,798**	**53,329**	**34%**	**14%**
Import	5,800										20,880		100%	
Total	**50,830**	**9,300**	**64,800**								**414,678**		**37%**	**13%**

Table 26 Power and heat production at the Hungarian power plants, 2020

Power plants	Electricity, GWh		Heat, TJ	Fuel consumption for electricity and heat production, TJ							Fuel for, TJ		Efficiency	
	Total	Incl. cogen.		Lignite	Brown coal	Hard coal	Oil	Gas	Nuclear	RES	Electri-city	Heat	Elect-ricity	Heat
Dunament	4,800	1,000	5,700				500	45,000			33,943	11,557	37%	13%
Paks Nuclear	14,770	100	650						161,127		160,326	801	31%	0%
Tisza II	2,500							25,000			25,000		35%	0%
Mátrai	7,600	30	300	60,000			100	2,500		1,000	62,852	748	40%	0%
Csepel	1,800	530	1,500					15,000			12,115	2,885	42%	10%
Kelenföld	1,100	600	3,000					8,500			4,636	3,864	42%	35%
Lőrinc	1,100		50				50	7,000			6,953	97	51%	1%
Pécs	850	500	2,700				300	5,000		4,000	4,829	4,471	30%	28%
Litér	5						75				75		24%	0%
Sajószöged	5						75				75		24%	0%
Újpest	650	550	3,000					7,500			3,200	4,300	30%	40%
Kispest	650	550	3,000					7,500			3,200	4,300	30%	40%
Debrecen	700	640	1,100					5,000			3,450	1,550	49%	22%
Pumped storage plant	210												70%	0%
New industrial	350	300	4,500					7,000			1,565	5,435	16%	57%
New heating	800	600	5,500					12,000			4,056	7,944	23%	46%
New condensational	3,200							20,000			20,000		54%	0%
New coal-based	2,500			20,000			50				20,050		41%	0%
Big power plants	**43,590**	**5,400**	**31,000**	**80,000**			**1,150**	**167,000**	**161,127**	**5,000**	**366,325**	**47,952**	**36%**	**7%**
Gas-turbine	800	800	16,000				2,850	7,000		16,000				
Gas turbine, combined cycle gas turbine	1,800	1,500	11,000					20,000						
Gas-motor	2,400	2,000	10,800				1,000	13,000		9,000				
Others	2,100									10,000				
Small power plants	**7,100**	**4,300**	**37,800**				**3,850**	**40,000**		**35,000**	**70,276**	**8,574**	**31%**	**44%**
Total power plants	**50,690**	**9,700**	**68,800**	**80,000**			**5,000**	**207,000**	**161,127**	**40,000**	**436,601**	**56,526**	**35%**	**13%**
Import	5,430										20,520		78%	
Total	**56,120**	**9,700**	**68,800**								**457,121**	**56,526**	**37%**	**13%**

Source for Table 23, Table 24, Table 25, Table 26: MAVIR 2005

Based on Table 23, Table 24, Table 25, Table 26, and on estimated emission factors of primary fuels provided by the Hungarian National Inventory (2007), the emission factor of electricity production and distribution is estimated for the years 2005, 2010, 2015, and 2020 and interpolated between these years. The results of these projections are presented in Table 27.

Table 27 Estimate of the CO_2 emission factor of electricity

Indicator	Units	2005	2010	2015	2020
Electricity produced domestically	PJ	124,9	144,1	162,1	182,5
Electricity imported	PJ	25,2	21,6	20,9	19,5
Heat produced domestically at power plants	PJ	55,9	60,8	64,8	68,8
Heat imported	PJ	0	0	0	0
CO_2 associated with electricity production	Million tonnes	15,3	15,5	15,3	18,3
CO_2 associated with heat production at power plants	Million tonnes	3,6	3,3	2,9	2,9
CO_2 emission factor of electricity produced domestically	g CO_2/kWh	440	386	339	361
CO_2 emission factor of electricity produced domestically and imported (emissions of imported electricity are 0 for Hungary)	g CO_2/kWh	366	336	300	326

Source: research forecast based on MAVIR 2005.

7.2.1.3 Emission factor of heat

The emission factors of heat used by the residential sector of Hungary are also uncertain. For the purposes of the dissertation research, the author relied on the information about district heat installation provided by the National Allocation Plan of Hungary (GKM & KVVM 2007) and on the information about heat production at power plants (MAVIR 2005). GKM & KVVM (2007) details the expected capacity, efficiency, and CO_2 emissions of district heat installations until 2012. According to expert opinion (Kovacsics per. comm.), it is unlikely that the production of district heat will grow or change significantly in the near future. Therefore, it is assumed that the structure of fuel consumption at district heat installations and the overall heat production stays constant over the period 2008 – 2020. The estimate of CO2 emissions of heat produced at district heat installation is described in Table 28.

Table 28 Estimate of the CO_2 emission factor of heat produced at district heat installations

Indicator	**Units**	**2005**	**2010**	**2015**	**2020**
Heat produced at district heat installations	PJ	18	18	18	18
CO_2 emissions	Million tons	1,3	1,3	1,2	1,2
Emission factor of heat produced at district heat installations	gCO_2/kWh	264	255	244	232
Efficiency of district heat production and distribution	%	77	80	83	87
Structure of fuel consumption for district heat production					
Fuel oil	%	1.6	Constant		
Gas/diesel oil	%	0.1	Constant		
Natural gas	%	98.3	Constant		

Source: estimated based on GKM & KVVM (2007) and Hungarian Ministry of Environment and Water (2007).

Heat consumed in the residential sector is supplied from both district heat installations and power plants. Therefore, the overall CO_2 emission factor of heat is estimated as a weighted average of emission factors of both of these heat sources. The detailed calculation of the CO_2 emission factor of heat is described in Table 29.

Table 29 Estimate of the CO_2 emission factor of heat

Indicator	Units	2005	2010	2015	2020
CO_2 emissions of heat generated by power plants	Million tonnes	3,6	3,3	2,9	2,9
CO_2 emissions of heat generated at district heat installations	Million tonnes	1,3	1,3	1,2	1,2
Total emissions	Million tonnes	4,9	4,5	4,1	4,0
Heat produced at power plants	MWh	15,5	16,9	18,0	19,1
Heat produced at district heat installations	MWh	5,0	5,0	5,0	5,0
Total heat produced	MWh	20,5	21,9	23,0	24,1
Estimated CO_2 emission factor of heat	g CO_2/kWh	238	208	178	167

Source: estimated based on GKM & KVVM (2007); MAVIR (2005); and Hungarian Ministry of Environment and Water (2007).

The estimates of heat and electricity emission factors described in sections above are conducted for the period 2008 – 2020. It is assumed that the emission factors during 2021 – 2025 are somewhat similar to those for 2020 given the high uncertainty of the fuel mix of electricity and heat production over a twenty year period. The dynamics of estimated emission factors of electricity and heat are illustrated in Figure 32 .

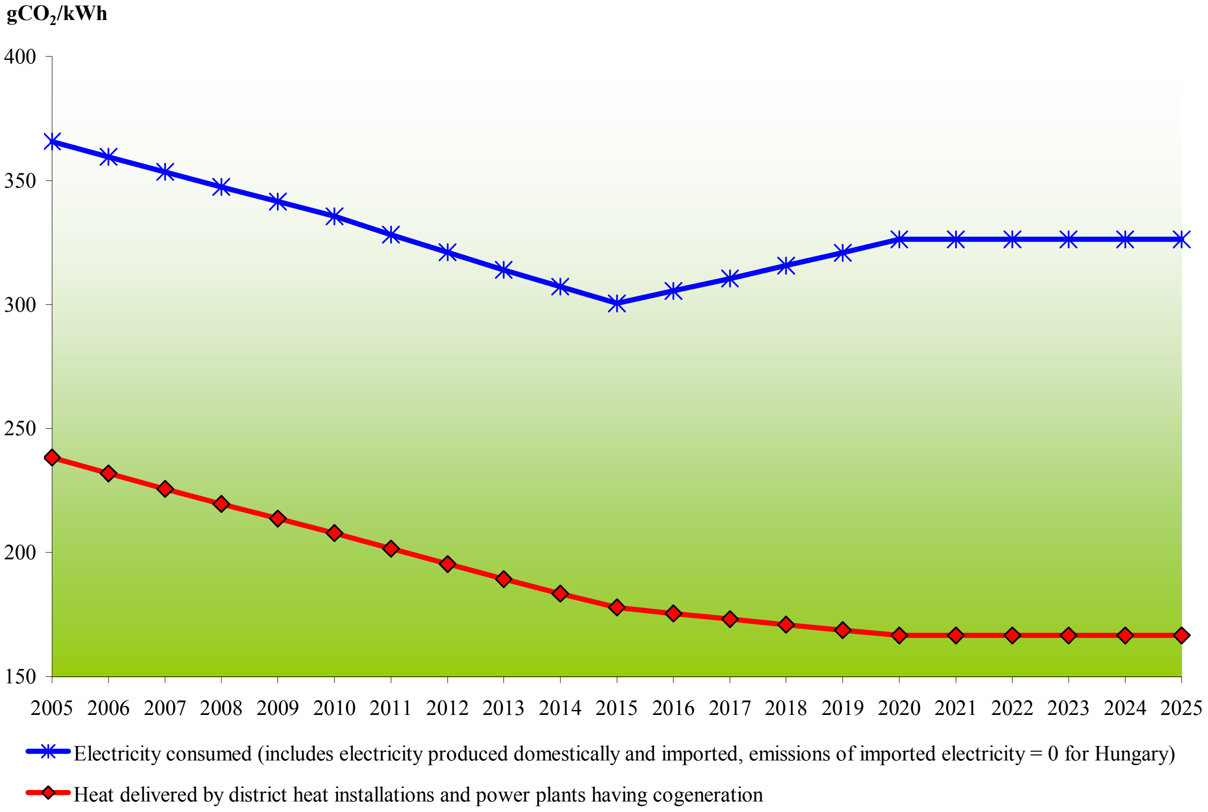

Figure 32 Projected emission factors of electricity and heat in Hungary, 2005 – 2025

Source: research forecast based on GKM & KVVM (2007); MAVIR (2005); and Hungarian Ministry of Environment and Water (2007).

7.3 Results of the research forecast

Once the methodology, calculation procedures, and assumptions were defined and documented, the input parameters were inserted into the spreadsheets to calculate the final energy consumption and associated CO_2 emissions, first in the start year and then to 2025. The present section describes the procedure for forecasting these outputs and discusses the results.

7.3.1.1 The start year energy consumption and its calibration to the national statistics and other research available

The first step of the forecast was to estimate the final energy consumption and associated CO_2 emissions in the base years. Upon making this step however, it appeared that the final energy consumption calculated per technology and aggregated at the energy end-use level and then at the sectoral level does not correspond to the sectoral balance as reported by national statistics. For this reason, the disaggregated input parameters were reviewed again.

As described in Section 2.2 (p. 12), the detailed fuel breakdown of energy end-uses has not been assessed within the last ten years and therefore it was not possible to calibrate the model accordingly. This is why the forecast was mainly compared to the sectoral balance according to energy carriers (the national statistics reported by ODYSSEE NMS 2007) and according to the energy end-use balance (thermal end-use versus electrical end-use in PRIMES, Capros *et al.* 2007). This analysis showed that the smallest difference was in the electricity consumption whereas the largest occurred in the fuels used for space heating. The reason for the difference in the thermal energy use was the estimate of space heating requirement in different building types. This parameter was the most influential and at the same time the most uncertain among others used to calculate energy consumption for space heating. The author was unable to find any statistics on space heating requirement for Hungarian households of different types of buildings, and for this reason the parameter was calculated according to the procedure described in Section 4.2.1 (p. 55) and Section 7.1.1.1 (p. 130). The main variables which were changed until the forecast approximately met the balances were the U-values of building shell components and the

ACH rates of different types of buildings. The final results of the modelling of the start year sectoral energy consumption are presented in Figure 33.

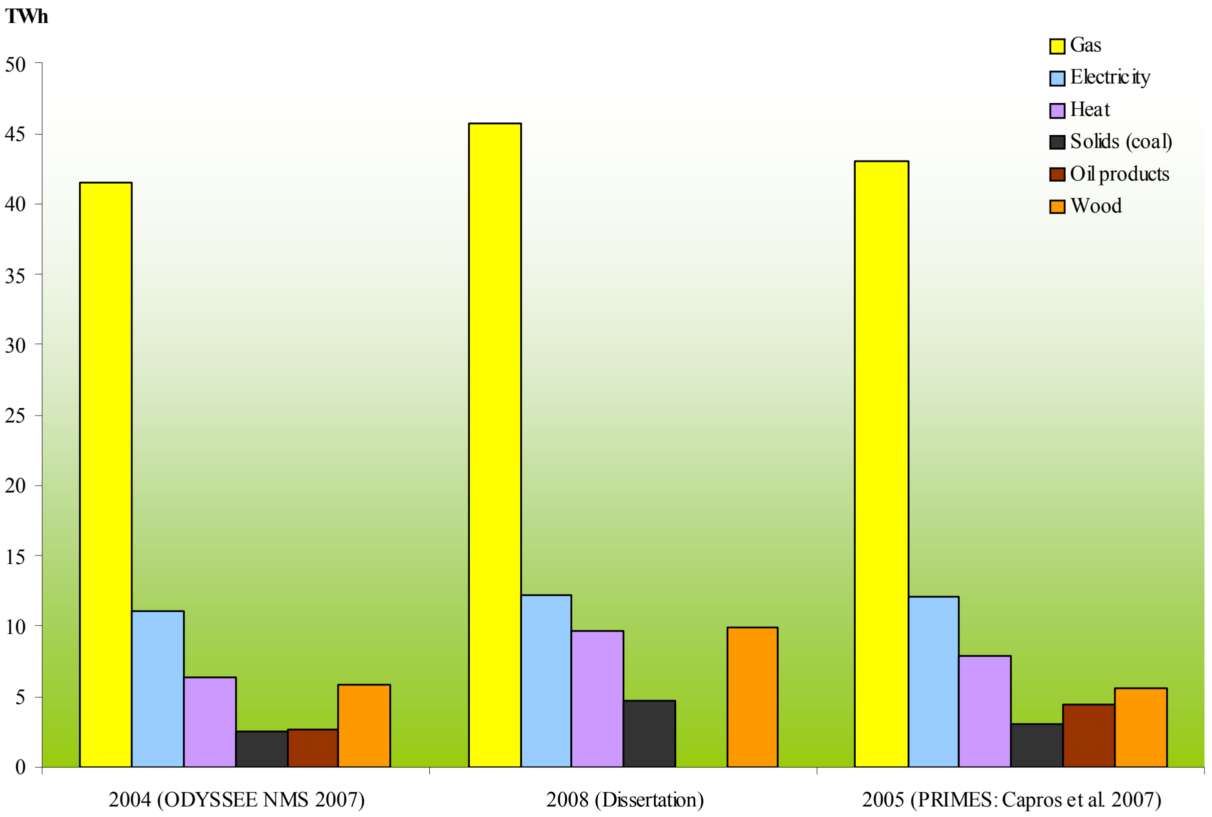

Figure 33 Comparison of the sectoral energy balance of the research model, national statistics, and the external model

7.3.1.2 Results of the research forecast

Following the calibration of the data for the start year, the forecast of the sectoral energy consumption was developed based on procedures described in Section 4.2.1 (p. 55) and Section 7.1 (p. 129). Figure 34 presents the results of this step. The Figure illustrates that the final energy consumption for space and water heating barely changes from 2008 to 2025. This is because the efficiency improvement of thermal energy use is closely negated by the growing number of households. The final energy consumption of appliances and lights is growing over the projection period boosted by the growing number of miscellaneous electrical appliances. The overall result of the energy baseline forecast is that the final energy consumption of the residential sector is expected to grow from 81.9 TWh in 2008 to 84.2 TWh in 2025.

