Economic efficiency and policy questions of energy saving potentials in the European building sector

DISSERTATION

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Abstract

The European Union in 2011 has developed a roadmap for moving to a competitive low carbon economy in 2050, which provides a long term pathway to achieve an 80% cut in domestic emissions compared to 1990 by 2050 (European Commission, 2011). Considering the Paris COP 21 agreement, the reduction in CO_2-emissions will need to be definitely higher than the previously envisaged 80%. The building sector provides a high potential to contribute to this target. The main research question of this doctoral thesis is: What are the perspectives to increase the energy performance in the building sector?

Four case studies are presented addressing different methodology approaches, building sectors, countries, policies and economic framework. Firstly, cost curves for selected European countries´ building stock are derived to show cost and benefits of energy efficiency solutions and related energy saving for space heating by 2030. Secondly, policy based energy demand scenarios to 2050 are modelled and their consistency with Paris COP21 decarbonisation targets is tested. Thirdly, buildings and energy efficiency solutions for the Lithuanian residential building sector are identified which have to be addressed by policy makers in order to achieve high energy savings in the most-cost effective way. And fourthly, the current and future energy demand in the European shopping centre building stock is investigated.

The calculation of the final energy demand (for space heating and hot water) is based on a bottom-up approach taking into account disaggregated building stock data. Two different models are applied, the existing Invert-EE/Lab model and a newly developed Cost Curve Tool. Invert/EE-Lab is a dynamic bottom-up techno-socio-economic simulation tool that evaluates the effects of different policies on the future energy demand in the building sector. The Cost Curve Tool provides different types of cost curves aiming to show the cost and energy related benefits of investments in energy efficiency solutions.

Energy efficiency improvements of the building sector provide a high potential to reduce its energy demand by 2030 and 2050. However, the economic energy saving potential in the building sector varies from one country to another. This is due to the following key parameters for the energy savings; current energy performance of buildings, renovation rates and depth, policy packages and energy prices. The main drivers of the CO_2-emission reduction in the building sector are the renovation rate and depth, the heating system exchange rate and the substitution of the fossil energy based heating systems with renewable systems. The target of keeping the increase in global average temperature below 2°C set in Paris Agreement requires the CO_2-reductions beyond 80-90% in the building sector. The results show that an achievement of COP21 agreements require higher policy ambitions, going beyond the assumptions of ambitious policy scenarios developed in this thesis.

Keywords: Energy efficiency, energy demand, building sector, space heating, bottom-up approach, energy modelling, Invert-EE/Lab, cost curves, policy instruments, COP21

Foreword

This doctoral thesis is a result of five-years' experience working at the Energy Economic Group, TU-Wien. It consists of the following activities: analysing scientific literature, applying models, collecting data, presenting own results at conferences and last but not least working with people. The last component is the most important to me and therefore I would like to thank people who were part of my life during this time of period.

First of all I would like to thank my colleague and good friend Raphael Bointner. Thank you for your support and friendship. Your enthusiasm, crazy ideas and stories you told with all small details, were a usual working day life. Suddenly you were gone. However you will be alive as long as I because I will be always keeping you in my mind and hard.

I would like to thank Lukas Kranzl for being my supervisor all these years. You are the best supervisor I ever had. You always managed to communicate with constructive critic by inspiring me to work even harder. Your motivation, enthusiasm and objectivity have always reasoned me to do it better.

Many thanks to my supervisor and colleague Reinhard Haas for supporting me by reading my work and giving constructive comments. Also thank you for being a part of pleasant atmosphere at the institute.

Many thanks to my reviewer Matthias Haase for reading my work and giving helpful comments.

Special thanks go to all my colleagues at EEG for great atmosphere in and outside the office. Thank you all for your company at lunch time spending it together in the heart of Karlsplatz. Thank you all for your delicious and sweet breakfast cakes. I wish that this special spirit will never disappear from Gusshaustraße 25-29.

The biggest thank is to my family. Without you everything might not have sense. Thank you for your support every minute. When Oscar my nephew came to this world I understood that everything we do is the beginning.

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List of acronyms

COP	Coefficient of performance
COP21	the 21st Conference of the Parties (or “COP”) to the United Nations Framework Convention on Climate Change (UNFCCC)
CSC	Conservation supply curves
EED	Energy Efficiency Directive of the European Parliament and of the Council of 25 October 2012
EPBD	Energy Performance building directive of the European Parliament and of the Council of 16 December 2002
EPBD -recast	Energy Performance building directive of the European Parliament and of the Council of 19 May 2010
EPC	Energy Performance Certificate
ESCC	Energy saving cost curve
EU	European Union
EU-28	28 member states of the European Union
HVAC	Heating, Ventilation and Air Conditioning
MACC	Marginal abatement cost curve
MFH	Multi-family house
nZEB	Nearly-Zero Energy Building
O&M	Operation and maintenance
RED	Renewable Energy Directive of the European Parliament and of the Council of 23 April 2009
SFH	Single-family house
VAT	Value added tax

1. Introduction

1.1.Motivation

The Paris Agreement which entered into force on 4 November 2016, aims to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius (United Nations, 2017). The European Union has set a long-term aim to reduce greenhouse gas (GHG) emissions by 80-95% below 1990 levels by 2050 (European Commission, 2016). Moreover, European Union has developed a roadmap for moving to a competitive low carbon economy in 2050, which provides a long term pathway to achieve an 80% cut in domestic emissions compared to 1990 by 2050 (European Commission, 2011).

The EU has proposed a 40% goal for the reduction of GHG emissions by 2030, together with targets of 27% for both renewable energy and improved energy efficiency. In the Clean Energy for All Europeans package, the European Parliament and Council proposed a binding 30% energy efficiency target for 2030, up from the current target of at least 27%. This aim is particularly addressing the building sector (Arias Cañete et al., 2017).

The building sector within the European Union accounts for about 40% of final energy consumption (European Commission, 2017). European households in EU-28 were responsible for 26% of the final energy consumption in 2012 (Eurostat, 2014). Increasing the renovation rate, renovation quality and effectiveness of building renovation are the key activities to achieve the targets. Moreover, in a proposed update of the Energy Performance of Buildings directive, buildings will not just consume energy; they will become an active part of energy system, producing and storing renewable energy onsite (Arias Cañete et al., 2017).

The current renovation rate is very low; 1%-2% of the building stock is renovated each year. Besides, these renovation do not utilize the full saving potential (Artola et al., 2016). This shows that two of the main three issues, the rate and quality of building renovation have not gone well in the recent years. Moreover, building stock differs from one European country to another. The thermal building characteristics, energy performance standards, climate and economic framework have an impact on the rate and quality of building renovation.

1.2.Main research questions

The overarching research question of this doctoral thesis is: What are the perspectives to increase the energy performance in the building sector? This research question is specified by the following questions:

1) What is the cost-effectiveness of different energy efficiency solutions in the building stock and how does their implementation contribute to the energy savings in buildings?
2) Do ambitious energy saving scenarios and assumed policy package in buildings reflect the recently adopted climate and energy targets?
3) What building sectors and energy efficiency solutions have to be addressed by policy instruments to achieve the climate and energy targets?
4) What are the perspectives to increase the energy performance in the shopping centre building stock?

In the following, I will outline the case studies and analyses I carried out in order to deal with these questions.

1.3.Case studies

In order to answer above-mentioned questions, four case studies are provided. Each case study is built on different methodology approach, building sector, countries, policies and economic framework.

What is the cost-effectiveness of different energy efficiency solutions in the building stock and how does their implementation contribute to the energy savings in buildings?

Cost curves for selected European countries´ building stock are derived to show cost and benefits of energy efficiency solutions and related energy saving for space heating by 2030. Six European countries are chosen which are located in different climate zones, France, Italy, Norway, Romania, Poland and Spain. The cost-effectiveness of energy efficiency solutions is investigated looking at the building thermal characteristics, climate conditions, supplied energy fuel prices, interest rates, cost of energy efficiency solutions and saved fuel costs.

Case study I “Cost curves for the selected European countries´ building stock” implements the following methodology steps:

- Analyse building stock and its technical characteristics;
- Assess the current energy performance requirements for building renovation;
- Define energy efficiency solutions including insulation of the building envelope;
- Calculate cost-effectiveness of energy efficiency solutions;
- Calculate total energy savings for space heating by 2030;
- Provide cost curves showing the investor perspective;
- Provide two different scenarios with different sets of economic conditions;

- Investigate the role of subsidies for deep renovation, CO_2 taxes for fossil energy fuels and cost reduction of renovation packages, on the total energy savings.

This analysis delivers key insights into the cost efficiency of various retrofitting measures in the building stock. In particular, the results indicate the share of efficiency measures which are profitable under certain economic and policy related conditions. However, it is not clear whether the implementation of certain retrofitting measures is sufficient to achieve recently adopted climate mitigation targets. I will draw nearer to this aspect with the following question and analysis:

Do ambitious energy saving scenarios and assumed policy package in buildings reflect the recently adopted climate and energy targets?

The target of keeping the increase in global average temperature below 2°C set in Paris Agreement requires the CO_2-reductions beyond 80-90% in the building sector. The second case study provides policy based energy demand scenarios and analyses their consistency with Paris COP21 decarbonisation targets.

Case study II "Policy based energy demand scenarios to 2050" investigates energy demand for space heating and hot water until 2050 in the building sector in France, Italy, Norway, Poland, Romania and Spain. It implements the following methodological steps:

- Model policy based energy demand scenario for space heating and hot water to 2050 using the building stock simulation tool Invert-EE/Lab;
- Investigate current policies and implement them in the model Invert-EE/Lab;
- Provide indicators to assess the consistency with the climate targets;
- Investigate the consistency between the energy savings under the current policies and climate target;
- Provide ambitious policies which may bridge part of the gap between the energy savings under the current policies and climate target.

The results of this analysis show that the current policies – and even discussed "ambitious" policies – are not sufficient to reach the adopted Paris COP 21 targets. Rather, it will require enhanced policies. Therefore, it is also essential to better understand where the most cost-effective solutions are situated and how those potentials and building sectors which are not yet profitable could be properly addressed by policies:

What building sectors and energy efficiency solutions have to be addressed by policy instruments to achieve the climate and energy targets?

Target-oriented policy measures can lead to substantial progress in building renovation and more effective and efficient policies (Kranzl et al., 2014d). In order to set target-oriented policy measures, there is a need to identify buildings and energy efficiency solutions which have to be implemented to achieve energy and climate targets. In the third case study I provide an additional approach of deriving cost curves: the energy saving cost curve showing overall economic perspective. To test this approach, I analyse the Lithuanian residential building sector.

Case Study III: “Cost curves for the Lithuanian residential building sector” aims to calculate energy saving potential for space heating and hot water by 2030 using two different perspectives of selecting cost-effective energy efficiency solutions. It implements the following methodological steps:

- Analyse the Lithuanian building stock and its technical characteristics;
- Define energy efficiency solutions including insulation of envelope, heat pumps and solar thermal panels;
- Calculate cost-effectiveness of energy efficiency solutions;
- Calculate total energy savings for space heating by 2030;
- Provide cost curves showing the investor perspective in an overall economic perspective;
- Provide policy recommendations on what type of buildings should be addressed and what policy instruments might be applied in order to achieve the highest energy saving potential in the most cost-effective way.

The cost-effectiveness of investments has been considered as the main driver to invest in energy efficiency solutions and thus reduce the overall energy demand in the building sector in this thesis. However, in many cases, the cost-effectiveness of energy efficiency solutions is not always the main driver to invest. In the shopping centre, for example, indoor environmental quality is of primary importance for the attractiveness of the sale place. Moreover, this sector is more complex sector compared to the residential sector due to variations in usage pattern, energy intensity and construction techniques (Bointner et al., 2014). All these issues require corresponding policy framework to enhance energy efficiency. Thus, modelling of the future energy demand has also be extended by taking different energy services into account such as space heating and cooling, lighting, appliances, refrigeration and ventilation. I will draw nearer to this aspect with the following question and analysis:

What are the perspectives to increase the energy performance in the shopping centre building stock?