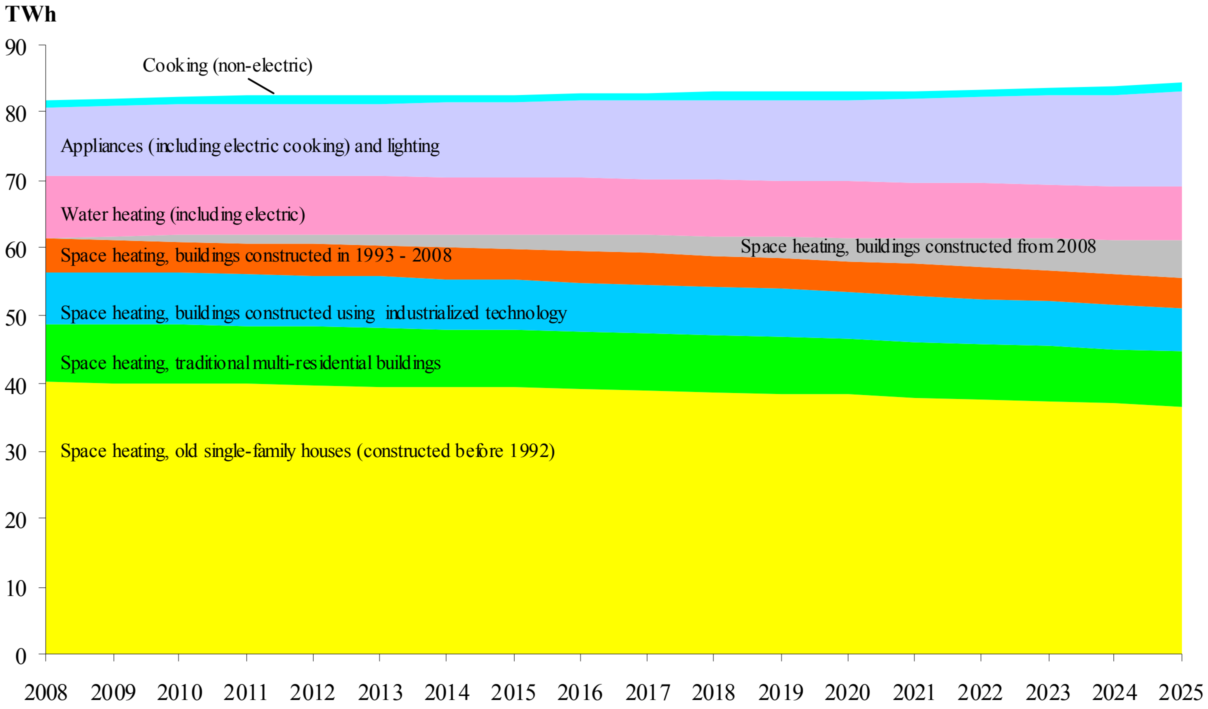

Figure 34 Sectoral final energy consumption projected in the reference case, 2008 - 2025

Source: research forecast.

The sectoral CO_2 emissions are estimated based on the results of energy consumption forecast and assumptions about the emission factors of fuels described in Section 7.2 (p. 139). Figure 35 demonstrates that the sectoral CO_2 emissions are expected to decline until 2015 (mainly due to decreasing emission factors of electricity and district heat) but then they are likely to rise again, reaching the 2008 level by the year 2025. The CO_2 emission growth is caused by the increasing demand for electricity multiplied by its growing CO_2 emission factor (from 2015) due to the installation of new lignite power plants. Table 30 details the annual values of the final energy consumption and associated CO_2 emissions of the residential sector by energy end-use.

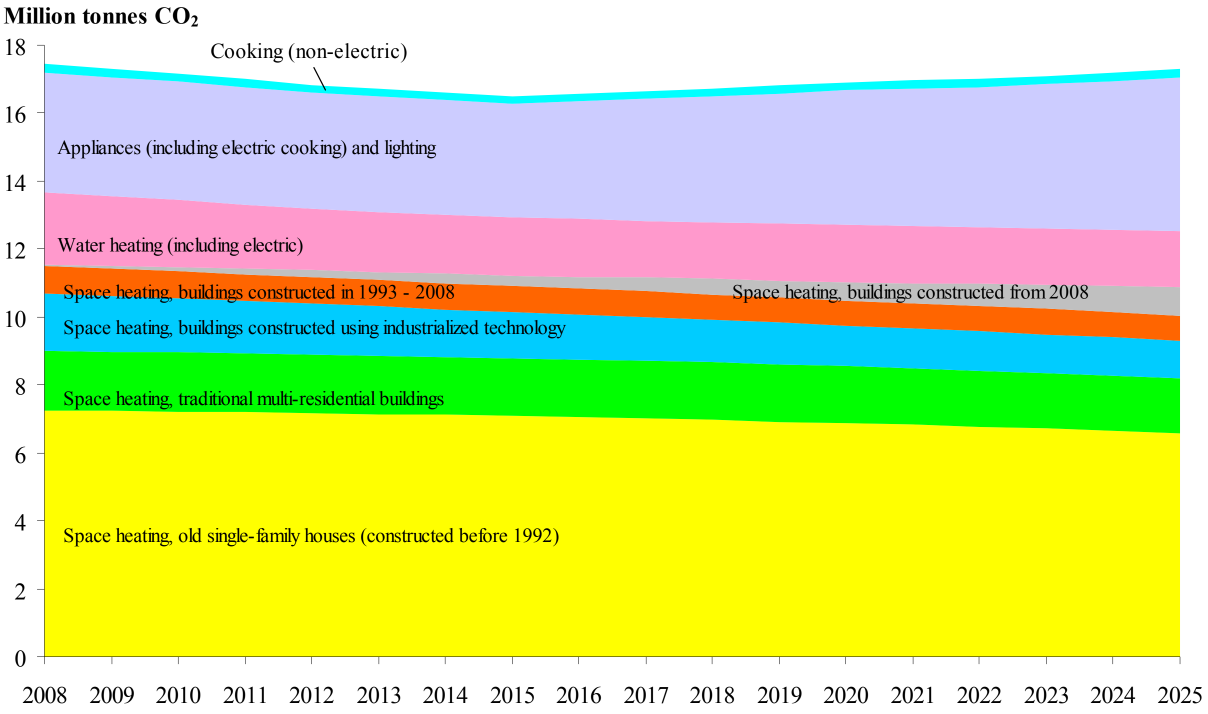

Figure 35 Sectoral CO_2 emissions projected in the reference case, 2008 - 2025

Source: research forecast.

Table 30 Baseline energy consumption (TWh) and associated CO_2 emissions (million tonnes CO_2) by energy end-use

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
REFERENCE ENERGY CONSUMPTION	**81.9**	**82.1**	**82.2**	**82.4**	**82.5**	**82.6**	**82.6**	**82.7**	**82.8**	**82.9**	**83.0**	**83.1**	**83.1**	**83.3**	**83.4**	**83.7**	**83.9**	**84.2**
Space heating in households of	***61.5***	***61.7***	***61.8***	***61.8***	***61.9***	***61.9***	***61.9***	***61.9***	***61.8***	***61.8***	***61.7***	***61.7***	***61.5***	***61.5***	***61.4***	***61.3***	***61.2***	***61.0***
Single-family houses (built before 1992)	*40.1*	*40.0*	*39.9*	*39.9*	*39.7*	*39.6*	*39.5*	*39.3*	*39.1*	*38.9*	*38.7*	*38.5*	*38.2*	*37.9*	*37.7*	*37.3*	*37.0*	*36.6*
Traditional buildings	*8.6*	*8.6*	*8.6*	*8.6*	*8.6*	*8.6*	*8.6*	*8.5*	*8.5*	*8.5*	*8.5*	*8.4*	*8.4*	*8.3*	*8.2*	*8.2*	*8.1*	*8.0*
Industrialized buildings	*7.9*	*7.8*	*7.7*	*7.7*	*7.6*	*7.5*	*7.4*	*7.3*	*7.2*	*7.2*	*7.1*	*7.0*	*6.8*	*6.7*	*6.6*	*6.5*	*6.4*	*6.3*
Buildings constructed in 1993-2007	*4.7*	*4.7*	*4.7*	*4.7*	*4.7*	*4.7*	*4.7*	*4.7*	*4.6*	*4.6*	*4.6*	*4.6*	*4.6*	*4.6*	*4.6*	*4.6*	*4.6*	*4.6*
Buildings constructed after 2008	*0.3*	*0.5*	*0.8*	*1.0*	*1.3*	*1.5*	*1.8*	*2.0*	*2.3*	*2.6*	*2.9*	*3.2*	*3.5*	*3.8*	*4.2*	*4.6*	*5.0*	*5.4*
Water heating (including electric)	***9.1***	***9.0***	***8.9***	***8.9***	***8.8***	***8.7***	***8.6***	***8.6***	***8.5***	***8.4***	***8.4***	***8.3***	***8.2***	***8.2***	***8.1***	***8.1***	***8.0***	***8.1***
Electrical appliances and lights	***10.1***	***10.3***	***10.4***	***10.5***	***10.7***	***10.8***	***11.0***	***11.1***	***11.3***	***11.5***	***11.7***	***11.9***	***12.2***	***12.4***	***12.7***	***13.1***	***13.4***	***13.9***
Studied appliances (refrigerators, freezers, clothes washing machines) and lights	*5.9*	*5.8*	*5.7*	*5.6*	*5.5*	*5.4*	*5.3*	*5.2*	*5.1*	*4.9*	*4.8*	*4.7*	*4.6*	*4.4*	*4.3*	*4.3*	*4.2*	*4.2*
Other appliances (including electric cooking)	*4.2*	*4.4*	*4.7*	*4.9*	*5.1*	*5.4*	*5.7*	*5.9*	*6.2*	*6.6*	*6.9*	*7.2*	*7.6*	*8.0*	*8.4*	*8.8*	*9.2*	*9.7*
Cooking (non-electric)	***1.1***	***1.1***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***
REFERENCE CO_2 EMISSIONS	**17.4**	**17.3**	**17.2**	**17.0**	**16.8**	**16.7**	**16.6**	**16.5**	**16.6**	**16.6**	**16.7**	**16.8**	**16.9**	**17.0**	**17.0**	**17.1**	**17.2**	**17.3**
Space heating in households of	***11.5***	***11.5***	***11.5***	***11.4***	***11.4***	***11.3***	***11.3***	***11.2***	***11.2***	***11.1***	***11.1***	***11.1***	***11.0***	***11.0***	***11.0***	***10.9***	***10.9***	***10.9***
Single-family houses (built before 1992)	***7.2***	***7.2***	***7.2***	***7.2***	***7.2***	***7.1***	***7.1***	***7.1***	***7.0***	***7.0***	***7.0***	***6.9***	***6.9***	***6.8***	***6.8***	***6.7***	***6.7***	***6.6***
Traditional buildings	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.6***	***1.6***	***1.6***
Industrialized buildings	***1.7***	***1.7***	***1.6***	***1.5***	***1.5***	***1.4***	***1.4***	***1.3***	***1.3***	***1.3***	***1.2***	***1.2***	***1.2***	***1.2***	***1.2***	***1.1***	***1.1***	***1.1***
Buildings constructed in 1993-2007	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***	***0.8***
Buildings constructed after 2008	***0.0***	***0.1***	***0.1***	***0.2***	***0.2***	***0.2***	***0.3***	***0.3***	***0.4***	***0.4***	***0.4***	***0.5***	***0.5***	***0.6***	***0.6***	***0.7***	***0.8***	***0.8***
Water heating (including electric)	***2.1***	***2.0***	***2.0***	***1.9***	***1.8***	***1.8***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.7***	***1.6***	***1.6***	***1.6***
Electrical appliances and lights	***3.5***	***3.5***	***3.5***	***3.5***	***3.4***	***3.4***	***3.4***	***3.3***	***3.5***	***3.6***	***3.7***	***3.8***	***4.0***	***4.1***	***4.1***	***4.3***	***4.4***	***4.5***
Studied appliances (refrigerators, freezers, clothes washing machines) and lights	*2.1*	*2.0*	*1.9*	*1.8*	*1.8*	*1.7*	*1.6*	*1.6*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.4*	*1.4*	*1.4*	*1.4*
Other appliances (including electric cooking)	*1.5*	*1.5*	*1.6*	*1.6*	*1.6*	*1.7*	*1.7*	*1.8*	*1.9*	*2.0*	*2.2*	*2.3*	*2.5*	*2.6*	*2.7*	*2.9*	*3.0*	*3.2*
Cooking (non-electric)	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***	***0.2***

Source: research forecast.

7.3.1.3 Comparison of the research forecast to the results of the PRIMES model

Table 31 compares the residential reference energy consumption and associated CO_2 emissions of the dissertation forecast and the results of the PRIMES model (Capros *et al*. 2007). The Table shows that starting from approximately the same point, by 2025 the sectoral energy consumption of the dissertation research is higher by a quarter than that of the PRIMES model. An interesting fact is that the reference levels of direct CO_2 emissions in the dissertation research are lower than those of the PRIMES model, although this difference decreases over the projection period. These data suggest that the difference in results of the two models is largely due to the projected electricity consumption of the sector. The total emissions reported by the national statistics in the base year 2004 ODYSSEE NMS (2007) are higher than those of both the dissertation forecast and the PRIMES model. Thus, in general the dissertation forecast is between the national statistics and the results of the PRIMES model.

Table 31 Energy consumption and associated CO_2 emissions: the start year balance and the forecast for 2008 – 2025 according to different sources

	Units	2004	2005	2006	2008	2010	2015	2020	2025
The present dissertation									
Energy consumption	TWh	-	-	-	81.9	82.2	82.7	83.1	84.2
CO_2 emissions, total	1000 tCO_2	-	-	-	17.4	17.2	16.5	16.9	17.3
CO_2 emissions, direct					13.2	13.0	12.6	12.4	12.3
CO_2 emissions, indirect					4.2	4.1	3.9	4.5	5.0
PRIMES model (Capros et al. 2007)									
Energy consumption	TWh		76.3			85.3	93.6	98.5	101.5
CO_2 emissions, direct	1000 tCO_2		10.7			11.0	11.3	11.4	11.3
ODYSSEE NMS database (2007)									
Energy consumption	TWh	69.8	-	-	-	-	-	-	-
CO_2 emissions, total	1000 tCO_2	16.2	-	-	-	-	-	-	-
Energy Efficiency Action Plan of Hungary (GKM 2008)									
Energy consumption	TWh	-	-	75.7	-	-	-	-	-

Chapter 8 ECONOMIC EVALUATION OF MITIGATION OPTIONS AND THEIR AGGREGATION TO THE SUPPLY CURVE OF CO_2 MITIGATION

Chapter 8 summarises the mitigation options assessed in the research, assumptions for their economic evaluation, and the results of this analysis. This section discusses the estimates of the sectoral mitigation potential as a function of CO_2 mitigation costs of technological options separately installed. Then, the section estimates such potential if the options are installed according to the supply curve method. The scenario which implies the realisation of all mitigation options is referred to in this section as ***the mitigation scenario***.

8.1 Summary of mitigation technological options

This section summarises the discussion of mitigation options provided in Chapter 6 and identifies the key energy efficiency and fuel switch technologies applicable in the residential sector of Hungary. This summary is subject to the research limitations described in Section 4.5.3 (p. 69). These disregard the thermal envelope improvement for buildings constructed from 1993 to 2008, the exchange of heating solutions in all buildings constructed after 1993, the insulation of heat- and water- delivering pipes, the exchange of doors, the options aimed at efficient cooking and air-conditioning. In regard to electrical efficiency, improvement of the efficiency of electrical appliances and equipment other than cold appliances, washing machines, lights, and TV and PC-related equipment in low power mode is not studied. Also the research does not consider the effect of more efficient biomass heating systems. The studied options are listed in Table 32.