Case Study IV: “Modelling of energy demand of shopping centres” aims to model the current and future energy demand in the European shopping centre building stock. It implements the following methodological steps:

- Analyse shopping centre building stock;
- Calculate energy demand for lighting, appliances, refrigeration and ventilation, space heating and space cooling;
- Define energy efficiency solutions for lighting, appliances, refrigeration and ventilation, space heating and space cooling;
- Model energy demand of the European shopping centre building stock to 2030;
- Model four scenarios by taking different economic and technical conditions into account.

1.4.Structure of work

This doctoral thesis is structured as follows: Chapter 2 gives state of research focusing on energy-economic models and cost curves application examples; Chapter 3 explains the major methodology applied in this work. Chapters 4-7 provide different case studies addressing different methodology approaches, building sectors and countries as outlined above. These chapters contain input data, results and discussions for these specific analyses.

Chapter 4 shows the input data on total building stock in France, Norway, Italy, Romania, Poland and Spain; defines three technical measures of retrofitting including better insulation on envelope and mechanical ventilation. It provides two different scenarios with different sets of economic conditions. Finally, it shows energy savings cost curves of investments for each investigated country.

Chapter 5 is built on the same country´s building stock data as in Chapter 4. It presents current policy measures and programmes in the investigated countries. Further, this chapter shows ambitious policy instruments. Finally, it shows two policy based energy demand scenarios to 2050 and discuss the consistency with COP21 agreement.

Chapter 6 provides data for the Lithuanian residential building stock and 15 technical measures of retrofitting. The measures include better insulation on envelopes, heat pumps and solar thermal panels. They are related to Energy Performance Certificates. The chapter shows three different cost curve approaches and discusses their applicability. Finally, it provides policy recommendations.

Chapter 7 provides shopping centre building stock data for EU-28 and Norway. It shows energy demand calculation for space heating, space cooling, lighting, ventilation, refrigeration and appliances. Four different scenarios and their framework are defined and energy demand scenarios are provided.

2. Literature review

Above raised questions deal with two main methods of approach: modelling of the energy demand in the building sector and deriving energy saving cost curves. In this part, literature review is provided addressing these two methods of approach.

The first question **“What is the cost-effectiveness of different energy efficiency solutions in the building stock and how does their implementation contribute to the energy savings in buildings?”** requires to investigate the energy saving measures based on their costs and benefits. There are several scientific studies showing cost curves to evaluate the energy saving measures based on their cost and benefits across different sectors, countries and mitigating measures (McKinsey & Company, 2017), (The World Bank, 2009). However, relevant to my thesis, I have to deal with the cost curves applied on the building sectors (Kesicki, 2012), (Jakob, 2006), (Promjiraprawat et al., 2014), (Staniaszek et al., 2015) and (Kranzl et al., 2016). With respect to the renovation measures and their economic viability from an investor’s perspective, (Staniaszek et al., 2015) and (Kranzl et al., 2016) provide Energy-Saving cost curves for Germany´s building stock. Case study I of this thesis is based on the calculation approach provided in these papers. Additionally, I provide and discuss different indicators of cost of investments; their applicability and propriety.

In order to answer the further question of this thesis **“What building sectors and energy efficiency solutions have to be addressed by target-oriented policy instruments to achieve the climate and energy targets?”** I deal with the same approach as described above. However, this approach is expanded by considering the overall economic perspective going beyond the pure investor’s perspective. This allows me to identify building and energy efficiency solutions in different intensities which have to be implemented to achieve energy and climate targets in the most cost-effective way. Up to now, there are no papers and studies implementing this approach for concrete efficiency measures. With my work I intend to fill the research gap.

“Do ambitious energy saving scenarios and assumed policy package in buildings reflect the recently adopted climate and energy targets?” There are numerous papers which investigate long-term energy demand scenarios for the buildings located in different European countries. Many papers investigate technical building standards, fluctuation in temperature, macro-economic factors to derive energy demand scenarios in the building sector (Damm et al., 2017), (Pilli-Sihvola et al., 2010), (Asimakopoulosa et al., 2011) and others. These papers, however, do not deal with the energy demand modelling looking at the economic efficiency and policy questions. With respect to these issues (Müller, 2015), (Kranzl et al., 2006), (Toleikyte et al., 2016) provide energy demand scenarios of building stock in different EU countries up to 2030/2050/2080 and investigate impact of different policy programmes on the long-term energy demand. Case study II is built on the methodology provided in these papers. Additionally, I provide an approach on how to analyse the consistency of the scenario results and climate targets set in the Paris Agreement.

“What are the perspectives to increase the energy performance in the shopping centre building stock?” While there are many scientific papers and studies showing energy demand modelling for the residential building sector and for the aggregated total building sector, I found very few scientific papers and studies specifically investigating shopping centre building sector. Most of the papers analyse the shopping energy consumption using engineering methods (Dipasquale, 2016), (Dipasquale et al., 2017), (Haase et al., 2015), (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2011) or using monitoring data (Stensson, 2014) (Stensson et al., 2009), (Canbay et al., 2004), (Ding et al., 2013), (Lam and Li, 2003). Most of these papers analyse the best technical and management strategies to reduce energy demand in single shopping centres. There are, however, no studies investigating future energy demand in the total shopping centre building stock of a country or region. Looking at the scientific content of the research, I could say, that this part of my PhD thesis which was made in the frame of an European project called “Commonenergy” (Commonenergy project, 2017) , was the first attempt to model the energy demand scenarios for the shopping centre building stock in European countries using a bottom-up approach.

This chapter is divided into three following parts giving an insight into the above-mentioned papers and scientific studies:

- Energy saving cost curves
- Energy-economic models for the building sector
- Energy demand modelling for the shopping centre buildings

2.1.Energy saving cost curves

The costs and benefits of reducing energy demand and correspondingly reducing carbon emissions has been a focus in political discourse (Keay, 2011), (Kesicki, 2012), (Tomaschek, 2015), (Kesicki and Strachan, 2011). There are several questions here. Are there cost-effective opportunities to improve energy efficiency? If so- what are the most cost-effective potentials and what are the costs to achieve a certain energy saving target? What are the preferred energy saving measures according to their costs and benefits? These are questions raised by policy makers in order to set the preferences of investments to achieve energy saving targets or to reduce GHG emissions (Keay, 2011), (Kesicki, 2012), (Tomaschek, 2015), (Kesicki and Strachan, 2011). In order to evaluate the energy saving measures based on their cost and benefits, the following instruments have been developed and widely used by policy makers and the scientific community, **the conservation supply curves (CSC), marginal abatement cost curve (MACC) and energy saving cost curves (ESCC).** The following part of the literature review gives an insight into selected papers and scientific studies which use these abovementioned three types of cost curves.

The method to calculate the economic feasibility of energy efficiency investments was initially developed in the 1970´s after the oil price crisis. (Meier, 1982) developed the first cost curve called conservation supply curve (CSC) for the reduction of electricity consumption. This tool started to be widely used across the transport, industry and building sectors to investigate energy-efficiency improvements and their economic feasibility. Conservation supply curves show the cost and the conserved energy of different mitigation measures which are then ranked from the cheapest to the most expensive. The cost of conserved energy shows the investments, annualized over a lifetime, by using the capital recovery factor. The annualised investments are divided by the annual energy savings. The investments are cost-effective if the costs of conserved energy are lower than the price of the supplied energy. Fig. 1 shows a supply cost curve of conserved electricity for California´s residential sector provided by (Meier, 1982). The curve shows the costs and yearly energy savings by implementing conservation measures. Accumulated electricity savings after implementing conservation measures after 10 years, corresponds to about 25% of the total electricity used in the total California´s residential building sector.

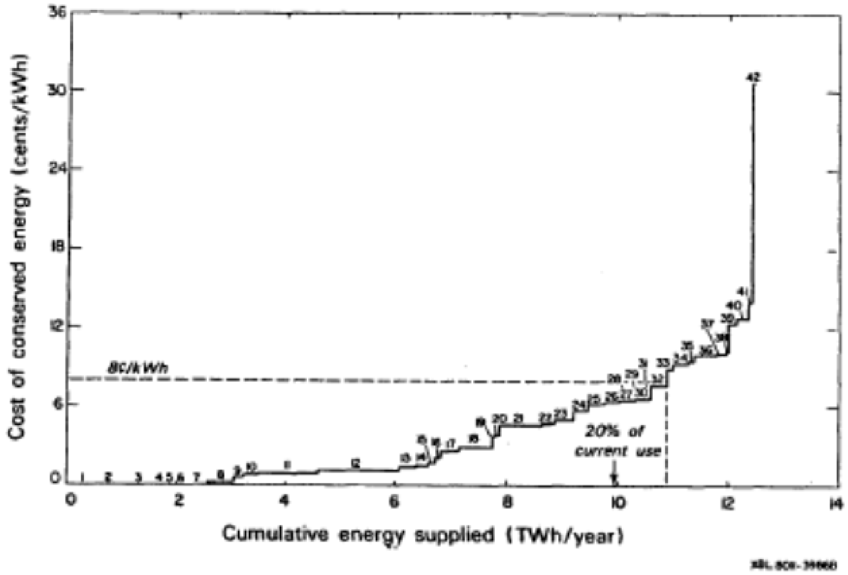
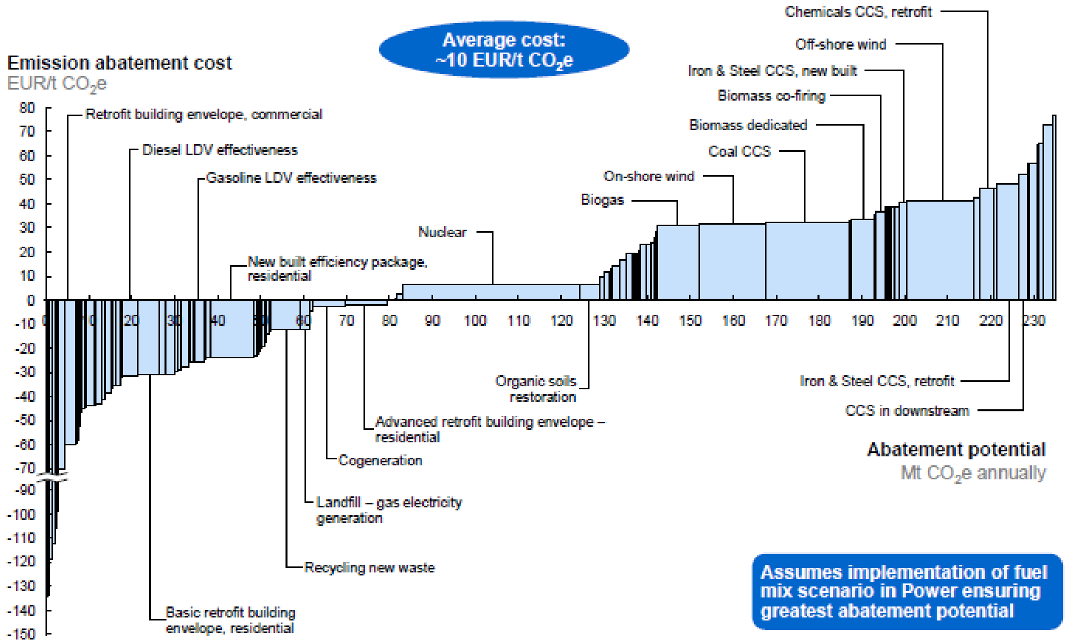


Fig. 1 The supply cost curve of California’s residential sector’s electricity conservation. Each step corresponds to a conservation measure (price is given in $ for 1982) (Meier, 1982)

This tool was later transformed to the marginal abatement cost curve (MACC). A MAC curve is a graph that shows the marginal abatement cost per saved CO_2-emissions or kWh of saved energy on the y-axis and the emission or energy abatement level on the x-axis (Kesicki, 2012). The marginal abatement cost (MAC) curve is an instrument to show energy or emission reduction potentials together with the costs of each suggested saving option. It is often used as a tool for political decisions on setting preferences for climate protection and energy saving measures according to their cost and potentials (Kesicki, 2012), (Wächter, 2013), (Promjiraprawat et al., 2014), (Jaccard, 2010).

In recent studies and journal papers, MACC curves have been frequently used across different sectors, countries and mitigating measures. McKinsey & Company developed global greenhouse gas mitigation cost curves for many countries. The cost curve shows GHG emission abatement costs for different sectors and mitigation measures on the y-axis (cost in EUR per reduced tonne of CO_2e) and the abatement potential (how much emissions can be reduced by the measure) on the x-axis (McKinsey & Company, 2017). Fig. 2 shows McKinsey & Company GHG abatement cost curve for Poland. Sectors and technologies to reduce GHG emissions by 2030 are identified. The results show that 70% of total abatement potential is related to energy efficiency improvements and low-carbon energy supply opportunities (McKinsey & Company, 2009).

Other global GHG abatement cost curves were developed by the World Bank´s Energy Sector Management Assistance Program (ESMAP) showing the costs and benefits of actions across multiple sectors for six countries with emerging economies (The World Bank, 2009). The study provides the governments of these countries with GHG mitigation opportunities and the additional costs and benefits of lower carbon growth. The exemplary highlights of the outcomes are as follows; China should focus on renewable energy and energy efficiency, whilst Brazil should focus on land use change model (The World Bank, 2009).



1 Only the most significant abatement opportunities are named

Fig. 2 McKinsey & Company GHG abatement cost curve for Poland (McKinsey & Company, 2009)

Global GHG abatement cost curves show energy or emission reduction potentials together with the costs of each distinguished saving option. It is often used as a tool for political decisions for setting preferences for climate protection and energy saving measures according to their cost and potentials. Although this instrument delivers a beneficial effect and is widely used by the policy makers, the instrument is often criticized for lack of information about the assumptions or for applying a too simplified methodology (Kesicki and Strachan, 2011) (Chappin, E. J. L., 2016). There are many studies providing cost curves for one particular sector (Kesicki, 2012), (Jakob, 2006), (Promjiraprawat et al., 2014), (Staniaszek et al., 2015).

Relevant to my thesis, studies showing cost curves applied on the building sectors of different countries will be presented.

(Kesicki, 2012) calculates marginal abatement cost curves for the UK residential sector up 2030. The results show that it is cost optimal to implement energy efficiency measures which include wall insulation, loft insulation, efficient lighting, more efficient boilers and electric appliances, as their implantation can save 8% of the total energy demand on heating space. Furthermore, the results show that it is cost-effective to switch from fossil fuel heating systems to district heating and biomass heating. An increased use of wood-fired and pellet boilers, a wider distribution of district heat and heat pumps contribute to high GHG emission reduction. Electricity and district heat wpuld provide 39% of the final energy use in the domestic sector, if all building owners would follow the economic rationale of this approach.

(Jakob, 2006) provides the marginal costs of energy efficiency investments (i.e. additional insulation, improved windows systems, ventilation and heating systems) for the Swiss residential sector. The economic evaluation of co-benefits such as improved comfort of living, indoor air quality and energy related benefits are shown (see Fig. 3).

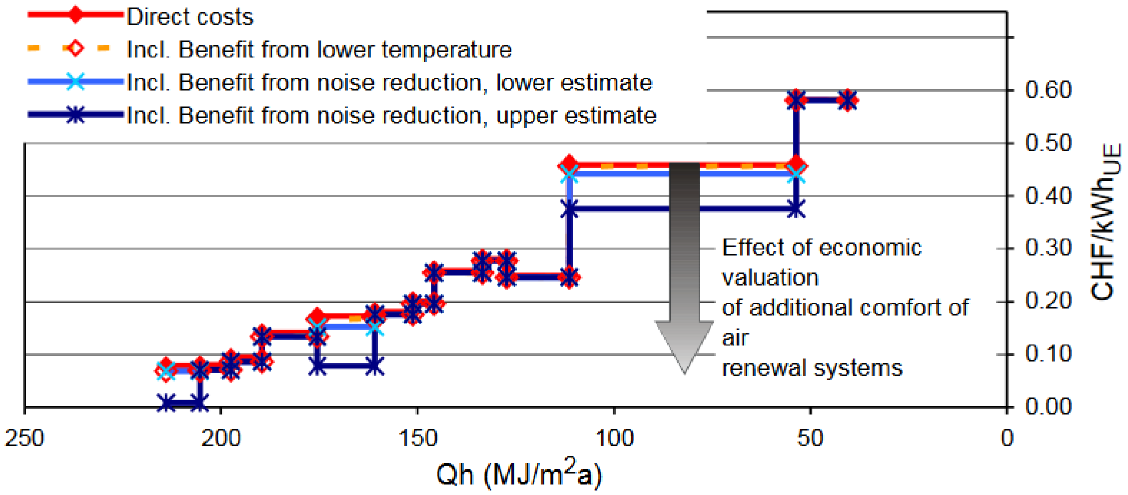


Fig. 3 Marginal cost curve for insulation investments with consideration of selected co-benefits. Case study for a single-family house built between 1900 and 1961 with oil heating in Switzerland (Jakob, 2006).

(Promjiraprawat et al., 2014) investigates GHG emissions reduction potential for the Thai residential building sector, by implementing the following energy efficiency measures; efficient lighting efficient devices, efficient cooling devices, efficient heating devices, other electrical devices, insulated houses and building codes. Without implementing these energy efficiency measures, the GHG emission will increase to app. 52 Mt-CO2 by 2050. By implementing these solutions the GHG emission can be reduced by 35% until 2050. Investments in efficient cooling devices and air conditioners are economic feasible.

BPIE together with TUWien and Fraunhofer 2015 (Staniaszek et al., 2015), (Kranzl et al., 2016) developed Energy-Saving cost curves for Germany´s building stock. They investigated different renovation levels and their economic viability from an investor's perspective. The energy refurbishment potential until 2030 for different building segments is assessed, taking into account different variables, such as energy-price evolution, subsidy levels, transaction costs, discount rates, learning and cost reduction and co-benefits. Fig. 4 shows an Energy-Saving cost curve for the Status Quo scenario. This scenario assumes the prevailing economic conditions, such as discount rate of 4% on renovation measures, subsidies for renovation measures from 10-25% and others. The results show that 150 TWh/year can be reduced in the period to 2030. Half of the buildings can be renovated in a cost-effective way. The additional black line on the graph indicates the case if utility benefits are taken into consideration. It shows that when utility benefits are valued in the economic appraisal, both subsidies and investor contributions more than double in response to the doubling of cost effective energy savings.

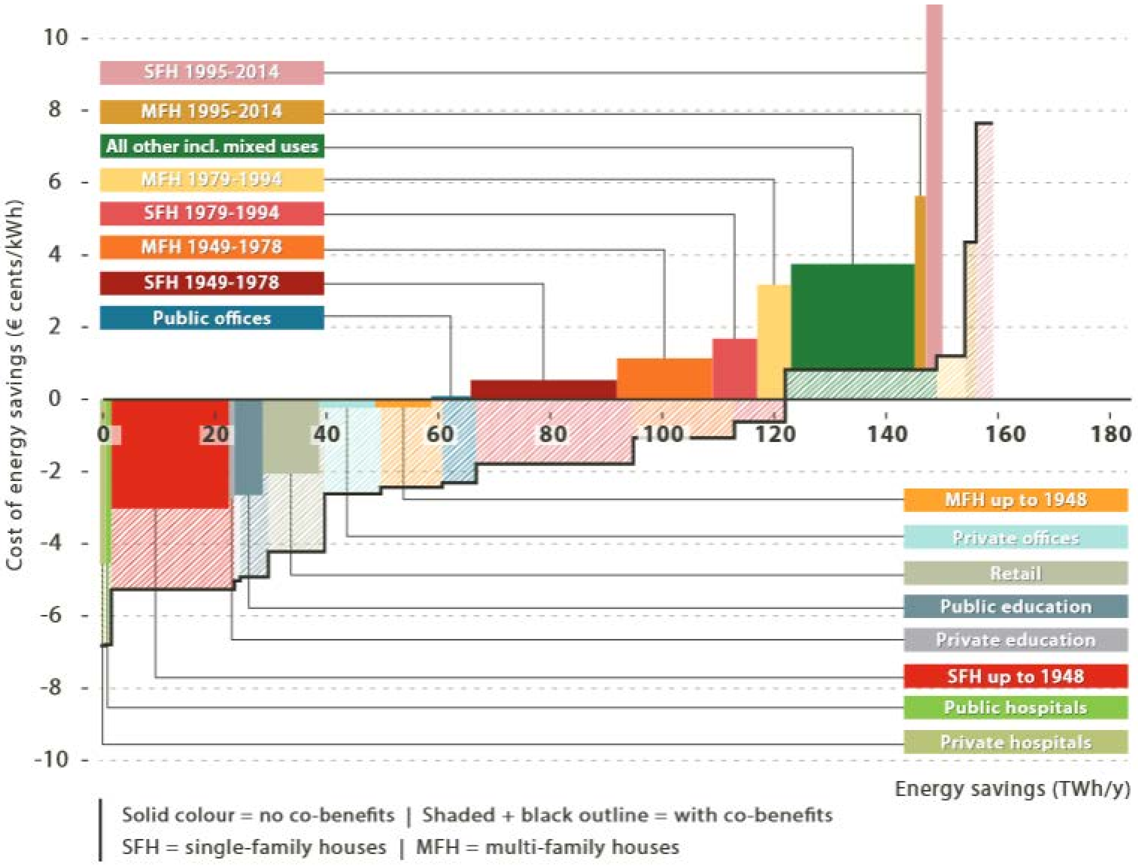


Fig. 4 MESC curve for Germany´s building stock (Staniaszek et al., 2015)

Many of the cost curves showing cost and benefits for multiple sectors, indicate that energy efficiency actions are related to the lowest costs. However there are many debates on the profitability of energy efficiency (Kesicki and Strachan, 2011) (Keay, 2011) (Jaccard, 2010). Keay 2011 (Keay, 2011) indicates various market barriers and issues which prevent these savings from being realised. Barriers to be overcome especially in the energy efficiency sector are; imperfect information (lack of information prevents consumers investing in energy efficiency measures), absence of markets (it is difficult to sell energy efficiency as a product on a market, however, energy efficiency services and energy performance contractors could fill this gap), split incentives (the classic example of landlord/tenant relationship), rebound effect, transactions and hidden cost.

(Jaccard, 2010) distinguishes these barriers into three categories. „Information barriers“ refer to barriers which result in a lack of awareness of efficiency opportunities by households or firms. “Financial barriers” applies to the up-front costs of efficiency measures. The last being “Split-incentive barriers” also known as the landlord/tenant dilemma.

2.2.Energy-economic models for the building sector

This part of my thesis aims to show and describe methods used in different papers and scientific reports to model long term energy demand scenarios in the building stock. The papers which use energy-economic models can be differentiated according to their scope and modelling methodology. Energy-economic models can be classified into top-down and bottom-up models. This aggregation is based on the different sectoral and technological aggregation levels (Steinbach, 2013). (Steinbach, 2013) derives the taxonomy and classified different models used in the scientific society (see Fig. 5).