Table 32 Efficiency and fuel switch options investigated in the dissertation research

Mitigation options	**Households in**				
	Multi-residential traditional buildings	**Multi-residential industrialized buildings**	**Old single-family houses (constructed before 1992)**	**Buildings constructed from 1993 to 2007**	**Buildings constructed from 2008**
Thermal envelope					
Insulation of walls, roofs, and cellars		X	X		
Exchange of windows	X	X	X		
Weather stripping of windows			X		
Application of the passive energy design					X
Heating efficiency and fuel switch					
Exchange of central building standard gas systems with central building condensing gas systems	X	X			
Exchange of premise and central dwelling gas systems and premise and central dwelling coal systems with central dwelling condensing gas systems	X		X		
Exchange of premise and central dwelling gas systems and premise and central dwelling coal systems with space and water heating pumps			X		
Exchange of premise and central dwelling gas systems and premise and central dwelling coal systems with pellet space and water heating systems			X		
Exchange of premise and central dwelling gas systems and premise and central dwelling coal systems with solar thermal space and water heating systems backed-up with pellets			X		

Mitigation options	**Households in**				
	Multi-residential traditional buildings	**Multi-residential industrialized buildings**	**Old single-family houses (constructed before 1992)**	**Buildings constructed from 1993 to 2007**	**Buildings constructed from 2008**
Heating controls					
Installation of thermostatic radiator valves (for district and centrally heated households only)	X	X			
Installation of programmable thermostats (except households with district and central heating and those having coal and biomass heating systems)	X		X		
Installation of individual heat metering (for district and central heated households only)	X	X			
Water heating					
Efficiency improvement of combined space and water heating systems (according to the options described in the space heating opportunities)	X	X	X		
Exchange of dedicated water heating appliances with more efficient appliances of the same class (electric storage, gas storage and gas instantaneous water heaters)	X	X	X	X	X
Installation of water saving fixtures (showerheads and sink faucets)	X	X	X	X	X
Electrical appliances and lights					
Higher efficiency refrigerators and freezers	X	X	X	X	X
Higher efficiency clothes washing machines	X	X	X	X	X
Reduction of electricity consumption of TV- and PC-related appliances in low power mode	X	X	X	X	X
Exchange of incandescent lamps with CFLs	X	X	X	X	X

8.2 Assumptions of economic analysis

The economic evaluation of applying the mitigation options was conducted based on calculative procedures described in the methodological Section 4.2.4 (p. 62). Analysis of the methodology shows that the CO_2 mitigation costs are the most sensitive to the discount rate chosen and the cost of energy and fuels projected over the modelling period. These and other assumptions of the economic analysis are discussed further in this section.

8.2.1 Discount rate

The research is constructed on the assumption that the major part of the costs for energy conservation and CO_2 mitigation is paid for by the households. Some of these purchases are supported by government programmes (e.g. building renovations). This is why the discount rates from the households' and the government's perspectives are considered.

As Table 4 (p. 32) shows, there is a wide range of discount rates used by studies. This is due to the fact that discount rates are highly dependant on a number of national circumstances and most importantly, there is a difference in defining the discount rates. Studies often use consumer discount rates that are based on expected rates of return of competing investments. Sometimes, somewhat lower discount rates are used to identify the economic potential from a social perspective. Sathaye and Meyers (1995) propose not to discount costs and benefits of GHG emissions at all because not discounting them assumes the future economic damage which is caused by a GHG increase at the real rate. This is probably true because this effect is likely to be increasing dramatically and is largely unknown. Another approach is setting the discount rate as high as 100% based on observed consumer behaviour (often referred to as 'hurdle' rates) and considering all possible costs associated with implementation of mitigation measures discounting direct investment, operation, and maintenance costs (Rufo 2003).

As explained, in an ideal situation, households compare the expected rates of return on investing in energy efficiency with other investments such as the interest rate of a bank balance. If consumer behaviour is rational, the decision is made for the investments which pay back with the highest rates of return. Typically, the investments in energy efficiency have medium and long term pay back periods of more than five years, except for a few electrical appliances, some lighting options, and weather stripping; therefore, it is reasonable to compare the internal rates of return to the long-term interest rate of a bank deposit. As of August 2007, this rate at the Hungarian Central Bank[61] was 3.09% (Hungarian Central Bank 2007). This interest rate is very close to that of the EURO-area at the indicated date (see European Central Bank website). Since, as described in the previous paragraph, in reality the discount rate of the household sector is higher than the long-term interest rate provided by banks due to numerous barriers associated with efficiency improvement in households, it is assumed that the discount rate used in the model is at least double that of the long-term interest rate, i.e. it is about 6%.

If governmental agencies support the introduction of efficiency technologies, the discount rate for them is at least as high as the base rate of the Hungarian Central Bank, which was 7.75% as of August 2007 (Hungarian Central Bank 2007). It is expected that in the medium term future, the

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[61] For EUR deposits because the currency considered in the research is EUR.

financial indicators of Hungary will improve (Government of the Republic of Hungary 2006) and the base rate should decline. While there is an uncertainty about the fluctuation of the base rate between now and 2025, it is reasonable to assume that it will be close to the discount rate assumed for the household sector.

The proposed discount rate of 6% is in line with other case studies conducted for the CEE region. The EURIMA report (Petersdorff *et al.* 2005) analyses the EU Member States which joined the Union in 2004[62] with a discount rate of c. 6% over 2006 – 2015. The Hungarian country study developed in the frame of the UNEP series "Economics of GHG Limitations" (Szlavik *et al.* 1999) considered the residential and public sectors using discount rates of 3 - 5% over 2000 – 2030. The Estonian country study of the same UNEP series (Kallaste *et al.* 1999) used discount rate of 6% in the period 2000 – 2025 to analyze the residential and commercial sectors.

8.2.2 Prices of fuels[63] and energy

As discussed, the major part of costs for energy efficiency is paid for by the households and since the policy measures are designed to support their decisions, the assessment is conducted taking into account energy and fuel prices for the residential end-users (including the value added tax and the energy tax where applicable).

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[62] Hungary, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Poland, and the Czech Republic.

[63] Fuel is defined as any substance burned as a source of heat or power energy whereas energy refers only to heat and power (IEA 2005).

There is no single source or agency which collects and reports the dynamics of energy and fuel prices in Hungary. Therefore, this information was collected from different sources in December 2007. They are presented in Table 33 .

Table 33 Energy and fuel prices for the residential end-users of Hungary, December 2007

Fuels	Energy price, EUR/kWh	References
Natural gas	0.044	Hungarian Energy Office 2007a
Agripellet	0.030	Estimate based on DBO (2007)
Brown coal	0.024	Estimate based on Hungarian Energy Office (2007b)
Firewood	0.012	Estimate based on DBO (2007)
District Heat	0.041[64]	Call Centre FŐTÁV (2007)
Electric energy	0.155	Hungarian Energy Office 2007c

There is a large uncertainty associated with the future dynamics of fuel and energy prices. Figure 36 and Figure 37 illustrate the natural gas and electrical price dynamics in a few countries of the European Union from 2000 to 2007. The Figures show a dramatic increase in the natural gas and electricity prices since the 2nd half of 2006; however, these prices are still lower than those of the EU-27. Since saved energy costs (calculated as final energy savings x fuel/energy prices) directly influence the cost of CO_2 mitigation, more detailed research is needed to understand the fuel and energy price evolution. In agreement with other pieces of research, which focused on the CEE region (Waide 2006; Petersdorff *et al.* 2005), energy prices are assumed to grow by 1.5%/yr. in real terms.

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[64] To be consistent across the methodologies of estimation of energy saving costs of space heating options, it is considered that the district heat price is 100% flexible. In practice, only half of the district heat price is variable and it depends on heat consumption of a building distributed among heat payers. Another half of the price is not so called ‘capacity cost’ and is variable (Sigmond per. comm.).

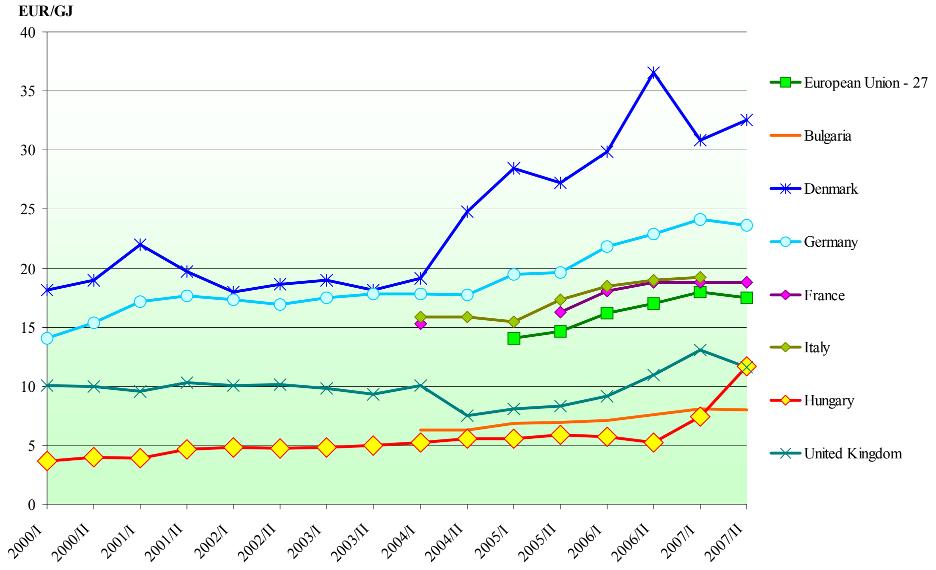

Figure 36 Half-yearly natural gas price for domestic consumers (including all taxes)

Note: The graph shows households with gas consumption in the interval 8.37 - 16.74 GJ/yr.

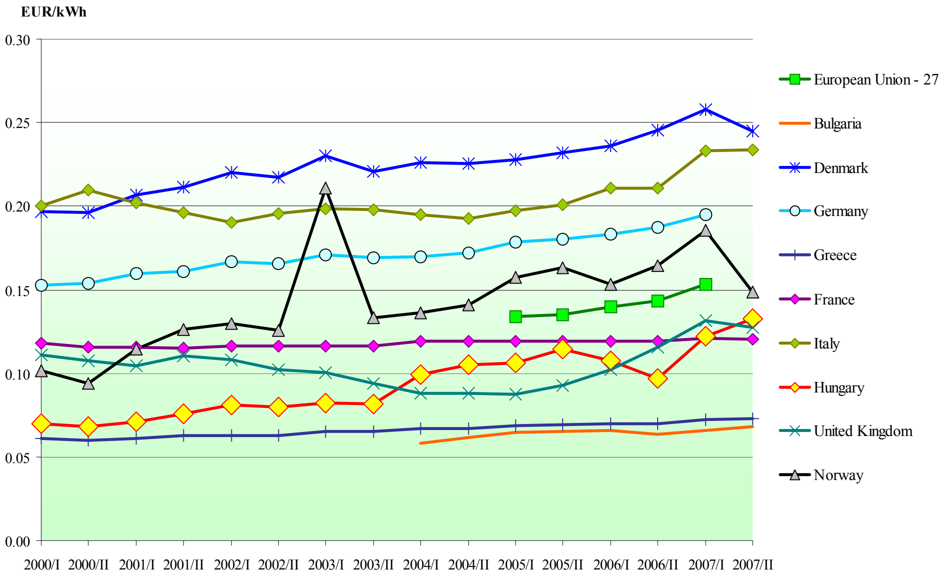

Figure 37 Half-yearly price for domestic electrical consumers (including all taxes)

Note: The prices are for the households with electrical consumption in the interval 1200 - 3500 kWh/yr.

Source: EUROSTAT 2008.

8.2.3 Assumptions of financial operations

The financial analyses are conducted based on real prices, i.e. not taking into account the expected inflation. Since the costs of energy conservation are mainly borne by households, the investment costs of technological options are estimated as the final price including the value added tax (and other taxes included in the price).

8.2.4 Split of investments in combined systems to separate analyses of space heating and water heating

For those systems which supply both space heating and hot water, the investment costs allocated for space heating are 92%, calculated as the share of heating energy requirement for space heat of an average Hungarian household[65]. The rest of the investment costs are allocated for water heating.

8.2.5 Penetration rates of mitigation technologies

In the mitigation case, the advanced technologies replace the reference technologies exchanged due to their stock turnover. They also replace some of the technologies currently installed and

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[65] Calculated as the dwelling heating energy requirement [calculated as the product of the average heating requirement (220 kWh/m^2-yr.) and the average size of a dwelling (74m^2)] divided by the dwelling energy requirement [the same as just described] plus the household water heating requirement [calculated as the energy heating requirement for water heating [0.06 kWh/liter] multiplied by 65 liters/household consumed per day and multiplied by 365 days/yr.]. Calculations are based on Kemna *et al.* (2007).

which will remain until 2025. This section outlines the assumptions about penetration rates of the mitigation technologies and other related assumptions.

First, it is assumed that the thermal envelope of all household stock, which is not retrofitted in the reference scenario and which remains at least until 2025, is retrofitted from 2008 to 2025. The stock is retrofitted by the same number of households per annum, i.e. the number of retrofitted households per year is the total stock divided by seventeen years. The technological options aimed to improve the thermal envelope retrofit of the existing buildings are the same as in the reference case. As regarding to the households which will be constructed from 2008, it was assumed that their whole stock would be constructed following the passive energy design (see Section 6.1.5, p. 104).

It is assumed that households install condensing gas boilers, or pellet boilers, or solar thermal systems backed-up with pellet boilers, or heat pumps for space and water heating (according to Table 32, p. 158) instead of the reference technologies. Advanced technologies replace the whole stock of space heating solutions in the old single-family houses (constructed until 1992), traditional and industrialized buildings by 2025. As with the thermal envelope improvement, the stock is retrofitted by the same number of households per annum. The only exception is made for the premise gas heating. This is one of the most economical and efficient space heating systems in Hungary and it is likely that a share of households would prefer to leave this system in place. Therefore, if the premise gas heating was not replaced in the reference scenario by another standard system, the author made the choice not to exchange this premise heating with mitigation solutions. It is also important to mention that due to infrastructural and spatial barriers only half of single-family houses can switch from the reference technologies to pellets or solar heating backed-up with pellet boilers, similarly only half of single-family houses can switch to ground-source heating pumps (see Sections 6.2.1 on p. 108, Section 6.2.2 on p. 110, and Section 6.2.3 on p. 111).

One of the easiest and most beneficial technological options is installation of space heating and water demand controls. It was assumed that households with district or central building heating are retrofitted with TRVs and all other households except those fuelled with coal and traditional biomass are retrofitted with programmable thermostats. Also, installation of individual heat exchanges and heat meters was applied to households with district or central building heating. All water heating system and appliances are retrofitted with low-flow fixtures. All water heating systems and appliances are retrofitted with low-flow fixtures. The number of households retrofitted with space heating per annum until 2025 is the same as the number in which the thermal envelope is retrofitted. The installation of water saving fixtures is a very simple option and it is assumed that it is possible to apply this option to the whole stock within five years.

For the electrical appliances modelled, the penetration rates in the mitigation case are the same as in the reference case. For the mitigation case, the purchased appliances are the best (presently known and estimated) available on the market for the projected year. It is assumed that the costs in real terms of the reference and the best available appliances do not change over time i.e. the current appliances become cheaper and the newer appliances become more expensive. The efficiency and cost details of the appliances and lights purchased in the reference scenario are described in Sections 6.5.1 - 6.5.4 (p. 122).

As mentioned in Section 7.1.2 (p. 136), replacing the six most commonly used lamps will produce about 85% of the total energy savings associated with lighting in households. Because of this, the mitigation case focuses on the exchange of only these six lamps. The exchange of lights is a very simple option and therefore is carried out on the whole stock in the first year of the modelling period.

8.3 Evaluation of the key individual CO_2 mitigation options

The economic evaluation of the mitigation options is subject to limitations described in Section 4.5.1 (p. 66) and Section 4.5.2 (p. 68). Among these, the most limiting factor for assessing the mitigation costs of technologies is the fact that the associated barriers and co-benefits are being disregarded. This section describes the results of the bottom-up assessment applied to mitigation options independently from each other. This information is useful for the design of policy tools in targeting a particular option and for the households which prefer to and are able to exchange a particular technology. Also Section 4.5 (p. 66) mentions that the application of measures does not necessarily follow the sequential technological opportunities according to their marginal cost-effectiveness but it is rather an integrated multi-attributive decision process. For this reason, both results of independent and subsequent installations of the mitigation options are useful

Figure 38 illustrates and Table 34 details the potential CO_2 savings and costs which result from the installation of individual mitigation options. In Table 34, the options related to space heating (including insulation) are grouped according to the building types, while options related to water heating and electrical efficiency (excluding water heating) are grouped in separate categories.

The options are ranked according to their cost-effectiveness within their groups. The potentials from individual options cannot be simply added together because of possible double-counting if the options are targeted to the same baseline technologies and energy end-uses (see Section 3.3, p. 39).