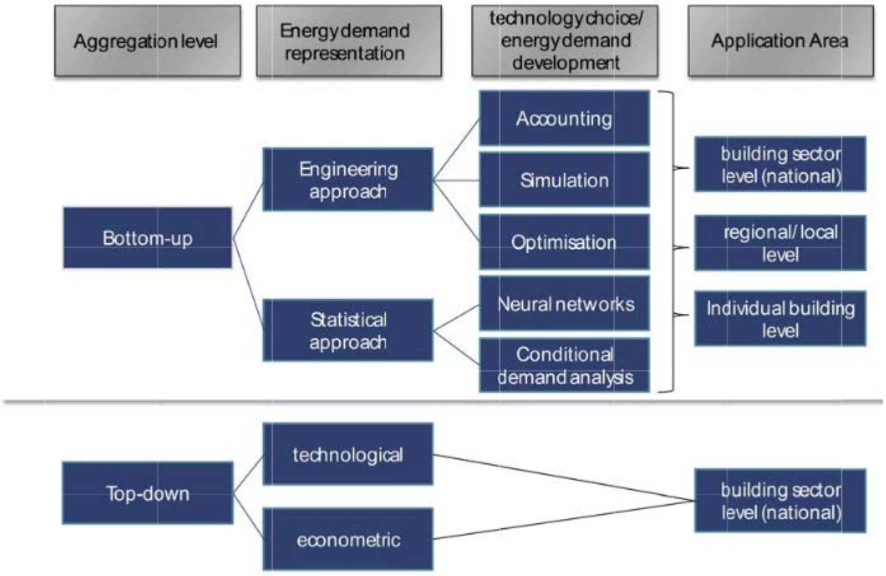


Fig. 5 Classification of energy-economic models for the building sector (Steinbach, 2013)

The top-down models are based on the macroeconomic social accounting matrix, while the bottom-up models take detailed data on buildings e.g. floor area, insulation levels, boiler characteristics. Each approach is based on different input data and different calculation techniques. In this section, the input data, the calculation techniques and their provided results in different papers and studies are analysed.

Several papers which use a bottom-up approach and several papers which use a top-down approach are investigated. The analysis covers the following countries: Austria, Switzerland, Germany, Slovenia, Greece, Spain, Italy, EU-15, EU-17, Finland, Netherland, France and Spain. First, I provide an overview on the papers which use the bottom-up approach to show the future energy demand. Second, I provide an overview of the papers which use a top-down approach. All investigated papers are given in Table 1.

All the investigated papers which use a bottom-up approach show the identical future trend: decrease of heating energy demand in winter and increase of cooling energy demand in summer. In Germany, heating energy demand decreases of around 81% occurs between 2010 and 2060 under scenario “3˚C warming and 3% retrofit rate” and around 56% under the scenario “1˚C warming, 1% retrofit rate”. Cooling energy demand in the scenario “high energy demand” increases by 235% between 2010 and 2060. The results of residential buildings in Switzerland show that heating energy demand goes down by 8-13% in the climate scenario C (+1 ˚C temperature) and by 33-44% in the scenario D (+4.4 ˚C temperature). The cooling energy demand increases by 365-1050% in scenario D (+4.4 ˚C temperature), while in a reference scenario energy demand increases by 223-457%. The results for Greece show energy reduction of heating energy of 22.4% for scenario A1B (2041-2050). A significant energy reduction of almost 42% can be achieved regarding scenario A2 (2091-2100). For scenario A1B (2041-2050) an increase of 83% and for scenario A1B (2091-2100) of 167% is estimated.

The main factors of these trends in all investigated countries are the fluctuation in temperature: increased trend in ambient temperature influences trends for both heating and cooling energy demand. The decrease in heating energy demand is mainly related to technical building standards in the future in all considered countries. The increase in cooling energy demand is also related to building standards, although the standards lead to differences between south and middle European countries, e.g. in Switzerland buildings with high insulation levels correlate to higher cooling energy demand, while in Greece passive residences correlate to lower cooling energy consumption. Despite the significant increase of cooling energy consumption in all countries, cooling energy consumption is still lower than heating energy consumption.

The results in the papers which use a top-down approach show the similar trends compared to papers mentioned above. These papers, however, consider the macroeconomic factors and investigate only electricity demand. The increase in cooling energy demand is related to the increase in comfort standards and greater use trend of air-conditioning and its market penetration. The steady increase in summer electricity demand is estimated to be greatest in southern European countries in the recent years. A change in air temperature becomes a significant role especially in the urban areas, where this trend is strengthened by the urban heat island effect. The results made for 16 continental European countries show the ratio between absolute decrease in heating and absolute increase in cooling electricity demand of 2:1 and 6:1depending on the climatic scenarios. In the moderate-temperature countries like French or Germany, cooling electricity demand is estimated to be relatively small compared to heating electricity demand and climate change will lead to a reduction of electricity consumption. However, in Italy the increase in cooling energy demand is predicted to be stronger than the decrease in heating electricity demand.

The comparison of these two approaches allows to say, that a bottom-up approach requires a very large input data set, but allows, however, determine and analyse each end-use energy consumption by type and investigate the impact of the penetration of new technologies. A top-down approach requires simple input information and investigates macroeconomic and socioeconomic effects.

Table 1 Model description to calculate energy demand in different papers

Country/ Source	**Approach/ Method or Software package/ Data volume**
AT/(Müller, 2015)	Bottom-up/Building simulation tool Invert-EE/Lab/Yearly energy demand for space heating and hot water, calculation is based on monthly energy balance approach
AT,DE,POL/(Kranzl et al., 2006),	Bottom-up/Building simulation tool Invert-EE/Lab/Yearly energy demand for space heating and hot water, calculation is based on monthly energy balance approach, policy based scenario modelling
AT,DE,ITA,ESP,FRA,ROU,POL/(Toleikyte et al., 2016)	Bottom-up/Building simulation tool Invert-EE/Lab/Yearly energy demand for space heating and hot water, calculation is based on monthly energy balance approach, policy based scenario modelling
CH/ (Frank, 2005)	Bottom-up/Building Energy Simulation Model HELIOS/Energy consumption: 1-hourtime step, based on one building consideration
DE/ (Olonscheck et al., 2011)	Bottom-up/German DIN Standard V 4108-6 (DIN, 2003)/Energy demand: yearly, based on total residential building stock of the country
SI/ (Dolinar et al., 2010)	Bottom-up/Transient systems simulation program TRNSYS/Energy use: hourly data, based on one building consideration
GR/ (Asimakopoulosa et al., 2011)	Bottom-up/Transient systems simulation program TRNSYS/Energy demand: hourly data, based on one building consideration
SP/ (Moral-Carcedo and Vicéns-Otero, 2005)	Top-down/Smooth Transition Regression (STR)/Daily electricity demand estimation (period: 1995 08 – 2003 08)

IT/ (Beccali et al., 2007)	Top-down/Artificial Neural Network, Linear-regression, HDD and CDD/Short-time prediction of the household electricity consumption
GR/ (Giannakopoulos and Psiloglou, 2006)	Top-down/Linear-regression, HDD and CDD/Monthly, daily, hourly electricity consumption (period: 1993 – 2001)
AT, BE, D, FI, FR, GE, GR, IR, IT, LU, NE, P, SP, SW, UK (Bessec and Fouquau, 2008)	Top-down/Panel threshold regression model/Monthly electricity consumption from Eurostat (period: 1985 – 2000)
PL, CZ, SK, DE, AT, NL, SI, RO, BE, HU, FR, BG, HR, IT, ES, PT/ (Damm et al., 2017)	Top-down/Smooth Transition Regression (STR)/ Daily load data from ENTSO-E (period: 2009 – 2010)
FI, DE, NE, FR, SP/ (Pilli-Sihvola et al., 2010)	Top-down/Linear-regression, HDD and CDD/ Monthly electricity consumption from Eurostat (period: 1985 – 2008

2.3.Energy demand modelling for the shopping centre buildings

European shopping centre building stock offers a high energy savings potential and good ground to implement energy efficiency measures. However, to analyse the energy saving potentials in this complex building sector requires a comprehensive analysis investigating: (I) different energy services, space heating and cooling, lighting, refrigeration, ventilation and (II) energy efficiency solutions addressing these services and (III) complex investment structure due to many following stakeholders in the decision process; managers and owners, tenants, customers and community.

All the investigated papers and studies come to the same following outcomes: (I) The heating energy demand makes up only small share on the total energy demand across all climate zones in Europe; (II) Energy load and demand are closely connected. (III) Rising internal loads and improved building envelopes result in increased cooling demand.

Dipasquale, 2016 provides dynamic simulation using the Integrative Modelling Environment (IME) based on the Trnsys simulation software to investigate energy savings, comfort and economic indicators by applying different retrofitting solutions for a shopping centre. The following components were analysed: building features, HVAC systems, refrigeration systems and components, daylight/shading/lighting, storage technologies, RES technologies, natural ventilation strategies and finally non-conventional envelope solutions (vegetation, multi-functional coating and materials). Building energy simulation using IME allows studying a shopping centre and identifying effective retrofitting solutions. The simulation was carried out for different types of thermal zones within a shopping centre (e.g. shops, common areas, food stores, and restaurant). The main outcome is that equipment and building load improvements have an influence on other shopping mall systems. Three aspects must be simultaneously considered during the retrofitting design: (I) the location and climate, (II) the architecture, (III) the selection and control of HVAC, lighting, refrigeration, RES and storage systems.

Dipasquale et al., 2017 investigate the impact of heat recovery solutions on the energy savings in different shopping centre buildings. The study provides an analysis on the potential of wasted energy in the installed systems (HVAC, refrigeration, lighting, storage and others) and provides solutions which include the recovery systems and control strategies that facilitate the system interactions. The dynamic building simulation software Trnsys was used to simulate energy savings by applying heat recovery systems and control strategies for artificial lighting, ventilative cooling, solar thermal panels, refrigeration technologies and others. The study stays that the following improvements can bring up to 70% of the energy savings: the set of the internal temperature in function of external temperature; installation of efficient refrigeration systems and management of internal conditions.

Haase et al., 2015 investigate deep energy retrofitting for shopping centres and assess possible cost-optimal retrofitting actions for shopping centre manager. Energy consumption was divided into heating, cooling and electricity for different uses. Energy demand was calculated using the steady-state simulation tool called Passivhaus-Projektierungspaket (PHPP) for shopping centres located in different European countries. The results show that the largest primary energy savings can be achieved by implementing efficient lighting and appliances. A cost analysis has been performed and the results show positive net present value for lighting, infiltration, thermal bridges and allowing increase in summer temperatures. Additionally, the study also identified four main areas of energy use inefficiencies, main drivers and barriers to invest in the retrofitting solutions.

Stensson et al., 2009 provides an analysis of specific energy use in a Swedish shopping mall. The study monitors the climate inside a building as a result of the complex interplay between the building envelope, the activities inside it and the outdoor climate. Data comes from an energy auditing campaign for a shopping mall situated in Sweden. The study also determines the occupancy pattern by counting the number of visitors. The results show that the yearly purchased electricity is 204 kWh/m^2, including both landlord and tenant electricity. The paper shows that the rising internal loads and improved building envelopes have resulted in major cooling demands even in a Nordic climate. Thus, load and demand are closely connected. The paper says that the main issues are removal of surplus heat and of airborne pollutants in order to reduce energy demand and that the heating demand is a minor problem. Moreover, the energy need for electricity for lighting and equipment make up a major part of the total energy.