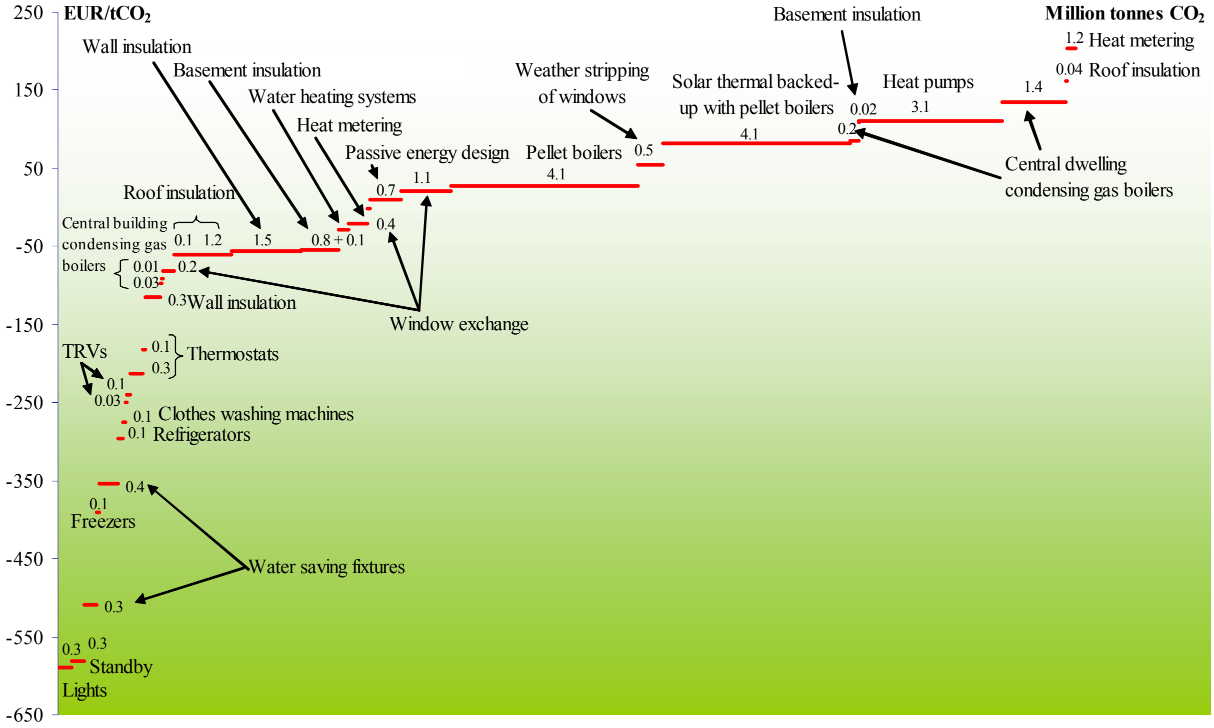

Figure 38 Potential and costs of individual options for CO_2 mitigation

Note: Some thermal technological options are applied to different types of buildings and they are referred to several times in the figure.

Note: The potentials from individual options cannot be simply added together because of possible double-counting if the options are targeted to the same baseline technologies and energy end-uses.

Figure 38 shows that technological options supplying the potential for CO_2 mitigation at negative costs are available for each building type and each energy end-use. The top negative-cost measure in terms of cost-effectiveness is the exchange of incandescent lamps with CFLs. This is in line with the conclusion of other studies conducted in economies in transition and worldwide according to Levine *et al.* (2007). It is followed by the reduction of electrical consumption of TV- and PC- related appliances in the low power mode and efficient appliances such as freezers, refrigerators, and clothes washing machines, the application of which is justified by the high price of electricity in Hungary. Installation of heat and hot water demand controls such as low-flow fixtures, TRVs and programmable thermostats ranks the third. Many options aimed at insulation of building components (walls, basements, and roofs) and weather stripping or exchange of windows are characterized with negative mitigation costs as do actions towards installation of condensing central building gas boilers. Installation of improved water heating systems and individual central and district heat meters in traditional buildings are the last in the list of measures with negative costs of CO_2 mitigation.

There is a limited number of technological options with costs in the interval 0-100 EUR/tCO_2. Among these, the application of passive energy design to buildings constructed from 2008 is the only option with the mitigation costs between 0 and 20 EUR/tCO_2. Window exchange and the installation of pellet boilers for water and space dwelling heating in single-family houses (constructed before 1992) are characterized with the costs between 20 and 50 EUR/tCO_2. Weather stripping of windows and installation of solar thermal systems backed-up with pellet boilers in single-family houses (constructed before 1992), and installation of condensing gas dwelling central boilers in households of traditional multi-residential buildings are in the category of options with the mitigation costs of 50 – 100 EUR/tCO_2.

Table 34 Potential available through application of options installed separately, 2025

Mitigation measure	CO_2 savings	Costs of mitigated CO_2	Energy savings	Costs of energy savings
	Thousands tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh
Buildings constructed using industrialized technology				
Installation of thermostatic radiator valves	89	-240	529	0.01
Wall insulation	332	-115	1931	0.03
Installation of condensing gas central building boilers for space heating	6	-97	30	0.04
Window exchange	236	-81	1369	0.04
Basement insulation	19	109	110	0.07
Roof insulation	38	161	219	0.08
Individual metering of district and central heating	177	203	1057	0.09
Traditional buildings				
Installation of thermostatic radiator valves	26	-249	131	0.01
Installation of programmable thermostats	68	-183	335	0.02
Installation of condensing central building gas boilers for space heating	35	-91	171	0.04
Roof insulation	90	-61	449	0.04
Basement insulation	58	-54	290	0.05
Individual metering of consumed district and central heat	51	-1	263	0.06
Window exchange	399	-21	1987	0.05
Installation of condensing central gas dwelling boilers for space heating	169	86	837	0.07
Old single-family houses (constructed before 1992)				
Installation of programmable thermostats	255	-213	1261	0.01
Roof insulation	1172	-60	5173	0.04
Wall insulation	1500	-56	6620	0.04
Basement insulation	757	-54	3340	0.04
Weather stripping of windows	4073	27	1447	0.30
Installation of pellets boilers for water and space central dwelling heating	1067	21	4709	0.06

Mitigation measure	CO_2 savings	Costs of mitigated CO_2	Energy savings	Costs of energy savings
	Thousands tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh
Window exchange	528	54	1347	0.05
Installation of solar collectors for water heating backed up with pellet boilers for water and space central dwelling heating	4073	82	6348	0.13
Installation of condensing gas boiler for water and space central dwelling heating	1381	134	3206	0.08
Installation of pumps for water and space central dwelling heating	3093	110	14778	0.05
Buildings constructed after 2008				
Application of passive energy design	697	9	4651	0.05
Appliances and lights				
Exchange of incandescent lamps with CFLs	305	-589	935	0.01
Reduction of electricity consumption by TV and PC-related equipment in low power and off - modes	266	-582	815	0.01
Efficient freezers	67	-391	206	0.07
Efficient refrigerators	107	-297	328	0.11
Efficient clothes washing machines	54	-275	167	0.11
Water heating				
Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	263	-508	1231	0.00
Installation of water saving fixtures in households with central district hot water	400	-354	1942	0.00
Improved combi- space and water heating systems and dedicated water heating appliances	217	-28	420	0.14

The rest of the options are considered as expensive and have mitigation costs in the interval of c. 100 – 200 EUR/tCO_2. These include the installation of central dwelling condensing gas boilers and heating pumps in single-family houses (constructed before 1992) and the installation of individual heat meters, together with roof and basement insulation in buildings constructed using industrialized technology.

In terms of the quantity of CO_2 reductions, the improvement of the thermal envelope, fuel switch and efficiency improvement of heating systems in old single-family houses (constructed before 1992) are able to supply the largest potential in the residential sector. Thus, the installation of pellet boilers and solar space and water heating systems backed-up with pellet boilers supplies c. 4.1 million tonnes of CO_2/option; the installation of heat pumps and condensing boilers in this type of household can provide potential of c. 3.1 and c. 1.4 million tonnes of CO_2 respectively (please note that these options exclude or reduce the potential of each other if applied in sequence). Insulation of building components such as walls, roofs, basements, window exchange and weather stripping of windows may result in annual CO_2 savings of c. 1.5, 1.2, 0.8, 1.1, and 0.5 million tonnes respectively in 2025; installation of programmable thermostats can save 0.2 million tonnes CO_2.

Among other options is the application of passive energy design to buildings constructed from 2008 which can save 0.7 million tonnes of CO_2 by 2025. Improved water heating systems and installation of water saving fixtures can cut 0.2 and 0.7 million tonnes CO_2 respectively. Installation of CFLs, exchange of refrigerators, and reduction of electrical consumption by TV- and PC-related equipment in low power mode could save 0.1 – 0.3 million tonnes of CO_2/option. Thermal options in industrialized buildings such as window exchange, insulation of walls, and installation of individual heat meters can save 0.2 – 0.3 million tonnes of CO_2/option. Thermal options in traditional multi-residential buildings such as window exchange and installation of central dwelling gas condensing boilers can save 0.2 – 0.4 million tonnes CO_2/option. The rest of the options supply less than 0.1 million tonnes of CO_2/option.

Table 34 also presents the energy savings from the implementation of CO_2 mitigation options and associated costs of conserved energy. If the costs of conserved energy are higher than the expected energy price in 2025, this option has not paid for itself in energy cost savings within this period. *It is important to highlight that the most efficient options in terms of the amount of saved CO_2 (as baseline share) or in terms of CO_2 mitigation cost-effectiveness are often not the same as the most efficient options for saving energy and energy conservation cost-effectiveness.* For instance, installation of a pellet boiler for space and water heating to a household can improve heating efficiency by 5% - 25% depending on the reference technology but pellet combustion neutralize 100% of CO_2 emissions due to its zero emission factor. Therefore, the results of the research can be applied to the analysis of energy efficiency options with great caution.

8.4 Countrywide potential for CO_2 mitigation and its supply curve

This section discusses the results of the bottom-up mitigation assessment of the mitigation options conducted with the supply curve method. The advantage of the supply curve method is that it allows an estimation of the total potential to be made without double-counting the mitigation potential supplied by individual options targeted at the same baseline technologies and energy end-uses (for instance, insulation improvement reduces the need for space heating and, thus, also reduces the energy saving potential from installation of more efficient heating systems). For more details about the methodology please see Section 3.3 (p. 39). *The principal difference of the results described in this section from the previous one is that this section describes results without double-counting the potential supplied by technological options. Therefore, the potential estimates described in this section can be added together.*

Figure 39 illustrates the potential for CO_2 reductions as a function of costs for investigated technological options for CO_2 mitigation. Table 35 decodes the numbered measures and provides detailed data on the associated CO_2 mitigation potential and costs. Table 35 also gives the estimates for energy saving which will result from implementation of mitigation options as well as the required investments into each of the options and the subsequent energy cost savings.

Figure 39 demonstrates a wide range of opportunities for negative- and low- cost CO_2 mitigation in all studied types of residential buildings. In general, the thermal options supply the most significant savings in both terms of absolute values as well as the share of their baseline emissions compared to the electrical efficiency options.

Figure 39 shows that there is a potential for CO_2 mitigation at negative costs in 2025 with various technological options, such as efficient appliances and lighting technologies, space heating and water flow controls, TV- and PC- related equipment with reduced electrical consumption in low power mode, construction according to the passive energy design principles and many insulation options. If all these options were implemented, they would cumulatively reduce CO_2 mitigation by 5.1 million tonnes in 2025. This is about 29% of total CO_2 emissions emitted by the residential sector of Hungary in 2025. Implementation of the mitigation options at negative cost of CO_2 would result in energy savings of 22.1 TWh/yr., which is about 26% of the total final energy consumption of the residential sector in 2025. Realisation of this potential would require total investment over the period 2008 – 2025 of about 9.6 billion EUR but would save 17.1 billion EUR in energy costs.

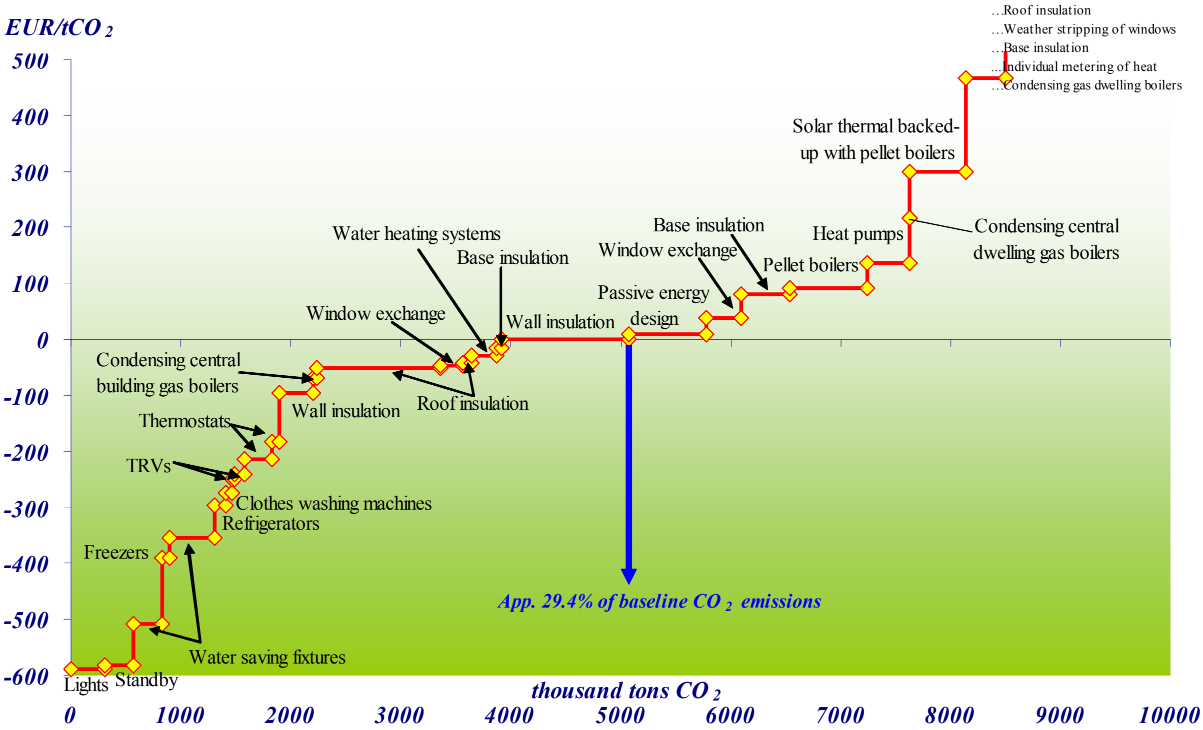

Figure 39 Supply curve of CO_2 mitigation for the residential sector of Hungary, 2025

Table 35 Potential and costs of CO_2 mitigation estimated with the supply curve method, 2025

Rank	Measure	CO_2 savings in 2025	Cost of mitigated CO_2	Energy savings in 2025	Investments 2008-2025	Saved energy costs 2008-2025
		Thousand tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	Million EUR	Million EUR
1	Exchange of incandescent bulbs with CFLs	305	-589	935	73	551
2	Reduction of electricity consumption of TV and PC-related equipment in low power and off - modes	266	-582	815	20	391
3	Installation of water saving fixtures in households with district and central hot water	263	-508	1231	501	868
4	Efficient freezers	67	-391	206	239	245
5	Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	400	-354	1942	78	1905
6	Efficient refrigerators	107	-297	328	103	1637
7	Efficient clothes washing machines	54	-275	167	126	2892
8	Installation of TRVs in households of traditional multi-residential buildings	26	-249	131	13	66
9	Installation of TRVs in households of buildings constructed using industrialized technology	89	-240	529	80	258
10	Installation of programmable thermostats old single-family houses (constructed before 1992)	255	-213	1261	204	654
11	Installation of programmable thermostats in households of traditional multi-residential buildings	68	-183	335	95	167
12	Wall insulation of buildings constructed using industrialized technology	304	-96	1763	159	14
13	Installation of central building condensing gas boilers for space heating in households of traditional multi-residential buildings	31	-70	154	76	77
14	Roof insulation of old single-family houses (constructed before 1992)	1127	-51	4948	2858	2327
15	Window exchange in buildings constructed using industrialized technology	205	-47	1190	760	825
16	Roof insulation of traditional multi-residential buildings	83	-42	413	276	208
17	Improved combi- space and water heating systems and dedicated water heating appliances	217	-28	420	50	1536

Rank	Measure	CO_2 savings in 2025	Cost of mitigated CO_2	Energy savings in 2025	Investments 2008-2025	Saved energy costs 2008-2025
		Thousand tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	Million EUR	Million EUR
18	Basement insulation of traditional multi-residential buildings	50	-16	248	166	125
19	Wall insulation of old single-family houses (constructed before 1992)	1160	-0.4	5092	3753	2394
20	Application of passive energy design to single-family and multi-residential buildings constructed from 2008	697	9	4651	3927	1841
21	Window exchange in traditional multi-residential buildings	326	38	1626	1448	818
22	Base insulation of old single-family houses (constructed before 1992)	439	80	1926	1905	905
23	Installation of pellets boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	702	92	258	1336	574
24	Installation of pumps for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	386	136	1877	1744	1531
25	Installation of central building condensing gas boilers for space heating of households in buildings constructed using industrialized technology	2	216	11	607	741
26	Installation of solar collectors backed-up with pellet boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	511	300	818	2488	600
27	Installation of condensing gas boilers for central dwelling space heating in old single-family houses (constructed before 1992)	359	467	773	2109	188
28	Individual metering of consumed district and central heat in households of traditional multi-residential buildings	17	558	90	169	59
29	Base insulation of buildings constructed using industrialized technology	8	743	43	131	20
30	Weather stripping of windows in old single-family houses (constructed before 1992)	64	746	419	1367	744
31	Installation of central dwelling condensing gas boilers for space heating in households of traditional multi-residential buildings	56	829	278	715	177
32	Roof insulation of buildings constructed using industrialized technology	15	897	85	340	40
33	Individual metering of district and central heat in households of buildings constructed using industrialized technology	65	1113	386	1062	284

There is only one option with associated mitigation costs in the interval from 0 to 20 EUR/tCO_2 in 2025, namely application of passive energy design to newly constructed buildings. Even so, this option can save 0.7 million tonnes CO_2 or 4.0% of the reference emissions of the residential sector in 2025. A switch to passive energy design would help to avoid final energy consumption of 4.7 TWh or c. 5.5% of reference energy consumption of the sector in 2025. About 3.9 billion EUR would be needed to invest in newly constructed buildings in the period of 2008 - 2025 but c. 1.8 billion EUR would be paid back during this period.

Also, there is only one option with mitigation costs in the interval from 20 to 50 EUR/tCO_2 in 2025, this is window exchange in traditional multi-residential buildings. This option can save 0.3 million tonnes CO_2 or 1.9% of the reference emissions of the residential sector in 2025 and 1.6 TWh or c. 1.9% of reference energy consumption of the sector in 2025. The investment costs and saved energy costs from 2008 to 2025 are c. 1.4 billion EUR c. 0.8 billion EUR respectively.

There are two options with associated mitigation costs in the interval from 50 to 100 EUR/tCO_2. These are basement insulation and fuel switch to pellets in old single-family houses (constructed before 1992). Cumulatively, they are able to supply about 1.1 million CO_2 in 2025, i.e. c. 6.6% of the sectoral baseline emissions. These savings correspond to c. 2.2 TWh of final energy or c. 2.6% of the sectoral final energy consumption. The investment needs over 2008 -2025 are estimated to be 3.2 billion EUR with 1.5 billion EUR are returned in the form of saved energy costs.

The list of “expensive” options which are above 100 EUR/tCO_2, includes a few insulation options, weather stripping, installation of individual heat meters, and switch to more efficient space heating solutions. The fact that these options are expensive if they are implemented incrementally does not mean that, if these options are implemented individually, they are also expensive (see the results described on the previous section). These “expensive” options are able to reduce c. 6.6% and 5.7% of reference CO_2 emissions and final energy consumption. These savings correspond to an additional 1.5 million tonnes of CO_2 and 4.8 TWh/yr. savings in 2025. “Expensive” options would cost in total about 10.7 billion EUR over 2008 – 2025.

The technical potential achieved due to the implementation of all investigated measures is estimated to be as high as c. 50.5% and 42% of the sectoral baseline CO_2 emissions and final energy consumption in 2025. In absolute terms, these savings represent about 8.7 million tonnes of CO_2 and 35.3 TWh/yr. The total investments over 2008 – 2025 needed to realize the maximum potential are about 29.0 billion EUR and they return 25.7 billion EUR in terms of saved energy costs. Figure 40 and Figure 41 illustrate the cumulative potential for CO_2 reduction and final energy consumption of the residential sector of Hungary over the projection period of 2008 – 2025. Table 36 details the investment requirement over 2008 – 2025 in realisation of the described technological options. Table 37 calculates the saved energy costs over 2008 – 2025 resulting from the implementation of these options.

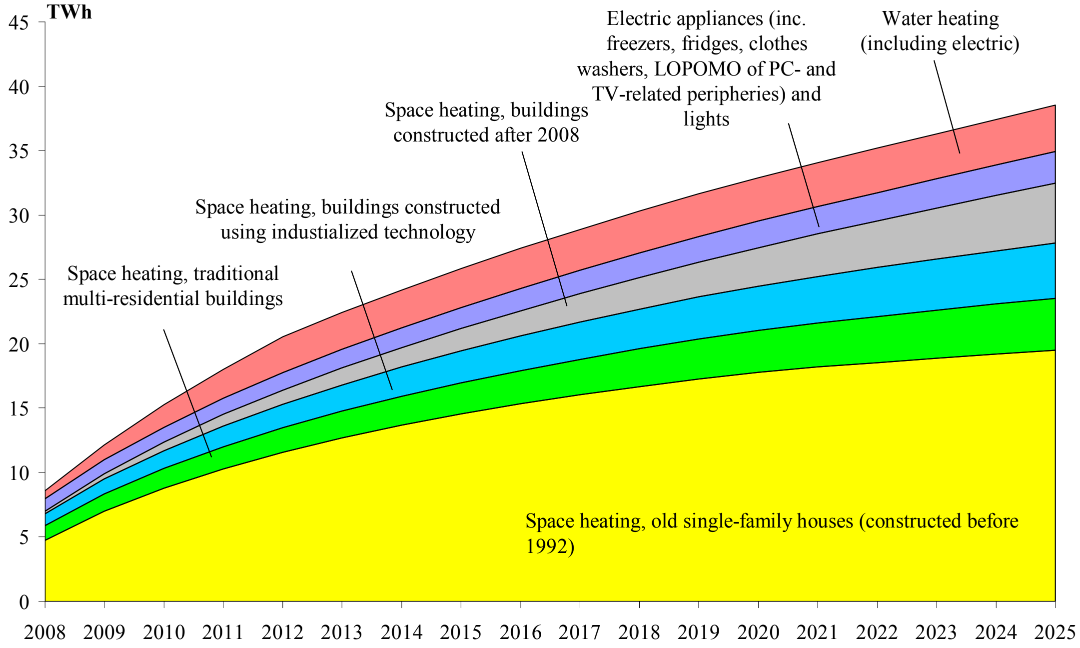

Figure 40 Cumulative potential final energy savings, 2008 - 2025

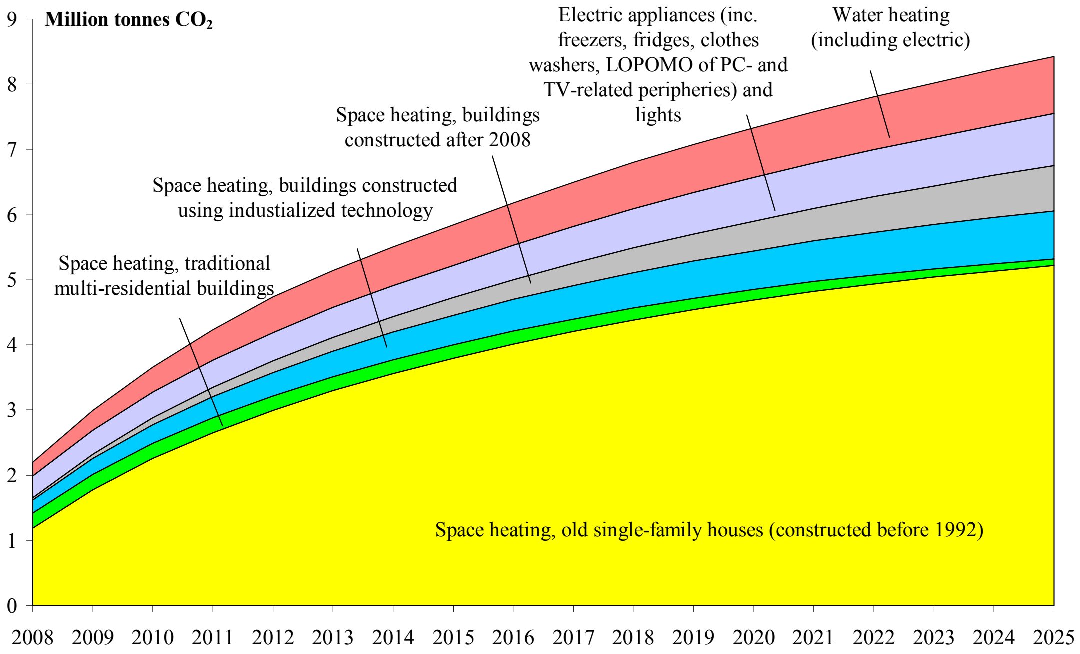

Figure 41 Cumulative potential CO_2 reductions, 2008 - 2025

Source: research results.

Table 36 Annual investment costs into mitigation options, million EUR

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	*Total*
Thermal retrofit of households in traditional houses																			
TRVs	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	*13*
Programmable thermostats	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	*95*
Central building condensing gas boilers for space heating	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	*76*
Roof insulation	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	*276*
Basement insulation	4	4	4	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	*166*
Window exchange	90	89	87	86	85	84	83	82	81	80	79	78	77	76	75	74	73	72	*1448*
Individual metering	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	*169*
Central dwelling condensing gas boilers for space heating	40	40	40	40	40	40	40	40	40	40	40	40	40	39	39	39	39	39	*715*
Total	174	173	172	171	169	168	167	166	165	164	163	162	160	159	158	157	156	155	*2959*
Thermal retrofit of households in industrialized buildings																			
TRVs	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	*80*
Central building condensing gas boilers for space heating	49	49	49	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	*159*
Wall insulation	6	6	6	49	49	49	49	49	49	49	49	49	49	49	49	49	49	49	*760*
Window exchange	1	1	1	44	44	43	42	42	41	41	40	40	39	39	38	38	37	37	*607*
Base insulation	14	14	14	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	*131*
Roof insulation	46	45	45	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	*340*
Individual metering of district and central heat	59	59	59	59	59	59	59	59	59	59	59	59	59	59	59	59	59	59	*1062*
Total	179	179	178	177	177	176	176	175	175	174	173	173	172	172	171	171	170	170	*3138*
Thermal retrofit of old single-family houses (constructed before 1992)																			
Installation of programmable thermostats	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	*204*
Roof insulation	106	106	106	208	208	208	208	208	208	208	208	208	208	208	208	208	208	208	*3445*
Wall insulation	208	208	208	159	159	159	159	159	159	159	159	159	159	159	159	159	159	159	*3007*
Basement insulation	159	159	159	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	*2064*
Pellet boilers for space and water heating	370	355	341	328	316	305	294	283	273	263	253	244	235	227	219	211	203	196	*4915*
Heat pumps for space and water heating	222	219	216	213	211	208	205	202	200	197	195	192	190	187	185	182	180	178	*3581*

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	*Total*
Solar thermal backed-up with pellets	139	136	134	131	128	125	123	120	118	118	119	120	121	169	184	175	167	160	*2488*
Central dwelling condensing gas boiler	117	117	117	117	117	117	117	117	117	117	117	117	117	117	117	117	117	117	*2109*
Weather stripping of windows	97	82	82	81	80	79	78	77	76	75	74	73	72	71	70	68	67	66	*1367*
Total	1119	1086	1069	1053	1039	1024	1010	997	983	971	959	948	937	935	926	914	902	891	*17764*
Thermal retrofit of buildings constructed after 2008																			
Passive energy design	253	245	234	214	206	204	203	203	204	206	209	213	217	220	223	224	225	222	*3,927*
Total	*253*	*245*	*234*	*214*	*206*	*204*	*203*	*203*	*204*	*206*	*209*	*213*	*217*	*220*	*223*	*224*	*225*	*222*	*3,927*
Appliances and lights																			
Efficient fridges	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	*73*
Efficient freezers	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	*20*
Efficient clothes washing machines	11	11	12	12	12	12	12	13	13	13	14	14	14	14	15	15	16	16	*239*
Reduction of electricity LOPOMO consumption by TV and PC-related equipment	4	4	4	4	4	4	5	5	5	5	6	6	7	7	8	8	9	10	*103*
Exchange of incandescent lamps with CFLs[66]	87	-9	-9	-9	-9	-9	-9	87	-9	-9	-9	-9	-9	-9	87	-9	-9	-9	126
Total	*107*	*11*	*11*	*12*	*12*	*12*	*12*	*109*	*14*	*15*	*15*	*16*	*17*	*18*	*115*	*21*	*22*	*23*	*562*
Water heating																			
Improved combi- space and water heating systems and dedicated water heating appliances	33	32	31	31	31	30	30	30	30	29	29	28	28	23	20	21	22	23	501
Water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	12	12	12	11	11	2	2	2	2	2	2	2	2	1	1	1	1	1	78
Water saving fixtures in households with central and district hot water	8	9	9	9	9	1	1	0	1	1	1	1	1	1	1	1	1	1	50
Total	*52*	*52*	*52*	*51*	*51*	*33*	*32*	*32*	*32*	*31*	*31*	*30*	*30*	*25*	*23*	*24*	*24*	*25*	*628*
Total	***1883***	***1746***	***1716***	***1678***	***1653***	***1617***	***1601***	***1682***	***1573***	***1561***	***1551***	***1542***	***1534***	***1529***	***1617***	***1510***	***1499***	***1486***	***28979***

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[66] Negative investment costs of lighting are explained by the fact that the incandescent pulps have the lifetime of less than a year and, therefore, have to be purchased annually whereas the CFLs serve several years. Due to this reason, the additional costs of CFLs purchase could be negative at years when they were not significant amount of CFL purchases.

Table 37 Saved energy costs of mitigation options, million EUR

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	Total
Thermal retrofit of households in traditional houses																			
Installation of TRVs	0.3	0.7	1.0	1.4	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.6	5.0	5.4	5.9	6.4	6.9	7.4	*65*
Programmable thermostats	0.8	1.7	2.6	3.5	4.4	5.3	6.3	7.3	8.4	9.4	10.5	11.7	12.8	14.0	15.3	16.5	17.8	19.1	*167*
Condensing building central gas boilers for space heating	0.4	0.8	1.2	1.6	2.0	2.5	2.9	3.4	3.9	4.4	4.9	5.4	5.9	6.5	7.0	7.6	8.2	8.8	*77*
Roof insulation	1.0	2.1	3.2	4.3	5.5	6.7	7.9	9.2	10.4	11.8	13.1	14.5	15.9	17.3	18.8	20.4	21.9	23.6	*208*
Basement insulation	0.6	1.3	1.9	2.6	3.3	4.0	4.7	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.2	13.2	14.1	*125*
Window exchange	4.1	8.3	12.6	17.1	21.6	26.3	31.1	36.0	41.1	46.3	51.6	57.0	62.6	68.3	74.2	80.2	86.4	92.7	*818*
Individual metering	0.5	0.9	1.3	1.7	2.1	2.5	2.8	3.2	3.5	3.8	4.0	4.3	4.5	4.6	4.8	4.9	5.0	5.1	*59*
Condensing dwelling central gas boilers for space heating	1.3	2.5	3.7	4.8	6.0	7.0	8.1	9.1	10.1	11.0	11.9	12.7	13.4	14.1	14.7	15.2	15.6	15.9	*177*
Total	*9*	*18*	*28*	*37*	*47*	*56*	*66*	*77*	*87*	*97*	*108*	*119*	*130*	*141*	*152*	*163*	*175*	*187*	*1697*
Thermal retrofit of households in industrialized buildings																			
Installation of TRVs	1.4	2.8	4.2	5.7	7.2	8.7	10.2	11.7	13.3	14.9	16.5	18.1	19.7	21.3	23.0	24.8	26.5	28.2	*258*
Condensing building central gas boilers for space heating	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.4	1.5	*14*
Wall insulation	4.2	8.3	12.7	17.2	21.8	26.5	31.3	36.3	41.4	46.7	52.1	57.6	63.0	68.8	74.9	81.1	87.4	93.9	*825*
Window exchange	45.9	45.3	44.7	44.2	43.6	43.0	42.4	41.9	41.3	40.8	40.3	39.8	39.2	38.7	38.2	37.7	37.2	36.7	*741*
Base insulation	0.1	0.2	0.3	0.4	0.5	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.7	1.8	2.0	2.1	2.3	*20*
Roof insulation	0.2	0.4	0.6	0.8	1.1	1.3	1.5	1.8	2.0	2.3	2.5	2.8	3.0	3.3	3.6	3.9	4.2	4.5	*40*
Individual metering of district and central heat	2.4	4.8	7.0	9.1	11.1	13.0	14.7	16.2	17.6	18.9	19.9	20.8	21.3	21.7	21.9	21.8	21.4	20.6	*284*
Total	*54*	*62*	*70*	*78*	*86*	*94*	*101*	*109*	*117*	*125*	*133*	*141*	*149*	*157*	*165*	*173*	*180*	*188*	*2183*
Thermal retrofit of old single-family houses																			
Programmable thermostats	3.5	7.0	10.6	14.2	17.9	21.7	25.5	29.4	33.4	37.5	41.6	45.8	50.0	54.3	58.7	63.1	67.6	72.1	*654*
Roof insulation	11.5	23.4	35.6	48.2	61.1	74.3	88.0	102.0	116.4	131.3	146.5	162.1	178.2	194.7	211.7	229.1	247.0	265.4	*2327*
Wall insulation	11.9	24.1	36.6	49.6	62.8	76.5	90.5	105.0	119.8	135.1	150.7	166.8	183.4	200.4	217.8	235.7	254.1	273.0	*2394*
Basement insulation	4.5	9.1	13.9	18.7	23.8	28.9	34.2	39.7	45.3	51.1	57.0	63.1	69.3	75.8	82.4	89.2	96.1	103.3	*905*
Pellet boilers for space and water heating	4.1	8.0	11.9	15.7	19.3	22.8	26.2	29.5	32.6	35.6	38.4	41.0	43.4	45.6	47.6	49.3	50.7	51.9	*574*
Heating pumps for space and water heating	15.7	29.9	42.8	54.5	65.2	74.8	83.5	91.3	98.1	104.0	108.7	112.5	115.2	113.8	110.5	107.1	103.5	99.7	*1531*