Lam and Li, 2003 present the electricity use in the commercial sector in subtropical Hong Kong during the 30 year period from 1970 to 2000. The paper shows that commercial buildings, especially shopping centres, are major electricity end-uses. The paper also investigates the electricity consumption characteristics of four fully air conditioned shopping malls in subtropical Hong Kong. The annual electricity use per unit gross floor area ranged from 391 to 454 kWh/m2, with an average of 430 kWh/m2. Air conditioning and electric lighting were the two major electricity end-uses, accounting for about 85% of the total building electricity use. The paper concludes that these should be the priority areas in any energy efficiency programmes.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2011 provides energy design guide for retail buildings on how to achieve 50% energy savings. The energy saving projection in this study is based on whole-building site energy savings, which include process and plug loads. The guide provides a methodology for achieving energy savings goals that are financially feasible and operationally workable. Energy modelling is based on three prototypical retail stores which were developed and analysed using hourly building simulations. Each prototype was split into the following space types, sales areas, entrance/exit vestibule, stocking room, mechanical room and others. Hour-by-hour simulations were run for each prototype for eight climate zones in U.S. Energy savings recommendations were derived for each climate zone. The guide concludes that to achieve 50% of the energy savings is challenging and requires implementation of innovative technical solutions and strong participation of different stakeholders. Among others, the guide recommends that the team of a retail building maximizes daylighting; minimizes process, heating, and cooling loads; and has highly efficient lighting and HVAC systems. The guide also recommends adopting an integrated design process which leads to cost-effective investments by taking into account indirect benefits, for example, installation of the highly efficient lighting system may cost more than a conventional one, but because it produces less heat, the building's cooling system often can be downsized.

3. Methodology

The main approach applied in this work is a bottom-up approach and the energy demand is investigated on the disaggregated description of the building sector. This chapter is divided into the following sub-chapters:

- Applied models
- Energy demand: definitions and calculation
- Techno-economics of investments
- Required data

Applied models: This sub-chapter presents two models which are applied in this work, building simulation tool Invert-EE/Lab and Cost Curves Tool. Invert/EE-Lab is a dynamic bottom-up techno-socio-economic simulation tool that evaluates the effects of different policies on the total energy demand. This tool is applied for the Case study II “Policy based energy demand scenarios to 2050”. Case Study IV “Modelling of energy demand of shopping centre” is carried out using some modules of the Invert-EE/Lab. The second model “Cost Curves Tool” shows cumulated energy savings for the considered time period and the cost-effectiveness of the selected renovation options. “Cost Curves Tool” is applied for the Case study I “Cost curves for the selected European countries´ building stock” and Case study III “Cost curves for the Lithuanian residential building sector”.

Energy demand: definitions and calculation: this sub-chapter provides the building system boundary and related energy definitions. It shows calculation of energy need for space heating and hot water, delivered energy and primary energy demand which are implemented in the above-mentioned models.

Techno-economics of renovation packages: this sub-chapter shows calculation of the economic attractiveness of different renovation packages. Definition of renovation packages is explained and calculation of levelized costs is derived.

Required data: this sub-chapter shows required data for both above mentioned models.

3.1.Applied models

3.1.1. The Invert-EE/Lab model

To calculate the final energy demand for space heating and hot water until 2050 and related primary energy demand as well as CO_2 - emissions, a bottom-up techno-economic approach is used. For this purpose, the building stock simulation tool Invert-EE/Lab is applied. Invert/EE-Lab is a dynamic bottom-up techno-socio-economic simulation tool that evaluates the effects of different policies on the total energy demand, energy carrier mix and CO_2-emission reduction (Müller, 2015), (Invert/EE-Lab, 2017). Invert/EE-Lab model has been used to model scenarios of development of building stock and its energy demand in the EU-28 up to 2030/2050/2080 and has been applied in different studies to investigate impact of different policy programmes on the long-term energy demand (Kranzl et al., 2006), (Stadler et al., 2007), (Kranzl et al., 2014b), (Bointner et al., 2016), (Steinbach, 2016) to show the pathways to decarbonise the European building stock (Toleikyte et al., 2016), (Kranzl et al., 2017) as well as to analyse the use of the energy fuel for heating and cooling (Kranzl et al., 2013), (Fleiter et al., 2017).

The model was originally developed by the Vienna University of Technology/EEG in the frame of the Altener project Invert (Investing in RES&RUE technologies: models for saving public money) in the years 2003-2005 (Invert/EE-Lab, 2017). In the frame of different projects, the model has been extended and modified. In 2010, the model was modified in a re-programming process, taking into account the inhomogeneous structures of decision makers (Müller, 2015). Later, the model was extended by integrating an agent-specific approach to consider stakeholder behaviours (Steinbach, 2013).

Fig. 6 shows the structure of the model Invert-EE/Lab containing the main following parts of the model; database, module of space heating and hot water energy demand calculation, invert-agent module, simulation algorithm, simulation results and exogenously defined specific parameters.

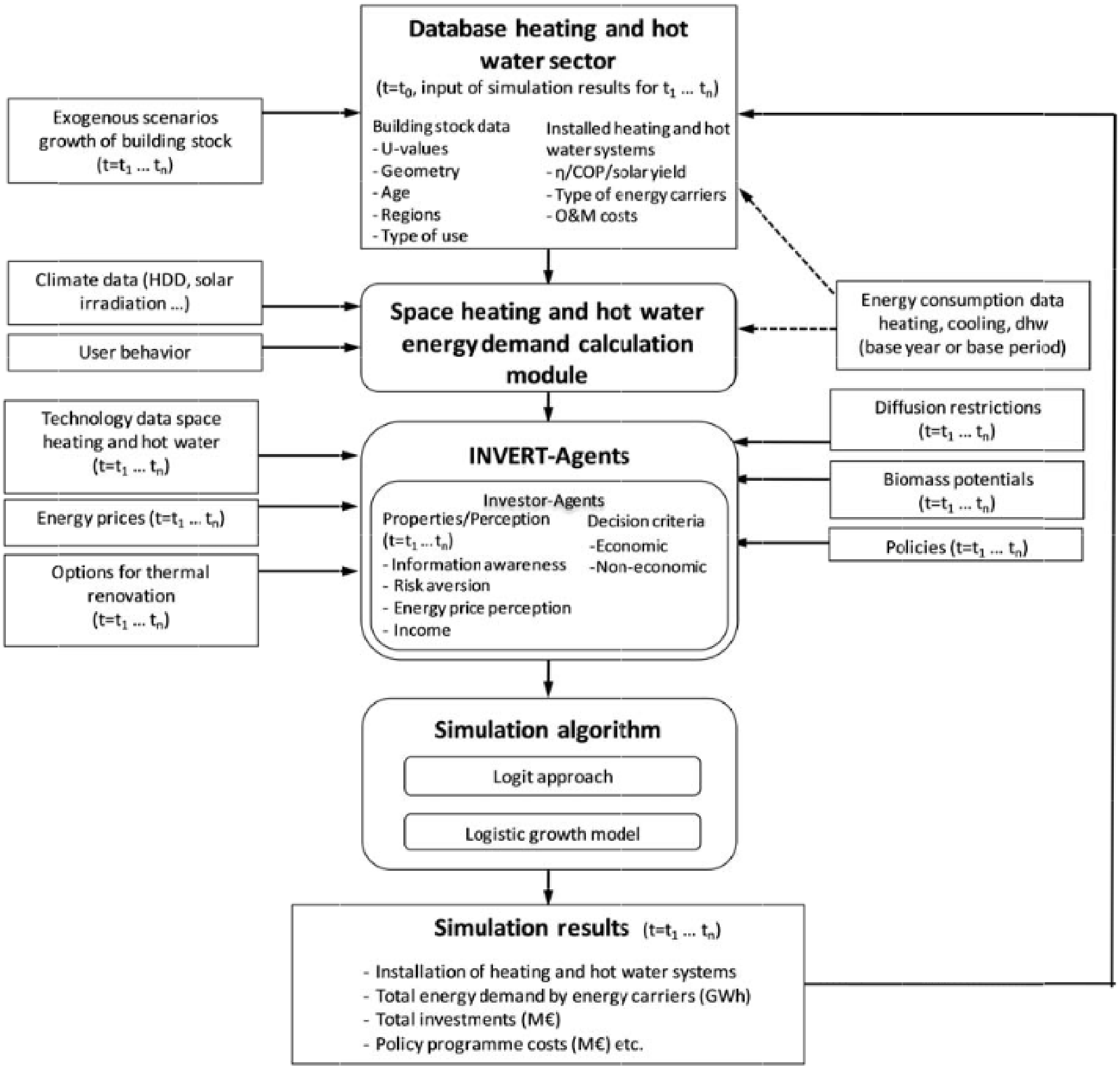


Fig. 6 Structure of the model Invert-EE/Lab (Steinbach, 2013) based on (Müller, 2015)

Database

The part “Database” describes input data used in the model. Building stock data are described following the strictly defined structure. The hierarchical structure contains three parts which provide corresponding properties. The first part defines the building categories (e.g. single family detached house, apartment), the second characterizes building classes which provide information on building categories, building periods, geometry, building envelope, user profiles etc. Based on the building classes, energy need is calculated. The third part called “reference buildings” gives information on heating systems, distribution systems, DHW systems etc. Required input data and structure is described in section 3.4. Next to the building stock data, database also includes data on the new building standards and options for thermal renovation.

Basic approach and Methodology

The method covers three following modules. **In the first module,** energy demand is calculated. The methodology to calculate energy demand in given in section 3.2.

The second module is the building penetration module which determines the building stock development describing demolition rate and building renovation rate. While the new building construction rate is exogenously defined parameter, the building renovation rate and building demolition rate are endogenously defined parameters. The annual renovation rate and demolition rate for each reference buildings are calculated following Weibull-distribution. Renovation rate λ(t) in year t is calculated according to equation 3-1.

$$\lambda(t) = \frac{\beta}{T} * (\frac{t}{T})^{\beta - 1} \tag{3-1}$$

β … Shape factor
T …Characteristic life time

In the third module, Invert-EE/Lab simulates investment decision in heating systems and renovation options. The investment decision passes through the following algorithm, the Invert-agent algorithm and simulation algorithm consisting of logit approach and logistic growth approach. The Invert-agent module takes the heterogeneity of decision-makers in the building sector and investor-specific barriers into account (Steinbach, 2016) cited in (Steinbach, 2013). The agent-based decision module defines different investor types which are described by different investor-specific variables reflecting barriers and perceptions of decision in heating systems and renovation options. The investor types were developed in the project ENTRANZE by investigating the structure of stakeholders, user and investor groups and their behaviours, preferences and interest in nine target European countries (Heiskanen et al., 2012). The investor types slightly differ from one European country to another. Here are some examples of typical implemented investor types: owner-occupied single-family houses, owner-occupied multi-family houses, rental multi-family house, rental social housing, state- and municipality owned public buildings, owner-occupied office buildings and others. Each investor type is descripted using investor-specific criteria values. The investor-specific criteria cover economic and non-economic values. The main three values are defined for each investor type: information awareness, the risk aversion and energy price. The agent-based model was developed and integrated into the Invert-EE/lab model by (Steinbach, 2016) in his PhD thesis.

The abovementioned agent-base model delivers total utility values for heating system technologies and renovation options. Investor- and building-specific market shares of technologies are determined based on the utility values using a nested logit model. The investment decision in heating system and renovation option is further simulated using other monetary and non-monetary criteria. The decision process of heating systems and renovation options slightly differ from each other. The decisions on the renovation packages are taken independently from the subsequently performed decision on the heating systems. The primary driver, for the decision to choose one of the heating systems, is the total costs. The total costs include the consumption-dependent energy costs, consumption-independent annual operating costs (fixed annual tariffs, maintenance and etc.) and the levelized investment costs. Moreover, the change of heating system passes through three categories of barriers. The first are non-monetary criteria which are mainly associated with the comfort level of the old heating systems: by installing a new heating system, the comfort cannot be decreased. Second criterion refers to economic criteria which are mainly dominated by the energy carrier change and the related change of the distribution system. For this reason, decision-makers have a preference to keep an existing energy carrier. And the third criteria include the local availability of energy carrier. The decision algorithm for renovation options follows a similar path. Two-level nested logit model is applied. In the first step it is decided whether thermal or not thermal renovation is taken. On the second level, the type of thermal renovation is chosen. The decision is based on the total costs.