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	Total
Installation of solar thermal backed-up with pellets	4.1	8.1	11.9	15.6	19.1	22.4	25.6	28.6	31.5	34.3	37.0	39.7	42.3	47.1	52.2	56.7	60.5	63.7	*600*
Installation of condensing gas central dwelling boiler	1.3	2.7	4.0	5.2	6.5	7.7	8.8	9.9	11.0	11.9	12.8	13.6	14.4	15.0	15.5	15.8	16.1	16.1	*188*
Weather stripping	65.3	60.9	57.2	53.9	51.0	48.3	45.8	43.4	41.0	38.8	36.6	34.5	32.5	30.6	28.8	26.9	25.0	23.0	*744*
Total	122	173	224	276	327	377	428	479	529	579	629	679	729	777	825	873	921	968	*9916*
Thermal retrofit of buildings constructed after 2008																			
Application of passive energy design	8.6	17.5	26.8	36.3	45.6	55.0	64.9	75.4	86.6	98.5	111.2	124.9	139.5	155.5	172.6	191.1	210.7	231.5	*1852*
Total	*9*	*18*	*27*	*36*	*46*	*55*	*65*	*75*	*87*	*98*	*111*	*125*	*139*	*155*	*173*	*191*	*211*	*232*	*1852*
Appliances and lights																			
Efficient fridges	2.4	4.9	7.5	10.3	13.3	16.4	19.6	23.0	26.6	30.3	34.2	38.3	42.5	46.9	51.5	56.2	61.2	66.3	*551*
Efficient freezers	2.3	4.6	6.8	9.1	11.4	13.7	15.9	18.2	20.5	22.7	25.0	27.3	29.7	32.0	34.4	36.7	39.1	41.5	*391*
Efficient clothes washing machines	0.7	1.5	2.4	3.5	4.6	5.9	7.3	8.9	10.6	12.4	14.4	16.6	19.0	21.5	24.2	27.2	30.3	33.7	*245*
Reduction of energy consumption by TV and PC-related equipment in low power and off - modes	11.0	21.4	30.8	40.6	50.7	60.8	71.2	80.5	90.1	100.1	110.3	115.7	122.3	129.3	137.0	145.5	154.7	164.7	*1637*
Exchange of incandescent lamps with CFLs	135.5	138.2	141.0	143.8	146.6	149.4	152.3	155.2	158.2	161.2	164.4	167.6	170.9	174.3	177.8	181.4	185.1	188.9	*2892*
Total	*152*	*171*	*189*	*207*	*227*	*246*	*266*	*286*	*306*	*327*	*348*	*366*	*384*	*404*	*425*	*447*	*470*	*495*	*5716*
Water heating																			
Improved combi- space and water heating systems and dedicated water heating appliances	8.1	15.6	22.1	27.3	31.0	36.7	42.0	47.1	51.7	56.0	59.9	63.2	65.9	67.9	68.8	69.2	68.7	66.7	868
Water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	18.9	38.0	57.3	76.8	96.4	100.6	104.7	108.8	112.8	116.8	120.8	124.7	128.5	132.3	136.0	139.7	143.3	148.1	1905
Water saving fixtures in households with central and district hot water	31.5	39.5	47.3	56.2	63.8	68.2	72.6	77.3	82.2	87.2	92.4	97.8	103.1	109.4	116.0	123.1	130.5	138.1	1536
Total	*59*	*93*	*127*	*160*	*191*	*205*	*219*	*233*	*247*	*260*	*273*	*286*	*298*	*310*	*321*	*332*	*342*	*353*	*4309*
Total	***404***	***535***	***664***	***794***	***922***	***1034***	***1146***	***1259***	***1372***	***1487***	***1603***	***1715***	***1828***	***1943***	***2059***	***2178***	***2298***	***2421***	***25661***

8.5 Sensitivity analysis of mitigation costs

The results of mitigation assessments are sensitive to the background assumptions, especially to technological costs, discount rates, fuel prices, and emission factors of energy. Due to this reason the experts (Halsnæs *et al.* 1999) recommend to consider alternative sensitivity cases in addition to the main scenario. For the dissertation research, the most influential parameters on the mitigation costs were the discount rate, fuel and energy prices, and emission factors.

Section 8.2.1 (p.160) discusses different approaches to setting the discount rate in the mitigation analysis. As Halsnæs *et al.* (1999) found, normally the mitigation costs are calculated for more than one rate to give guidance on how sensitive the results are: at high rates technological options with a long lifetime become unattractive compared to those with a shorter lifetime. Even small changes in the discount rate can cause reverse ranking of technological options. In this dissertation research, two more discount rates are considered, 4% and 8%, to characterize higher and lower economic stability of the Hungarian economy respectively. The short summary of results is presented in Figure 42; the information about potential and costs of technological options installed individually and according to the supply curve method is detailed in Appendix I and Appendix II for the scenarios with the discount rates 4% and 8% respectively.

Section 8.2.2 (p. 162) discusses the fuel and energy price forecast from 2008 to 2025 which was accepted as the main scenario. It would also be useful to consider another fuel price forecast because the fuel and energy prices are difficult to predict in the long-term. According to Feiler (pers. comm.), the natural gas price might grow by 35% by the end of 2008. The natural gas price growth will impact on the prices of other fuels (if the fuel switch is possible) and electricity. For electricity it can be estimated through the share of electricity produced by gas. The impact of the natural gas price increase on other fuels was assumed to be 20% of the natural gas price increase (based on the cross-price elasticity estimates given by IEA 2006c). As in the main scenario, fuel and energy prices are assumed to grow by 1.5%/yr. in real terms from 2009 to 2025. The short summary of results is presented in Figure 42; the information about potential and costs of technological options installed individually and according to the supply curve method is detailed in Appendix III for this scenario with higher energy prices.

Section 7.2.1.2 (p. 141) discusses the estimate of CO_2 emission factor for the generation of electricity from 2008 to 2025. This section concluded that the emission factor decreases until 2015 and then starts growing due to installation of a new lignite plant. Taking into account the targets of the European Commission's Climate Change and Energy Package by January 2008, the capacity plan of Hungary may change. There are discussions about the commissioning of a new nuclear power plant. Alternatively; the utilization of renewable energy might be improved. The ways of modifying the capacity plan are not clear; therefore the respective alternative scenario, which would have a different emission factor of electricity, is disregarded.

Figure 42 attests that there is the significant potential for CO_2 mitigation in different economic conditions (reflected in the lower and higher discount rates). This figure also illustrates that if the natural price were to grow, mitigation costs would be lower. The conclusion about high sensitivity of the potential from energy and fuel prices is especially important in the light of high dependency of Hungary of the imported fuels, electricity market liberalization in Hungary and highly volatile oil prices which also affect the price of other fuels.

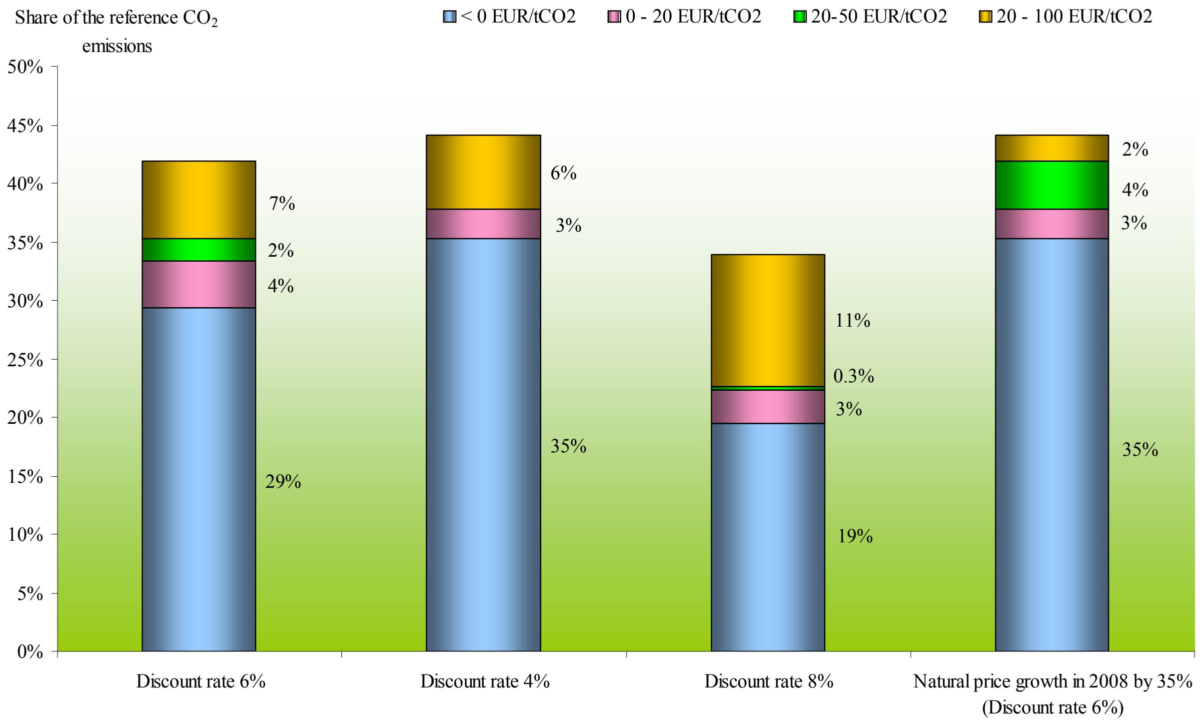

Figure 42 Comparison of the CO_2 mitigation potential estimated according to different sensitivity cases

Chapter 9 CONCLUSION

9.1 Overview of findings

The climate change challenge is at the top of the political agenda worldwide. For designing effective policies against this challenge, evidence-based knowledge of the potential for energy efficiency and low carbon opportunities is necessary. This dissertation research addresses this need and supplies the information on the potential for cost-effective reduction of CO_2 emissions in the residential buildings of Hungary. The choice of the sector is made due to its highest significance in the structure of final energy consumption and related CO_2 emissions in the national balance of Hungary. Also, residential buildings in economies in transition house the largest potential for CO_2 emission reductions worldwide, as demonstrated by abundant research, however estimates on the size of this potential and the associated costs is very scarce in the CEE region.

To solve the tasks stated in the dissertation, the author constructed a bottom-up, technology-rich model. The author developed a forecast of the reference final energy consumption and associated CO_2 emissions of the sector from 2008 to 2025. Then, the key CO_2 mitigation opportunities in the sector available on the Hungarian market were identified and economically evaluated as if they were installed individually and in sequence. The principal outcome of the research is a supply curve of mitigated CO_2 which characterizes the potential savings from a set of CO_2 mitigation measures as a function of the cost of mitigation technologies per unit of CO_2.

The research concludes that the final energy consumption of the residential sector is expected to grow to 84.2 TWh in 2025, whereas the sectoral CO_2 emissions decline until 2015 but then they rise again to reach c. 17.3 million tonnes CO_2 in 2025. The technological options considered to reduce the reference energy consumption and associated CO_2 emissions include the improvement of the thermal envelope of selected types of existing buildings, the application of passive energy design to newly constructed dwellings, the installation of high efficiency and low carbon space heating solutions, the installation of heating controls and individual heat meters, the exchange of dedicated water heaters and combined space and water heating solutions, the installation of water saving fixtures, and the exchange of electrical appliances and lights with more efficient analogues. The analysis of space heating and insulation opportunities is conducted separately for the building types with different architectural and thermal characteristics. The model does not consider the improvement of the thermal envelope and heating systems of buildings constructed during 1993-2008. Also, the research leaves for future research several mitigation options. These are the consideration of efficient cooking, air-conditioning, motor (lifts) and small electrical appliances. This research does not consider the effect of more efficient biomass heating systems because biomass is referred to as a sustainable source of energy and is thus reported with zero CO_2 emissions.

Next, the results of the analysis of the individual mitigation options installed separately are presented. This is useful if the information about a particular technological option is needed. Table 38 provides a summary of individual mitigation options according to their priority levels. The priority is defined by the ability to mitigate a significant share of the reference sectoral CO_2 emissions at low costs. The potential from individual options cannot be simply summed up due to overlap of the potential of some energy end-use options. The research concludes that technological options with the potential for CO_2 mitigation at negative costs are available for all building types and all energy end-uses.

Table 38 shows that there are thirteen *top priority* options which are able to mitigate more than 1% of reference sectoral CO_2 emissions at negative cost. These are the exchange of incandescent lamps with CFLs, the reduction of electricity consumption of TV- and PC- related equipment in low power mode, the installation of water flow controls, the installation of programmable thermostats in single-family houses (constructed before 1992), the improvement of water heating systems, a few insulation options (for walls, basements, and roofs) and the exchange of windows in different types of buildings.

Additionally, there are eight *medium priority* options which can mitigate 0.3% -1 % of the reference sectoral CO_2 emissions at negative cost. They include efficient refrigerators and freezers, the installation of space heating controls (TRVs and programmable thermostats) and individual heat meters, and the insulation of roofs and basements of traditional buildings. Furthermore, there are three *low priority* mitigation options which can save 0.1 – 0.3% of the reference sectoral CO_2 emissions at negative cost. These are the installation of TRVs and the installation of central building condensing gas boilers in traditional buildings.

There are also three “special priority” options which can conserve a significant potential at low costs (0-50 EUR/tCO_2). Among these are the application of passive energy design to buildings constructed from 2008, window exchange and the installation of pellet boilers for water and space dwelling heating in single-family houses (constructed before 1992). The rest of the options have mitigation costs higher than 50 EUR/tCO_2 and they are not included into the priority list.

Table 38 Priority levels of technological options, results for 2025

Priority level	Measure	CO_2 savings	CO_2 mitigation cost	Energy savings
		Baseline %	EUR/tCO_2	Baseline %
High priority **Mitigation potential > 1%** **Mitigation costs <0 EUR/tCO_2**	Wall insulation, single-family houses (constructed before 1992)	8.7%	-56	7.9%
	Roof insulation, single-family houses (constructed before 1992)	6.8%	-60	6.1%
	Base insulation, single-family houses (constructed before 1992)	4.4%	-54	4.0%
	Water saving fixtures on water heating appliances, water heaters linked to boilers	2.3%	-354	2.3%
	Window exchange in traditional multi-residential buildings	2.3%	-21	2.4%
	Wall insulation of buildings constructed using industrialized technology	1.9%	-115	2.3%
	Exchange of incandescent bulbs with CFLs	1.8%	-589	1.1%
	Reduction of standby electricity consumption of TV and PC-related equipment	1.5%	-582	1.0%
	Water saving fixtures in households with district and central hot water	1.5%	-508	1.5%
	Programmable thermostats in single-family houses (constructed before 1992)	1.5%	-213	1.5%
	Window exchange in buildings constructed using industrialized technology	1.4%	-81	1.6%
	Improved combi- space and water heating systems and water heating appliances	1.3%	-28	0.5%
Medium priority **Mitigation potential 0.3 - 1%** **Mitigation costs <0 EUR/tCO_2**	Efficient refrigerators	0.6%	-297	0.4%
	Roof insulation of traditional multi-residential buildings	0.5%	-61	0.5%
	TRVs in buildings constructed using industrialized technology	0.5%	-240	0.6%
	Programmable thermostats in traditional multi-residential buildings	0.4%	-183	0.4%
	Efficient freezers	0.4%	-391	0.2%
	Basement insulation of traditional multi-residential buildings	0.3%	-54	0.3%
	Efficient clothes washing machines	0.3%	-275	0.2%
	Metering of consumed district/central heat in traditional multi-residential buildings	0.3%	-1	0.3%
Low priority **Mitigation potential 0.1 – 0.3%** **Mitigation costs <0 EUR/tCO_2**	Central building condensing gas boilers in traditional multi-residential buildings	0.2%	-91	0.2%
	TRVs in traditional multi-residential buildings	0.1%	-249	0.2%
Special priority **Mitigation potential > 1%** **Mitigation costs <50 EUR/tCO_2**	Pellets boilers for central dwelling space heating and water heating in single-family houses (constructed before 1992)	23.6%	27	1.7%
	Window exchange in single-family houses (constructed before 1992)	6.2%	21	5.6%
	Application of passive energy design to buildings constructed from 2008	4.0%	9	5.5%

Note: The potential from individual options cannot be simply added.

Figure 43 illustrates the potential for CO_2 mitigation as a function of costs for the investigated technological mitigation options. The advantage of the supply curve method is that it allows the estimation of the total potential while avoiding double-counting of the mitigation potential supplied by individual options targeted to the same baseline technologies and energy end-uses. Figure 43 demonstrates that there is a wide range of opportunities for negative cost CO_2 mitigation in all studied types of the residential buildings. The figure depicts that technological options such as efficient appliances and lighting technologies, heating and water flow controls, equipment with reduced electricity consumption in the low power mode and many insulation options provide potential for CO_2 mitigation at negative cost in 2025.

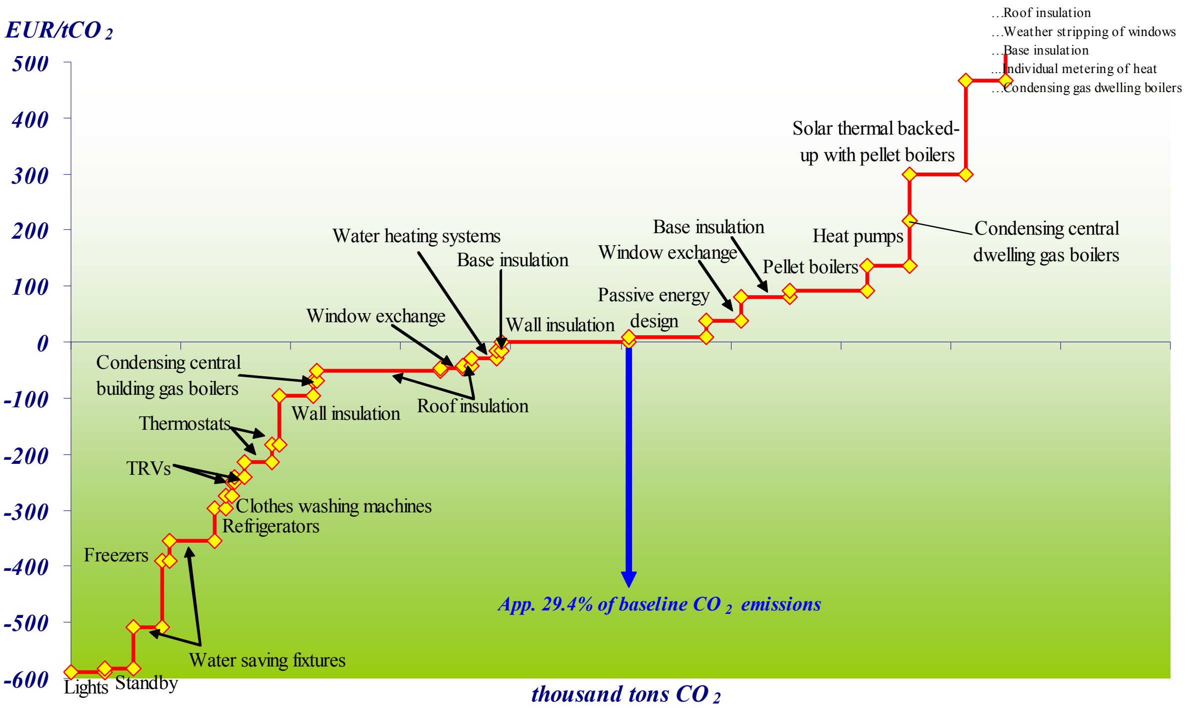

Figure 43 The supply curve of CO_2 mitigation for the residential sector of Hungary, 2025

If negative cost options are implemented, they can reduce CO_2 by 5.1 million tonnes in 2025. This is approximately 29% of the reference CO_2 emissions of the Hungarian residential sector. Implementation of these mitigation options results in an energy saving of 22.1 TWh/yr., that is approximately 26% of the reference final energy consumption of the sector in 2025. Realization of this potential requires total investments over the period 2008 – 2025 of approximately 9.6 billion EUR but saves 17.1 billion EUR in energy costs.

In addition to the potential at negative costs, at least 4% of the sectoral reference CO_2 emissions can be avoided in 2025 at costs up to 20 EUR/tCO_2. This represents an additional CO_2 reduction of 0.7 million tonnes of CO_2 in 2025. The potential at the cost level above 20 EUR/tCO_2 is also high. The CO_2 mitigation potential in cost categories, the associated energy savings, the required investment costs and the associated saved energy costs are presented in Table 39 . The total technical potential that would result from the implementation of all investigated measures is estimated as c. 50% of the sectoral reference CO_2 emissions in 2025. This is 8.7 million tonnes of CO_2/yr.

Table 39 Summary of results: CO_2 mitigation potential in cost categories, associated energy savings, investments and saved energy costs

Cost categories of CO_2 mitigation costs, EUR/tCO_2	**Cumulative CO_2 mitigation potential**		**CO_2 mitigation potential by cost category**		**Cumulative energy savings**		**Energy savings by cost category**		**Investments over 2008-2025, billion EUR**		**Saved energy costs 2008 – 2025, billion EUR**	
	Baseline share	**Million tCO_2/yr.**	**Baseline share**	**Million tCO_2/yr.**	**Baseline share**	**TWh/ yr.**	**Baseline share**	**TWh/ yr.**	**Total**	**By cost category**	**Total**	**By cost category**
< 0	29.4%	5.1	29.4%	5.1	26.3%	22.1	26.3%	22.1	9.6	9.6	17.1	17.1
0 – 20	33.4%	5.8	4.0%	0.7	31.8%	26.8	5.5%	4.7	13.6	3.9	19.0	1.8
20-50	35.3%	6.1	1.9%	0.3	33.7%	28.4	1.9%	1.6	15.0	1.4	19.8	0.8
20 – 100	41.6%	7.2	6.3%	1.1	36.2%	30.5	2.5%	2.1	18.1	3.1	21.9	2.1
>100	50.5%	8.7	8.9%	1.5	42.0%	35.3	5.7%	4.8	29.0	10.9	25.7	3.8

9.2 Discussion of the results

The key conclusion of the dissertation is that substantial potential for CO_2 emission reduction in the residential buildings can be achieved by 2025 with the application of advanced technological options. The costs of the potential are very sensitive to assumptions of economic analysis such as the discount rate and projected fuel and energy prices. This dissertation shows that the significant cost-effective potential for CO_2 mitigation in the residential sector exists in different scenarios of economic stability of the Hungarian economy.

It is proven that the technological options characterized with the lowest mitigation costs are often relatively cheap and easy to install options. These are, for instance, the exchange of incandescent lights with CFLs, the installation of water saving fixtures, the exchange of electrical appliances, the installation of space heating controls, and the reduction of standby power consumption of appliances. Options which are able to supply the largest amount of the potential reduction are relatively more expensive. These options mostly include retrofit of the thermal envelope, fuel switch and efficiency improvement of space heating solutions.

One of the important conclusions also relates to the extremely low building stock turnover. As a result, a large share of CO_2 mitigation potential is locked in the existing buildings. Therefore, retrofitting of the existing building stock and replacing energy using equipment is one of the key priorities for CO_2 mitigation in the country.

The majority of technological options assessed are established and widely available on the Hungarian market. As Section 4.5.3 (p. 69) notes, this dissertation covers only the options which are capable providing high mitigation potential. Therefore some of less significant options were disregarded. As a result, the estimates in this dissertation represent low estimates of the actual mitigation potential. Also, it is important to highlight that the potential estimates do not include the potential of non-technological options. The effect of non-technological options is highly uncertain and requires thorough research for the country. Furthermore, it is likely that the technologies which are not economically feasible today and not yet even discovered will be commercialized by 2025; they will open the window for opportunities to potentially mitigate a higher amount of CO_2.

The results of the dissertation are comparable with those of other research targeted at Hungary or the European Union. Table 40 presents a comparison of the potential estimates according to three scenarios developed in the dissertation, the IPCC Fourth Assessment Report (Levine *et al.* 2007), the UNEP country study(Szlavik *et al.* 1998) and the research on EU-15 (Joosen and Blok 2001). In particular, it is a good sign that the potential amount of CO_2 mitigation in the negative cost category of the IPCC Fourth Assessment Report and that of the dissertation are similar. The potential estimate in the former was based on the review and aggregation of regional (CEE and FSU) studies and therefore, the dissertation is well in line with them. The potential mitigation in the high cost categories of the IPCC Fourth Assessment Report (Levine *et al.* 2007) is highly uncertain; for this reason the comparison of the related potential is not relevant to this study. The interesting fact is that the potential projected for Hungary about ten years ago is similar to the one found in the present dissertation. Whereas such similarity cannot be explained by research assumptions and limitations (for example, the energy and fuel prices projected in Szlavik *et al.*

1998 are lower that those in the dissertation whereas the technologies are able to provide a higher potential than ten years ago) and may be accidental, it may also signal that there is not enough effort to realize the potential available in the sector.

Table 40 Comparison of the dissertation results to other research in the region

Country/ region	**Source**	**CO_2 mitigation potential as share of the baseline emission projections in cost categories (costs in USD/tCO_2)**				**Discount rate**	**Target year**	**Sectoral coverage**
		<0	**0-20**	**20-100**	**>100**			
Hungary	Dissertation	29%	4%	8%	9%	6%	2025	Residential
		35%	3%	0.0%	6%	4%	2025	
		19%	3%	0.3%	11%	8%	2025	
Economies in transition	Levine *et al*. 2007	29%	12%	23%	n/a	Aggregated results of studies which used 3%-10%	2020	Residential & commercial
Developed countries		27%	3%	2%	n/a		2020	
Hungary	Szlavik *et al.* 1998	31%	9%	0%	5%	5%	2030	Residential & commercial
EU-15	Joosen and Blok 2001	11%	6%	2%	3%	4%	2010	Residential

Finally, it is important to mention that the dissertation disregarded the impact of co-benefits and barriers to the penetration of CO_2 mitigation technologies. If the co-benefits of mitigation, such as higher comfort, improved productivity, higher welfare of households and others would be quantified and included into the present assessment, the mitigation costs might be lower than calculated otherwise. On another hand, the barriers for penetration of mitigation technologies and other side effects may limit the cost-effectiveness of investments into mitigation options. For instance, the construction of the household stock from 2008 according to the passive design principle may necessitate indirect labour costs to train the personnel of the construction and other related industries. Thus, co-benefits and barriers of CO_2 mitigation may significantly impact on the mitigation costs of technologies. However, more research is needed to develop a methodology to estimate this impact.

9.3 Implications of the research for policy design and final remarks

This dissertation provides background information to assist the design of new policies targeted at CO_2 mitigation in the residential sector of Hungary. The results of this dissertation, i.e. the information about the size and costs of the mitigation and energy conservation potential in different types of buildings, investment costs and saved energy costs, may be instrumental for designing such policy tools as capital subsidies and grants, energy performance contracting, the Joint Implementation Mechanism of the Kyoto Protocol, an energy efficiency certificate scheme and others. The database of mitigation options and the information about saved energy costs from the installation of the explored options may be useful for information awareness and education campaigns.

The research results have been already used in preparation of such policy documents as the Hungarian Climate Strategy for 2008 – 2025 (KVVM 2008) and the design of the Green Investment Scheme in Hungary (ongoing research implemented the Budapest University of Technology and Economics). This research may help set up the target for the post-Kyoto regime or the EU emission reduction commitment. If the potential at negative costs identified by this dissertation research is realized by 2025, it may offset c. 4.5% of the Kyoto Protocol base year (1985 – 1987) GHG emissions of Hungary or c. 5.4% of the GHG emissions of Hungary in

1990[67]. These research results may also contribute to the design of the Energy Efficiency Action Plan of Hungary and other sustainable strategies of the country.

It is important to highlight that no one single policy tool can capture the entire amount of the potential (Levine *et al*. 2007), therefore it is important to develop a policy package aimed to overcome different barriers hindering energy efficiency investments. The assessment of different policy packages would be the next important step in understanding the mitigation opportunities in Hungary and the author believes that the present dissertation will serve as a solid background for such future research.

In addition to the practical application, the research contributes to the theoretical knowledge on CO_2 mitigation modelling in economies in transition. The author believes that the research methodology and selected results could be replicated for other countries with similar economic and climate conditions. As described, there have been very limited research activities which assess the existing opportunities for CO_2 mitigation in the residential buildings sector due to, above all, the difficulty in collecting input data and then in incorporating these data into the framework of a highly detailed, bottom-up, technology-rich model. This dissertation research is therefore useful for methodological learning in order to conduct such research in the region.

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[67] For the information about GHG emissions please see Hungarian Ministry of Environment and Water (2007).

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APPENDIX I: MITIGATION SCENARIO WITH THE DISCOUNT RATE 4%

Table 41 Potential available through application of options installed separately, 2025

Mitigation measure	CO_2 savings	Costs of mitigated CO_2	Energy savings	Costs of energy savings
	Thousands tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh
Buildings constructed using industrialized technology				
Installation of thermostatic radiator valves	89	-252	529	0.01
Wall insulation	332	-155	1931	0.03
Window exchange	236	-128	1369	0.03
Installation of condensing gas central building boilers for space heating	6	-126	30	0.03
Basement insulation	19	23	110	0.06
Roof insulation	38	65	219	0.06
Individual metering of district and central heat	177	122	1057	0.07
Traditional buildings				
Installation of thermostatic radiator valves	26	-256	131	0.01
Installation of programmable thermostats	68	-199	335	0.02
Installation of condensing central building gas boilers for space heating	35	-121	171	0.03
Roof insulation	90	-107	449	0.04
Basement insulation	58	-101	290	0.04
Individual metering of consumed district and central heat	51	-46	263	0.05
Window exchange	399	-74	1987	0.04
Installation of condensing central gas dwelling boilers for space heating	169	28	837	0.06
Old single-family houses (constructed before 1992)				
Installation of programmable thermostats	255	-224	1261	0.01
Roof insulation	1172	-96	5173	0.03
Wall insulation	1500	-93	6620	0.03
Basement insulation	757	-92	3340	0.03

Mitigation measure	**CO_2 savings**	**Costs of mitigated CO_2**	**Energy savings**	**Costs of energy savings**
	Thousands tonnes CO_2/yr.	**EUR/tCO_2**	**GWh/yr.**	**EUR/kWh**
Window exchange	1067	-32	4709	0.05
Installation of pellets boilers for water and space central dwelling heating	4073	10	1447	0.25
Installation of solar collectors for water heating backed up with pellet boilers for water and space central dwelling heating	4073	50	6348	0.11
Weather stripping of windows	528	51	1347	0.05
Installation of pumps for water and space central dwelling heating	3093	76	14778	0.04
Installation of condensing gas boiler for water and space central dwelling heating	1381	104	3206	0.07
Buildings constructed after 2008				
Application of passive energy design	697	-100	4651	0.03
Appliances and lights				
Exchange of incandescent lamps with CFLs	305	-592	935	0.01
Reduction of electricity consumption by TV and PC-related equipment in low power and off - modes	266	-585	815	0.01
Efficient freezers	67	-432	206	0.06
Efficient refrigerators	107	-347	328	0.09
Efficient clothes washing machines	54	-338	167	0.09
Water heating				
Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	263	-511	1231	0.00
Installation of water saving fixtures in households with central district hot water	400	-356	1942	0.00
Improved combi- space and water heating systems and dedicated water heating appliances	217	-71	420	0.12