Modelling of policy instruments

In Invert-EE/Lab, policy instruments affect the investment decision in heating systems and renovation options process of the above mentioned investor agents. There are four different policy instruments implemented in Invert-EE/Lab: economic incentives, regulatory instruments, information instruments and Research & Development. Policy instruments may affect investment decisions (in reality and in Invert/EE-Lab) in the following ways (Kranzl et al., 2014a):

- Economic incentives change the economic effectiveness of different options and thus lead to other investment decisions. This change leads to higher market share of the supported technology in the Invert/EE-Lab (via the nested logit approach).
- Regulatory instruments (e.g. building codes or renewable heat obligations) restrict the technological options that decision makers have; limited compliance with these measures can be taken into account by limiting the information level of different agents regarding this measure (see next bullet point).
- Information, advice, etc: Agents have different levels of information. Lack of information may lead to neglecting innovative technologies in the decision making process or to a lack of awareness regarding subsidies or other support policies. Information campaigns and advice can increase this level of information. Thus, the consideration of innovative technologies, the knowledge about support programmes, and the compliance with regulatory standards increases.
- R&D can push technological progress. The progress in terms of efficiency increase or cost reduction of technologies can be implemented in Invert/EE-Lab.

3.1.2. Cost Curve Tool

Energy savings cost curves provide cumulated energy savings for the considered time period on the x-axis and the cost-effectiveness of the selected renovation options for each building typology on the y-axis.

Literature review shows that there exist different types of cost curves (see section 2.1). In my thesis, I create a Cost Curve Tool which provides these types of cost curves:

- A conservation supply curve (CSC)
- An energy saving cost curve (ESCC) showing an investor's perspective (using levelized costs per heated building area)
- Energy saving cost curve (ESCC) showing an overall economic perspective (using levelized costs per heated building area)

Cost curve plot Tool contains two main parts, the calculation algorithm and result visualisation part. Result visualisation part provides a traditional cost curve showing cumulated energy savings on the x-axis and the cost-effectiveness of investments on the y-axis. Additionally, the visualisation part can create other type of figures based on the same input data needed to create cost curves. Cost curve plot tool is computed using programming language R (the software environment for statistical computing and graphics).

Conservation supply curve (CSC)

(Meier, 1982) calculates cost of conserved energy according to equation 3-2.

$$\mathrm{CCE} = \frac{\mathrm{I}}{\mathrm{E}} \cdot \frac{d}{1-(1+d)^{-n}} \tag{3-2}$$

E … annual energy savings
I …Conservation investments
n …Lifetime
d …Discount rate

The rule in this case that governs the decision (to select the least-cost option) is "choose conservation investments having the lowest cost of conserved energy, but reject any for which the cost of conserved energy exceeds the price of the energy it displaced". The price of energy does not enter the cost of conserved energy; rather, that price serves as a scale, or benchmark (Meier, 1982).

This is a reason why the MACC and ESCC calculate the cost-effectiveness of investments using the levelized costs. The renovation measures with negative values are considered as the most-cost effective options. However, I found out that this approach is controversial. By using this indicator and by choosing the cheapest cost option, the problem of negative values occurs. The problem is highlighted by (Taylor, 2012), (Levihn, 2016) and (Ward, 2014). They show that the problem occurs when the negative specific cost is achieved either by a greater financial return (which is a desirable objective) or by a reduction in the energy or emission savings. This leads to the more negative cost when the energy savings are lower (meaning better value). This is a problem of using levelized costs per saved energy.

For this reason, I choose to use the "cost of conserved energy", to show the lowest cost options of investments per saved energy. If we consider the investor's perspective, economically feasible investments are those which are smaller than energy fuel price.

Energy Saving Cost Curve (ESCC)

In order to consider levelized costs of investments, I additionally derive an energy saving cost curve (ESCC), which shows cost-effective measures from an investor´s perspective. However, instead of using the levelized investment costs per saved energy, I use the levelized costs per heated building area.

Two approaches of deriving ESCC

Cost curves showing the building investors 'perspective

The first approach selects the most-cost effective solution for each building type. In other words, the first approach optimizes the investment for the building owner implementing the most cost-effective investment for the corresponding building and neglecting other possible solutions as shown in Fig. 7. It is an approach showing the investors 'perspective. Each bar presents a building type and selected lowest cost renovation option for this particular building type. All building types are ranked from the cheapest to the most cost expensive. The cost-effectiveness of the investments for each building type is shown on the y-axis and total energy savings achieved by implanting a selected renovation option on the x-axis. For each building type j, the least cost renovation option i is selected:

$$C_j = \min_i(C_{i,j}) \quad \text{3-3}$$

After selection of the lowest cost option C_j for each building type, the building types with implemented renovation options are ranked from the cheapest to the most cost expensive. Total energy savings ΔQ_j for a considered time of period is a sum of total energy savings in the building type j Δq_j taking into account the number of buildings (or floor area) n_j and the cumulated renovation rateρ_j:

$$\sum_j \Delta Q_j = \sum_j \Delta q_j * n_j * \rho_j \quad \text{3-4}$$

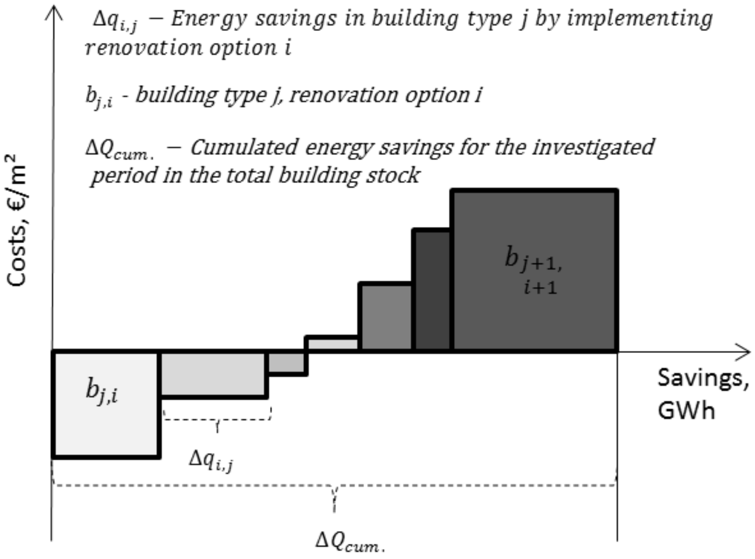


Fig. 7 Energy saving cost curves showing the building investors ‘perspective

<u>Cost curves showing the lowest cost renovation options to achieve energy saving target (overall economic perspective)</u>

By using cost curves from a building investors' perspective, information on the energy saving potential by using energy efficiency solutions with higher energy savings and costs is lost. That is why I provide the second approach which shows the least cost renovation options to achieve energy saving targets showing an overall economic perspective. All building types and renovation options are shown on the curve (Fig. 8). The first renovation option for a particular building type is the lowest cost option from an investor's point of view.

The second cheapest renovation option for the same building type is shown on the curve yet the total energy savings are presented as a margin of the first renovation option. All renovation options which lead to lower energy savings compared to the reference case (the first option) are excluded from further consideration. The vertical line shows an energy saving target (Fig. 8). Renovation option with the highest energy savings is selected for each building type.

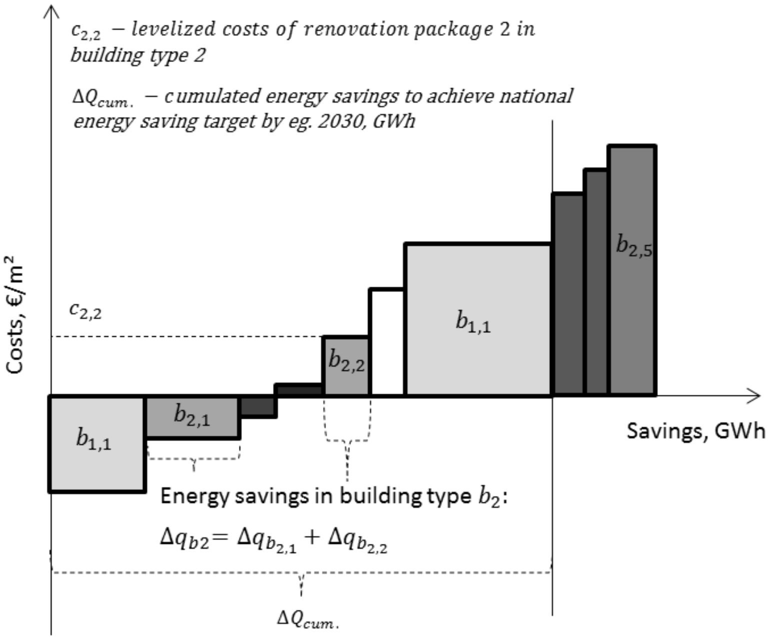


Fig. 8 Cost curves showing the lowest cost renovation option to achieve a certain energy saving target (overall economic perspective)

3.2.Energy demand: definitions and calculation

Current energy demand is calculated for each reference building. Firstly, energy need for space heating is calculated, followed by the calculation of delivered energy and primary energy demand. At this point, it is important to define the building system boundary and related energy definitions. Fig. 9 shows building system boundaries and the connection between energy need, final energy demand, energy use, delivered energy and primary energy.

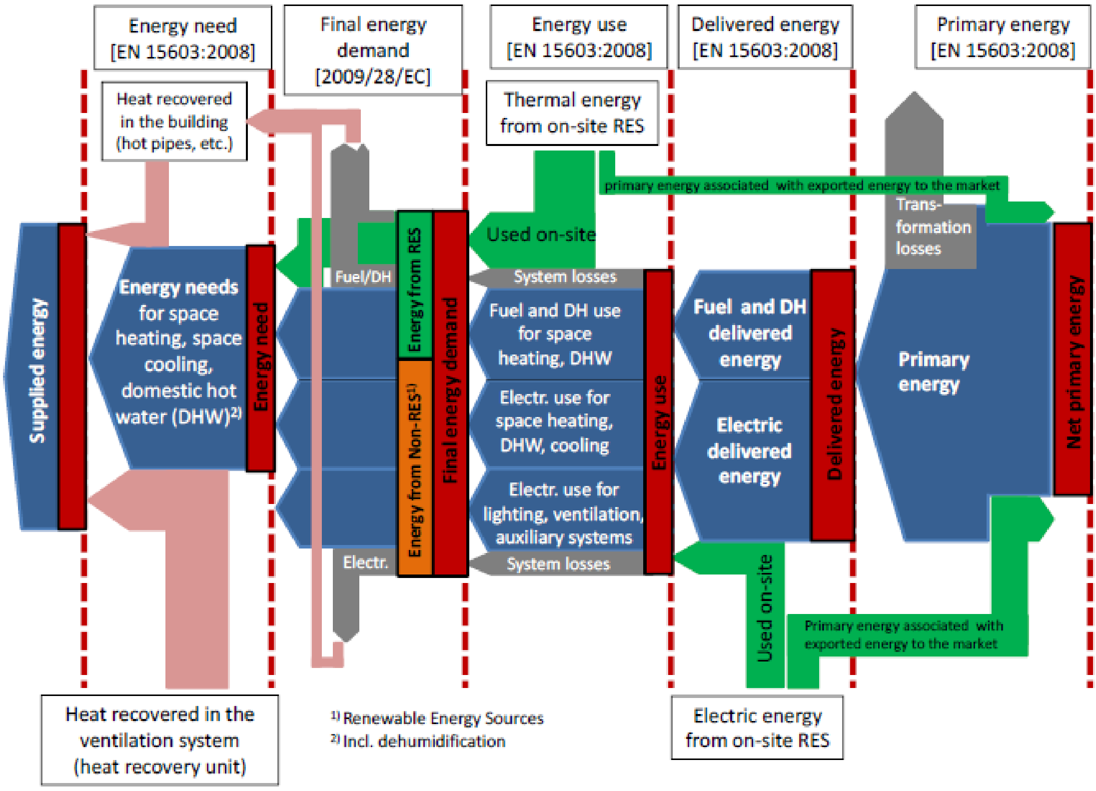


Fig. 9 Scheme of a yearly energy balance in a buildings and the connection between energy need, energy use, delivered energy and primary energy (Müller, 2015)

The calculation of the energy need for space heating and space cooling was carried out with the building simulation tool Invert-EE/Lab (Müller, 2015), (Invert/EE-Lab, 2017). Invert-EE/Lab model calculates the energy need for space heating and cooling using the monthly energy balance approach, the quasi-steady-method, based on the ISO EN13790:2008, EN 15603:2008 and Pöhn C. : "Bauphysik: Erweiterung1: Energieeinsparung und Wärmeschutz. Energieausweis – Gesamtenergieeffizienz" (Pöhn et al., 2007).