Table 42 Potential and costs of CO_2 mitigation estimated with the supply curve method, 2025

Rank	Measure	CO_2 savings in 2025	Cost of mitigated CO_2	Energy savings in 2025	Investments 2008-2025	Saved energy costs 2008-2025
		Thousand tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	Million EUR	Million EUR
1	Exchange of incandescent bulbs with CFLs	305	-592	935	73	551
2	Reduction of electricity consumption of TV and PC-related equipment in low power and off - modes	266	-585	815	20	391
3	Installation of water saving fixtures in households with district and central hot water	263	-511	1231	502	868
4	Efficient freezers	67	-432	206	239	245
5	Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	400	-356	1942	78	1905
6	Efficient refrigerators	107	-347	328	103	1637
7	Efficient clothes washing machines	54	-338	167	126	2892
8	TRVs in households of traditional multi-residential buildings	26	-256	131	13	66
9	TRVs in households of buildings constructed using industrialized technology	89	-252	529	80	258
10	Installation of programmable thermostats old single-family houses (constructed before 1992)	255	-224	1261	204	654
11	Installation of programmable thermostats in households of traditional multi-residential buildings	68	-199	335	95	167
12	Wall insulation of buildings constructed using industrialized technology	304	-140	1763	159	14
13	Installation of central building condensing gas boilers for space heating in households of traditional multi-residential buildings	31	-103	154	76	77
14	Window exchange in industrialized buildings	205	-100	1190	760	825
15	Application of passive energy design to single-family and multi-residential buildings constructed from 2008	697	-100	4651	3927	1841
16	Roof insulation of traditional multi-residential buildings	83	-92	413	276	208
17	Roof insulation of old single-family houses (constructed before 1992)	1127	-89	4948	2858	2327
18	Improved combi- space and water heating systems and dedicated water heating appliances	217	-71	420	50	1536

Rank	**Measure**	**CO_2 savings in 2025**	**Cost of mitigated CO_2**	**Energy savings in 2025**	**Investments 2008-2025**	**Saved energy costs 2008-2025**
		Thousand tonnes CO_2/yr.	**EUR/tCO_2**	**GWh/yr.**	**Million EUR**	**Million EUR**
19	Basement insulation of traditional multi-residential buildings	50	-70	248	166	125
20	Wall insulation of old single-family houses (constructed before 1992)	1160	-48	5092	3753	2394
21	Window exchange in traditional multi-residential buildings	326	-28	1626	1448	818
22	Base insulation of old single-family houses (constructed before 1992)	439	16	1926	1905	905
23	Installation of pellets boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	702	66	258	1336	574
24	Installation of pumps for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	386	74	1877	1744	1531
25	Installation of central building condensing gas boilers for space heating of households in buildings constructed using industrialized technology	2	138	11	607	741
26	Installation of solar collectors backed-up with pellet boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	511	234	818	2488	600
27	Installation of condensing gas boilers for central dwelling space heating in old single-family houses (constructed before 1992)	359	387	773	2109	188
28	Individual metering of consumed district and central heat in households of traditional multi-residential buildings	17	426	90	169	59
29	Base insulation of buildings constructed using industrialized technology	8	529	43	131	20
30	Roof insulation of industrialized buildings	15	651	85	340	40
31	Installation of central dwelling condensing gas boilers for space heating in households of traditional multi-residential buildings	56	655	278	715	177
32	Weather stripping of windows in old single-family houses (constructed before 1992)	64	726	419	1367	744
33	Individual metering of district and central heat in households of buildings constructed using industrialized technology	65	889	386	1062	284

APPENDIX II: MITIGATION SCENARIO WITH THE DISCOUNT RATE 8%

Table 43 Potential available through application of options installed separately, 2025

Mitigation measure	**CO_2 savings**	**Costs of mitigated CO_2**	**Energy savings**	**Costs of energy savings**
	Thousands tonnes CO_2/yr.	**EUR/tCO_2**	**GWh/yr.**	**EUR/kWh**
Buildings constructed using industrialized technology				
Installation of thermostatic radiator valves	89	-227	529	0.02
Wall insulation	332	-72	1931	0.04
Installation of condensing gas central building boilers for space heating	6	-66	30	0.04
Window exchange	236	-30	1369	0.05
Basement insulation	19	202	110	0.09
Roof insulation	38	266	219	0.10
Individual metering of district and central heat	177	291	1057	0.10
Traditional buildings				
Installation of thermostatic radiator valves	26	-242	131	0.01
Installation of programmable thermostats	68	-166	335	0.02
Installation of condensing central building gas boilers for space heating	35	-59	171	0.05
Roof insulation	90	-12	449	0.05
Basement insulation	58	-3	290	0.06
Individual metering of consumed district and central heat	51	48	263	0.07
Window exchange	399	38	1987	0.06
Installation of condensing central gas dwelling boilers for space heating	169	148	837	0.09
Old single-family houses (constructed before 1992)				
Installation of programmable thermostats	255	-202	1261	0.02
Roof insulation	1172	-21	5173	0.05
Wall insulation	1500	-15	6620	0.05
Basement insulation	757	-14	3340	0.05

Mitigation measure	**CO_2 savings**	**Costs of mitigated CO_2**	**Energy savings**	**Costs of energy savings**
	Thousands tonnes CO_2/yr.	**EUR/tCO_2**	**GWh/yr.**	**EUR/kWh**
Installation of pellets boilers for water and space central dwelling heating	4073	45	1447	0.35
Window exchange	1067	78	4709	0.07
Weather stripping of windows	528	56	1347	0.05
Installation of solar collectors for water heating backed up with pellet boilers for water and space central dwelling heating	4073	117	6348	0.16
Installation of condensing gas boiler for water and space central dwelling heating	1381	166	3206	0.10
Installation of pumps for water and space central dwelling heating	3093	147	14778	0.05
Buildings constructed after 2008				
Application of passive energy design	697	121	4651	0.07
Appliances and lights				
Exchange of incandescent lamps with CFLs	305	-585	935	0.01
Reduction of electricity consumption by TV and PC-related equipment in low power and off -modes	266	-579	815	0.01
Efficient freezers	67	-346	206	0.09
Efficient refrigerators	107	-242	328	0.12
Efficient clothes washing machines	54	-207	167	0.13
Water heating				
Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	263	-506	1231	0.00
Installation of water saving fixtures in households with central district hot water	400	-351	1942	0.00
Improved combi- space and water heating systems and dedicated water heating appliances	217	18	420	0.17

Table 44 Potential and costs of CO_2 mitigation estimated with the supply curve method, 2025

Rank	Measure	CO_2 savings in 2025	Cost of mitigated CO_2	Energy savings in 2025	Investments 2008-2025	Saved energy costs 2008-2025
		Thousand tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	Million EUR	Million EUR
1	Exchange of incandescent bulbs with CFLs	305	-592	935	73	551
2	Reduction of electricity consumption of TV and PC-related equipment in low power and off - modes	266	-585	815	20	391
3	Installation of water saving fixtures in households with district and central hot water	263	-511	1231	500	868
4	Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	400			78	1905
5	Efficient freezers	67	-432	206	239	245
6	Efficient refrigerators	107	-347	328	103	1637
7	TRVs in households of traditional multi-residential buildings	26			13	66
8	TRVs in households of buildings constructed using industrialized technology	89	-338	167	80	258
9	Efficient clothes washing machines	54	-256	131	126	2892
10	Installation of programmable thermostats old single-family houses (constructed before 1992)	255	-224	1261	204	654
11	Installation of programmable thermostats in households of traditional multi-residential buildings	68	-199	335	95	167
12	Wall insulation of buildings constructed using industrialized technology	304	-140	1763	159	14
13	Installation of central building condensing gas boilers for space heating in households of traditional multi-residential buildings	31	-103	154	76	77
14	Roof insulation of old single-family houses (constructed before 1992)	1127			2858	2327
15	Roof insulation of traditional multi-residential buildings	83			276	208
16	Window exchange in buildings constructed using industrialized technology	205	-585	935	760	825
17	Improved combi- space and water heating systems and dedicated water heating appliances	217	-579	815	50	1536

Rank	Measure	CO_2 savings in 2025	Cost of mitigated CO_2	Energy savings in 2025	Investments 2008-2025	Saved energy costs 2008-2025
		Thousand tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	Million EUR	Million EUR
18	Basement insulation of traditional multi-residential buildings	50	-506	1231	166	125
19	Wall insulation of old single-family houses (constructed before 1992)	1160	-351	1942	3753	2394
20	Installation of pellets boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	793	-346	206	1905	905
21	Window exchange in traditional multi-residential buildings	326	-242	328	1448	818
22	Application of passive energy design to single-family and multi-residential buildings constructed from 2008	697	-242	131	3927	1841
23	Installation of pumps for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	386	-227	529	1744	1531
24	Base insulation of old single-family houses (constructed before 1992)	349	-207	167	1336	615
25	Installation of central building condensing gas boilers for space heating of households in buildings constructed using industrialized technology	2	-202	1261	607	741
26	Installation of solar collectors backed-up with pellet boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	511	-166	335	2488	600
27	Installation of condensing gas boilers for central dwelling space heating in old single-family houses (constructed before 1992)	359	-49	1763	2109	188
28	Individual metering of consumed district and central heat in households of traditional multi-residential buildings	17	-34	154	169	59
29	Weather stripping of windows in old single-family houses (constructed before 1992)	64	-10	4948	1367	744
30	Base insulation of buildings constructed using industrialized technology	8	12	413	131	20
31	Installation of central dwelling condensing gas boilers for space heating in households of traditional multi-residential buildings	56	12	1190	715	177
32	Roof insulation of industrialized buildings	15	18	420	340	40
33	Individual metering of district and central heat in households of buildings constructed using industrialized technology	65	44	248	1062	284

APPENDIX III: MITIGATION SCENARIO WITH THE HIGHER GAS PRICE (35% GROWTH BY THE END OF 2008)

Table 45 Potential available through application of options installed separately, 2025

Mitigation measure	CO_2 savings	Costs of mitigated CO_2	Energy savings	Costs of energy savings
	Thousands tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	EUR/kWh
Buildings constructed using industrialized technology				
Installation of thermostatic radiator valves	89	-267	529	0.01
Wall insulation	332	-138	1931	0.03
Installation of condensing gas central building boilers for space heating	6	-190	30	0.04
Window exchange	236	-104	1369	0.04
Basement insulation	19	86	110	0.07
Roof insulation	38	138	219	0.08
Individual metering of district and central heat	177	177	1057	0.09
Traditional buildings				
Installation of thermostatic radiator valves	26	-330	131	0.01
Installation of programmable thermostats	68	-276	335	0.02
Installation of condensing central building gas boilers for space heating	35	-185	171	0.04
Roof insulation	90	-153	449	0.04
Basement insulation	58	-145	290	0.05
Window exchange	399	-112	1987	0.05
Individual metering of consumed district and central heat	51	-81	263	0.06
Installation of condensing central gas dwelling boilers for space heating	169	-8	837	0.07
Old single-family houses (constructed before 1992)				
Installation of programmable thermostats	255	-307	1261	0.01
Roof insulation	1172	-134	5173	0.04
Wall insulation	1500	-129	6620	0.04
Basement insulation	757	-128	3340	0.04

Mitigation measure	**CO_2 savings**	**Costs of mitigated CO_2**	**Energy savings**	**Costs of energy savings**
	Thousands tonnes CO_2/yr.	**EUR/tCO_2**	**GWh/yr.**	**EUR/kWh**
Window exchange	1067	-53	4709	0.06
Installation of pellets boilers for water and space central dwelling heating	4073	-36	1447	0.30
Installation of solar collectors for water heating backed up with pellet boilers for water and space central dwelling heating	4073	16	6348	0.13
Installation of pumps for water and space central dwelling heating	3093	34	14778	0.05
Weather stripping of windows	528	50	1347	0.05
Installation of condensing gas boiler for water and space central dwelling heating	1381	138	3206	0.08
Buildings constructed after 2008				
Application of passive energy design	697	-82	4651	0.05
Appliances and lights				
Exchange of incandescent lamps with CFLs	305	-647	935	0.01
Reduction of electricity consumption by TV and PC-related equipment in low power and off - modes	266	-641	815	0.01
Efficient freezers	67	-450	206	0.07
Efficient refrigerators	107	-355	328	0.11
Efficient clothes washing machines	54	-334	167	0.11
Water heating				
Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	263	-554	1231	0.004
Installation of water saving fixtures in households with central district hot water	400	-437	1942	0.00
Improved combi- space and water heating systems and dedicated water heating appliances	217	-105	420	0.14

Table 46 Potential and costs of CO_2 mitigation estimated with the supply curve method, 2025

Rank	Measure	CO_2 savings in 2025	Cost of mitigated CO_2	Energy savings in 2025	Investments 2008-2025	Saved energy costs 2008-2025
		Thousand tonnes CO_2/yr.	EUR/tCO_2	GWh/yr.	Million EUR	Million EUR
1	Exchange of incandescent bulbs with CFLs	305	-647	935	73	604
2	Reduction of electricity consumption of TV and PC-related equipment in low power and off - modes	266	-641	815	20	428
3	Installation of water saving fixtures in households with district and central hot water	263	-554	1231	501	1068
4	Efficient freezers	67	-450	206	239	268
5	Installation of water saving fixtures on dedicated water heating appliances and water heaters linked to boilers	400	-437	1942	78	2323
6	Efficient refrigerators	107	-355	328	103	1792
7	Efficient clothes washing machines	54	-334	167	126	3166
8	Installation of TRVs in households of traditional multi-residential buildings	26	-330	131	13	85
9	Installation of programmable thermostats old single-family houses (constructed before 1992)	255	-307	1261	204	869
10	Installation of programmable thermostats in households of traditional multi-residential buildings	68	-276	335	95	223
11	Installation of TRVs in households of buildings constructed using industrialized technology	89	-267	529	80	280
12	Installation of central building condensing gas boilers for space heating in households of traditional multi-residential buildings	31	-163	154	76	103
13	Roof insulation of traditional multi-residential buildings	83	-133	413	276	274
14	Roof insulation of old single-family houses (constructed before 1992)	1127	-124	4948	2858	3043
15	Wall insulation of buildings constructed using industrialized technology	304	-119	1763	159	19
16	Basement insulation of traditional multi-residential buildings	50	-107	248	166	165
17	Improved combi- space and water heating systems and dedicated water heating appliances	217	-105	420	50	1668
18	Application of passive energy design to single-family and multi-residential	697	-82	4651	3927	2357

Rank	**Measure**	**CO_2 savings in 2025**	**Cost of mitigated CO_2**	**Energy savings in 2025**	**Investments 2008-2025**	**Saved energy costs 2008-2025**
		Thousand tonnes CO_2/yr.	**EUR/tCO_2**	**GWh/yr.**	**Million EUR**	**Million EUR**
	buildings constructed from 2008					
19	Wall insulation of old single-family houses (constructed before 1992)	1160	-73.0	5092	3753	3131
20	Window exchange in buildings constructed using industrialized technology	205	-70	1190	760	887
21	Window exchange in traditional multi-residential buildings	326	-53	1626	1448	1080
22	Base insulation of old single-family houses (constructed before 1992)	439	8	1926	1905	1184
23	Installation of pellets boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	702	32	258	1336	1036
24	Installation of pumps for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	386	57	1877	1744	2003
25	Installation of central building condensing gas boilers for space heating of households in buildings constructed using industrialized technology	2	123	11	607	741
26	Installation of solar collectors backed-up with pellet boilers for central dwelling space heating and water heating in old single-family houses (constructed before 1992)	511	235	818	2488	908
27	Installation of condensing gas boilers for central dwelling space heating in old single-family houses (constructed before 1992)	359	478	773	2109	147
28	Individual metering of consumed district and central heat in households of traditional multi-residential buildings	17	480	90	169	76
29	Weather stripping of windows in old single-family houses (constructed before 1992)	64	651	419	1367	963
30	Base insulation of buildings constructed using industrialized technology	8	720	43	131	22
31	Installation of central dwelling condensing gas boilers for space heating in households of traditional multi-residential buildings	56	736	278	715	235
32	Roof insulation of buildings constructed using industrialized technology	15	874	85	340	43
33	Individual metering of district and central heat in households of buildings constructed using industrialized technology	65	1086	386	1062	308