According to the ISO EN13790:2008, **Energy need** is defined as *"Heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature conditions during a given period of time. Note 1 to entry: The energy need is calculated and cannot easily be measured. Note 2 to entry: The energy need can include additional heat transfer resulting from non-uniform temperature distribution and non-ideal temperature control, if they are taken into account by increasing (decreasing) the effective temperature for heating (cooling) and not included in the heat transfer due to the heating (cooling) system"* (ISO 13790, 2008).

Energy need for space heating and cooling is calculated on a monthly basis. Energy need for space heating $Q_{H,nd}$ is calculated as a balance of the heat gains and heat transfers (Riccabona and Bednar, 2013):

$$Q_{H,nd} = (Q_T + Q_V) - \eta(Q_S + Q_I) \qquad 3\text{-}5$$

$Q_{H,nd}$ ...Energy need for space heating [kWh]
Q_T ...monthly transmissions through the building envelope [kWh]
Q_V ...monthly heat transfer by ventilation [kWh]

Q_S …monthly heat gains through solar irradiation [kWh]
Q_I …monthly heat gains through persons and internal heat loads (lighting and appliances) [kWh]
η …utilization factor [-]

Energy need for space cooling is calculated according to equation 3-6 (Riccabona and Bednar, 2013).

$$Q_{C,nd} = f_{corr} \cdot (1-\eta) \cdot (Q_S + Q_I) \tag{3-6}$$

$Q_{C,nd}$ …Energy need for space cooling [kWh]
f_{corr} …correction factor for zone adjustments [-]

Energy need for hot water is calculated according to equation 3-7 (Riccabona and Bednar, 2013).

$$Q_{HW,nd} = \frac{1}{1000} \cdot wwwb \cdot A_{HFA} \cdot d_{use} \tag{3-7}$$

wwwb …specific monthly energy need for warm water [Wh/m²d]
A_{HFA} …Heated building floor area [m²]
d_{use} …days usage [-]

Further, **annual final energy demand** is calculated. According to Directive 2009/28/EC, final energy demand refers to physical flows and is a measured data on a national level. Final energy demand takes into account the energy need for space heating, the heat supply systems efficiency including system efficiency and distribution system efficiency and the use of on-site renewable energy sources. Final energy demand for space heating $Q_{H,FED}$ is calculated according to equation 3-8 (Müller, 2015).

$$Q_{H,FED} = \frac{Q_{H,nd} - Q_{H,sol} - Q_{H,ambient,HP} - Q_{H,gain,HW,recover}}{\eta_{H,sys}} \tag{3-8}$$

$Q_{H,FED}$ …Annual final energy demand for space heating [kWh]
$Q_{H,sol}$ …Energy from solar thermal collectors contributing to space heating [kWh]
$Q_{H,ambient,HP}$ …Ambient energy utilized by heat pumps contributing to space heating [kWh]
$Q_{H,gain,HW,recover}$ …Recoverable energy losses of the heating and DHW system [kWh]
$\eta_{H,sys}$ …Overall system efficiency for the heating system [-]

Annual final energy demand for hot water $Q_{HW,FED}$ is calculated according to equation 3-9 (Müller, 2015).

$$Q_{HW,FED} = \frac{Q_{HW,nd} - Q_{HW,sol} - Q_{HW,ambient,HP}}{\eta_{H,sys}} \tag{3-9}$$

$Q_{HW,FED}$ …Annual final energy demand for hot water [kWh]
$Q_{HW,sol}$ …Energy from solar thermal collectors contributing to hot water [kWh]
$Q_{HW,ambient,HP}$ …Ambient energy utilized by heat pumps contributing to hot water [kWh]
$\eta_{HW,sys}$ …Overall system efficiency for the hot water system [-]

Primary energy is defined as *"Energy that has not been subjected to any conversion or transformation process /…/ for a building, it is the energy used to produce the energy delivered to the building. It is calculated from the delivered and exported amounts of energy carriers, using conversion factors"* (ISO 13790, 2008).

Primary energy demand is calculated according to equation 3-10 (ISO 13790, 2008).

$$Q_{PED} = \sum_i (Q_{FED,i} \cdot f_{P,FED,i}) - \sum_i (Q_{exp,i} \cdot f_{P,exp,i}) \qquad 3\text{-}10$$

$\mathrm{Q_{FED,i}}$ …final energy demand by energy carrier i [kWh]

$\mathrm{Q_{exp,i}}$ …exported final energy demand by energy carrier i [kWh]

$\mathrm{f_{P,FED,i}}$, $\mathrm{f_{P,exp,i}}$ …primary energy factor by energy carrier i (final energy demand, exported final energy demand) [-]

CO_2-emissions are calculated according to equation 3-11 (ISO 13790, 2008).

$$m_{CO2} = \sum_i (Q_{FED,i} \cdot f_{CO2,FED,i}) - \sum_i (Q_{exp,i} \cdot f_{CO2,exp,i}) \qquad 3\text{-}11$$

$\mathrm{m_{CO2}}$ …CO2-emissions [t]

$\mathrm{f_{CO2,FED,i}}$, $\mathrm{f_{CO2,exp,i}}$ …CO2-emission factor by energy carrier i (final energy demand, exported final energy demand) [-]

Fig. 9 shows building boundary and definitions which are well known in the building physics and civil engineering community (Müller, 2015). It includes also delivered energy and energy use.

According to the ISO 13790:2008 (ISO 13790, 2008), **delivered energy** is *"Energy, expressed per energy carrier, supplied to technical building systems through the system boundary, to satisfy the uses taken into account (heating, cooling, ventilation, domestic hot water, lighting, appliances etc.) or to produce electricity*". **Energy use** can be described as delivered energy including local renewable energy carriers or on-site renewable energy carriers.

Calculated final energy demand is not exactly the same as real energy consumption due to the user-behaviours aspect. The user-behaviour aspect is not a focus of my thesis, however it is addressed in the model Invert-EE/Lab (Müller, 2015). Invert-EE/Lab derives a correction factor that describes user behaviour aspect. This correction factor has an impact on the energy need for space heating. The correction factor adjusts the surface coefficient of heat transfer by taking into account these parameters, heating degree days (HDD), running energy costs and household income.

This correction factor is calculated according to equation 3-12 (Müller, 2015).

$$f_{use} = 0.5 + \frac{2}{3 + 0.6 \cdot h_{corr}} \qquad 3\text{-}12$$

$\mathrm{h_{corr}}$ … corrected surface coefficient of heat transfer [W/(m²K)]

h_{corr} is a surface coefficient of heat transfer used in the user model, corrected by running energy costs, household income and heating degree days. It is calculated according to equation 3-13 (Müller, 2015).

$$h_{corr} = (\frac{c_{run,hs}}{c_{run,ref}})^{\alpha_{c,run}} \cdot (\frac{Y_{household}}{Y_{household,ref}})^{\alpha_{Income}} \cdot (\frac{HDD_{building\ side}}{3240})^{\alpha_{hdd}} \qquad 3\text{-}13$$

$\mathrm{HDD_{building\ side}}$ … Heating degree days at the specific building side conditions [Kd]

3240 …Average long term heating degree days in Germany 1980 – 2004

$c_{run,ref}$ …Reference running energy costs [€/MWh]

$c_{run,hs}$ …Marginal (running) heating costs based on the actual efficiency of the heating system and the price of the energy carrier [€/MWh]

$Y_{household,(ref)}$ ...(Reference-)Household income
$\alpha_{c,run}, \alpha_{hdd}, \alpha_{Income}$ ...1 for Households

3.3. Renovation packages

In order to calculate the economic attractiveness of different renovation packages and different types of buildings, the following steps were carried out.

Firstly, renovation packages, resulting in various levels of improvement in the building's energy performance are defined. A renovation package covers renovation of floor, roof, wall and window.

The energy performance of buildings can be described using different indicators. The European Member states describe the energy performance of buildings (renovated and new) using the following approaches:

- The prescriptive-based approach means that requirements for each building component are expressed in the U-values, and for different equipment for heating, ventilation, and lighting are set.
- The performance-based approach means that the building code requirements are set for the whole building. This requirement was firstly introduced in the Energy Performance Building Directive EPBD (Council Directive 2002/91/EC, 2002), asking the member States, to introduce minimum requirements on the energy performance of new buildings and large existing buildings. According to the updated EPBD-recast (Council Directive 2010/31/EU, 2010), EU countries have calculated the cost-optimal minimum energy performance requirements for new and renovated buildings. Thermal requirements are defined, using different indicators and approaches, in the national legislation. Article 5 of EPBD-recast (Council Directive 2010/31/EU, 2010), describes methodology framework on how to calculate and to set cost optimal levels of minimum energy performance requirements, for new and existing building. The methodology specifies how to define and select energy efficiency measures for reference buildings, based on their energy performance and costs. When it comes to energy performance, the level of (net) primary energy demand should be implemented. The calculation of primary energy demand, is carried out, using national primary energy factors associated with the energy carrier of delivered energy.

To calculate energy performance of the buildings after renovation and associated cost, I use a prescriptive-based approach. This means that I define the U-values of building elements before renovation and after renovation. With this data, I can calculate energy need for space heating before renovation and after renovation using monthly energy balance approach.

I define three different renovation packages; light, medium and deep. Each package covers renovation of floor, roof, wall and window. The deep renovation package additionally implements the installation of the mechanical ventilation. The renovation packages can be descripted as follows:

- "Medium" renovation package refers to the national building codes. The solutions are selected which achieve the U-values defined in the countries national legislation.

- “Light” renovation package means that in reality not all buildings fulfil the criteria set in the building legislation due to lack of compliance. The U-values of building elements are increased by 30% compared to the U-values defined in the “medium” renovation package.
- “Deep” renovation package is an ambitious renovation leading to a high energy performance. It is assumed that the U-values are reduced by 30% compared to the “Medium” renovation package. Additionally, mechanical ventilation is installed.

The U-values after renovation of the building components for each building type is calculated using a database of the renovation measures provided by the IEE project ENTRANZE (Fernandez Boneta, 2013). The database provides data on the single renovation solution for windows, roofs, floors, walls and ventilation for several European countries. The solutions are characterised by technical parameters (thickness of the material and thermal conductivity) and economic parameters (initial investment costs including material costs, labour costs, business profit and general expenditure). The U-value is defined based on the thickness of the material and thermal conductivity. To define the U-values of the solutions, I use an online calculation tool (u-wert.net, 2017). Input parameters and calculated U-values for all solutions for wall, windows and roof are given in Appendix C "Parameters to calculate U-values”.

The building stock in a particular country is broken down into building classes defining the building type, vintage, geometry and thermal conductivity of the building elements. For each building class, the U-values of building elements after implementing all renovation solutions given in the abovementioned database are calculated:

$$\frac{1}{U_{i,ren}} = \frac{1}{U_{i,before\ renovation}} + \frac{1}{U_{i,solution}} \qquad 3\text{-}14$$

$U_{i,befor\ renovation}$ ...U-value of a building component i before renovation [W/m^{2}K]
$U_{i,solution}$ ..U-value of a renovation solution [W/m^{2}K]

The overall U-value of a window is calculated as follows (Hens, 2012):

$$U_{window} = \frac{A_{glass} * U_{o,glass} + A_{frame} * U_{eq,frame} + \psi_{spacer} L_{spacer}}{A_{window}} \qquad 3\text{-}15$$

U_{window} ...Overall value of the window [W/m^{2}K]
$U_{o,glass}$ ...U-value of glazing [W/m^{2}K]
$U_{eq,frame}$ ...U-value of frame [W/m^{2}K]
ψ_{spacer} ...Linear heat transfer coefficient [W/mK]
A_{window} ... Floor area of the window [m²]
L_{spacer} ...Length of inside edge of frame profile [m]

The U-value of the building elements are calculated for each building classes and for each renovation solutions. Solution measures for each building component are selected which achieve the U-values given in the national building code. Subsequently, I defined renovation packages including the renovation of all building components. The mean value achieved after renovation is calculated as follows:

$$U_{mean} = \frac{\sum_i U_{i,ren} * A_i}{\sum_i A_i} \tag{3-16}$$

$U_{i,ren}$ …U-value of a building element i after implementing a renovation measure [W/m²K]
A_i …Surface of building element i [m²]

The initial investment costs of a renovation package k, $ic_{k,j}$ is calculated for each investigated building taking its gross floor area and area of a particular building element into account. Initial investment costs per building floor area of renovation package *k* in building type *j* are calculated according to equation 3-17.

$$ic_{k,j} = \frac{\sum_i ic_{i,ren} * A_i}{A_{GFA}} \tag{3-17}$$

$ic_{k,j}$ …Initial investment costs per building floor area of renovation package *k* in building type *j* [€/m²]
$ic_{i,ren}$ …specific costs of renovation measure of building element i [€/m²]
A_{GFA} …Building gross floor area [m²]
A_i … Surface of building element i [m²]

In the next step, levelized costs for renovation packages k and reference buildings j is calculated.

$$c_{k,j} = ic_{k,j} \cdot \alpha + O\&M + q_{k,j} \cdot \bar{p}_j \tag{3-18}$$

$c_{k,j}$… Levelized costs for renovation packages k and reference buildings j [€/m²]
α … Annuity factor [-]
$\bar{p}_j$ …Average energy price during the considered time period [€/kWh]
$q_{k,j}$ Final energy demand for space heating and hot water after implementation of renovation package k and building type j [kWh/m²/year]
$O\&M$ …Operation and maintenance [€/m²/yr]

Then, I calculate additional costs $\Delta c_{k,j}$ for heating energy service in building segment class j with renovation package k compared to base renovation package. Base renovation package is a maintenance renovation which is a renovation which is made for the aesthetic reasons.

$$\Delta c_{k,j} = c_{k,j} - c_{base,j} \tag{3-19}$$

$ic_{base,j}$ Initial investment costs per building floor area of renovation option *base* in building type *j* (€/m²)

3.4.Required data

Final energy demand is calculated for every reference building which is described by a wide range of indicators. Two models, applied in this work; the model Invert-EE/Lab and cost curves model use the same disaggregation of the building stock. The aggregated final energy demand in one country or region is the sum of the disaggregated data of the reference buildings. All required data was collected from different data sources and are presented in chapters 4, 5, 6 and 7.

Data on the building stock is arranged in a hierarchical structure (see Fig. 10).

Building classes consist of different types of buildings and associated parameters. The following data are selected:

- Building categories: single-family houses, apartment buildings, offices, heath buildings, education buildings and commercial buildings.
- Building vintage.
- U-values of building elements.
- Building geometry.
- Share of windows of total façade area.
- Glazing type.
- User profiles.
- Load profiles.
- Ventilation properties.
- Indoor temperature (set-point temperature).

This data is needed to calculate energy need for space heating, cooling and hot water. In model Invert-EE/Lab, energy need for space heating is calculated based on building classes and these parameters.

Reference buildings are defined by the aforementioned building class parameters and additionally heat supply technologies are described. Final energy demand for energy services and cost of investments are calculated for every defined reference building.

Each reference building is located in a particular country. Country specific parameters are defines, such as climate date (monthly outdoor temperature; solar irradiation), discount rates, fuel prices and primary energy factors.

Data on energy efficiency solutions are defined: U-values, thickness of the material, thermal conductivity, initial investment costs (including material costs, labour costs, and business profit and general expenditure costs). Data on active solutions is as follows: coefficient of performance, system efficiency and initial investment costs.

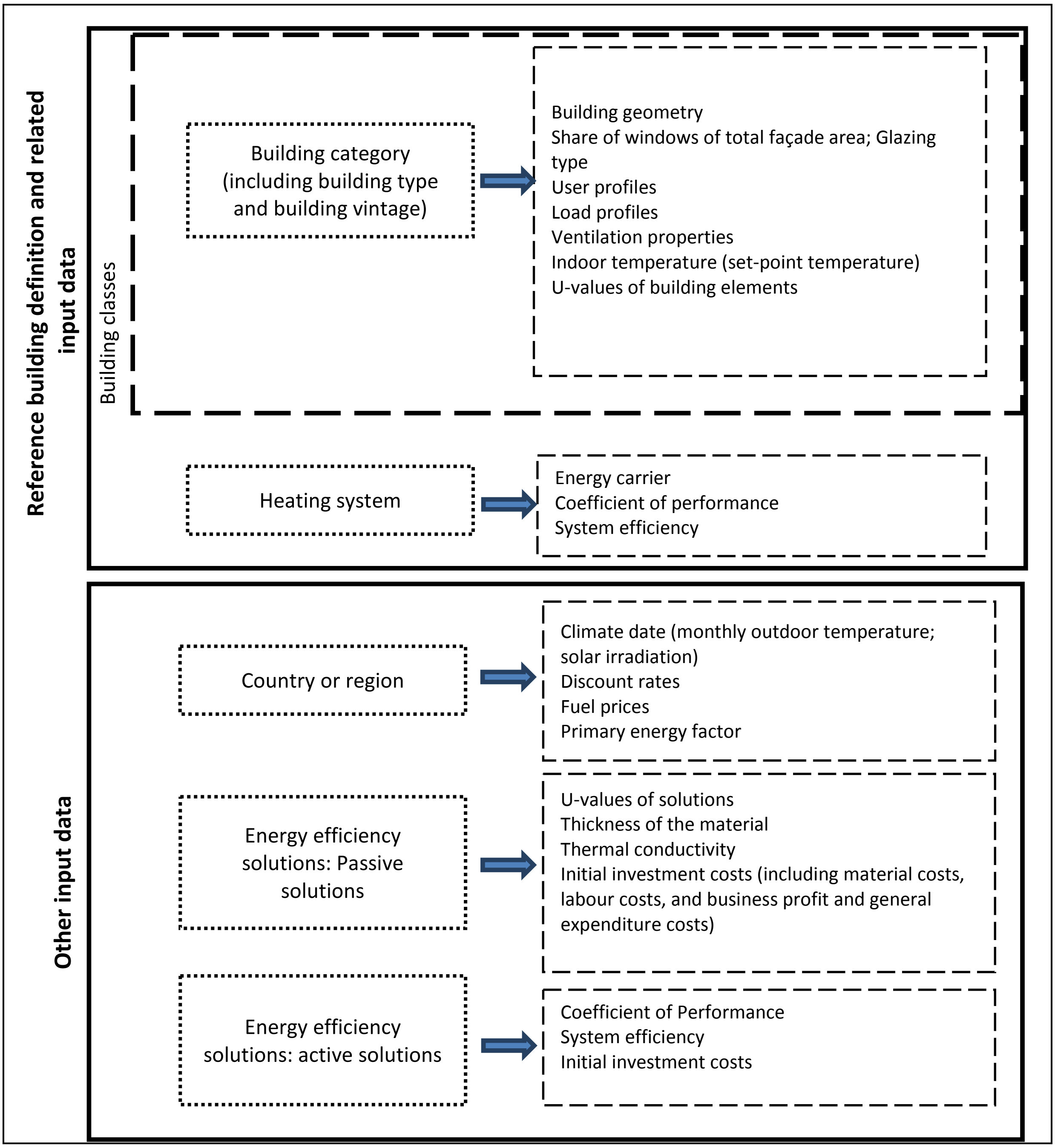


Fig. 10 Input data used to calculate energy demand for space heating and cost-effectiveness of investments

4. Case Study I: Cost curves for the selected countries´ building stock

This chapter aims to calculate energy saving potential for space heating by 2030 in the total building sector in the following countries; France, Italy, Norway, Romania, Poland and Spain. Cost curves showing the investor perspective are provided. The technical measures of retrofitting including insulation of envelope are investigated. These are defined for each country separately based on the national building requirements. Two different scenarios with different sets of economic conditions are calculated, a "Business-as-usual" scenario and "Towards higher energy savings" scenario. These sets of economic condition have an impact on the cost-effectiveness of investments in renovation packages. They cover subsidies for the deep renovation, CO_2 taxes for fossil energy fuels and cost reduction of the renovation packages.

To derive the energy saving cost curves, the following method steps are carried out:

(I) Building stock, taking into account different categories of buildings including residential and service, construction period and heating system, is described.
(II) Three renovation packages; light, medium and deep, related to the building envelope are defined.
(III) Final energy demand for space heating for each renovation package using the building simulation tool Invert-EE/Lab is calculated.
(IV) Cost-effectiveness of investments for building types and renovation packages is calculated.
(V) The lowest-cost renovation package for each building type is selected.
(VI) Energy saving cost curves are derived.

4.1.Input data

4.1.1. Building stock

Building stock in each country is disaggregated, defining the building categories, construction periods and energy fuel for space heating. The segmentation combining these parameters enables me to define the reference buildings. The sum of the reference buildings represents the total building stock in a particular country. The building stock data was collected in IEE project called ENTRANZE (ENTRANZE, 2016) and IEE project ZEBRA2020 (Zebra2020, 2016) in cooperation with other project partners. Data on the building stock including floor area by building categories, building construction periods and installed heating systems were collected. The main used data sources are as follows: national statistics, Eurostat statistics, statistics provided by the European Commission "Building stock observatory", the IEE projects TABULA/EPISCOPE (EPISCOPE, 2016) and the ODYSSEE database (ODYSSEE, 2017).

Fig. 11, Fig. 12 and Fig. 13 show disaggregated building stock data for each investigated country. It should be mentioned that data was collected for each country separately and thus slightly differs regarding the building categories and vintages. In order to compare the investigated countries, building categories, vintages and energy fuels for space heating were homogenized. I defined the building categories into: residential buildings and service buildings. Whilst the residential sector is divided into two different building types (singe family houses and apartment buildings), the service sector is divided into the following building categories: offices (covering private offices and public offices), heath buildings (covering hospitals), education buildings (covering schools and universities) and commercial buildings (covering hotels, restaurants, wholesale and retail buildings). Building vintages were divided as follows: before 1950, 1951 – 1990, 1991 – 2000 and buildings built after 2000. The following energy fuel types were taken into consideration, biomass, coal, district heat, electricity, gas, oil and others (covering mainly houses which are not supplied by any energy fuel). In this study, I assumed that all buildings which use oil, gas, biomass, use either a collective heating system (apartment buildings and service building) or individual central heating systems (single family houses). This is a simplified assumption for this calculation. It should be mentioned, that in reality there are also buildings which use room heating (mainly in the form of wood burning stoves). In Romania, for example, room heating is largely used in rural areas where access to gas or district heating is not available (Atanasiu et al., 2012).

Fig. 11 shows the total building gross floor area by vintages in 2012 in France, Italy, Norway, Poland, Romania and Spain. The total building gross floor area was 3,511 Mio.m², 3,832 Mio.m², 371 Mio.m², 1,501 Mio.m², 673 Mio.m² and 2,615 Mio.m² in France, Italy, Norway, Poland, Romania and Spain, respectively. Looking at the vintage of the buildings, it can be seen that the oldest building stock is in France followed by Norway and Italy. The share of their building floor area built before 1950 on the total building stock floor area is 36%, 34% and 30% respectively.

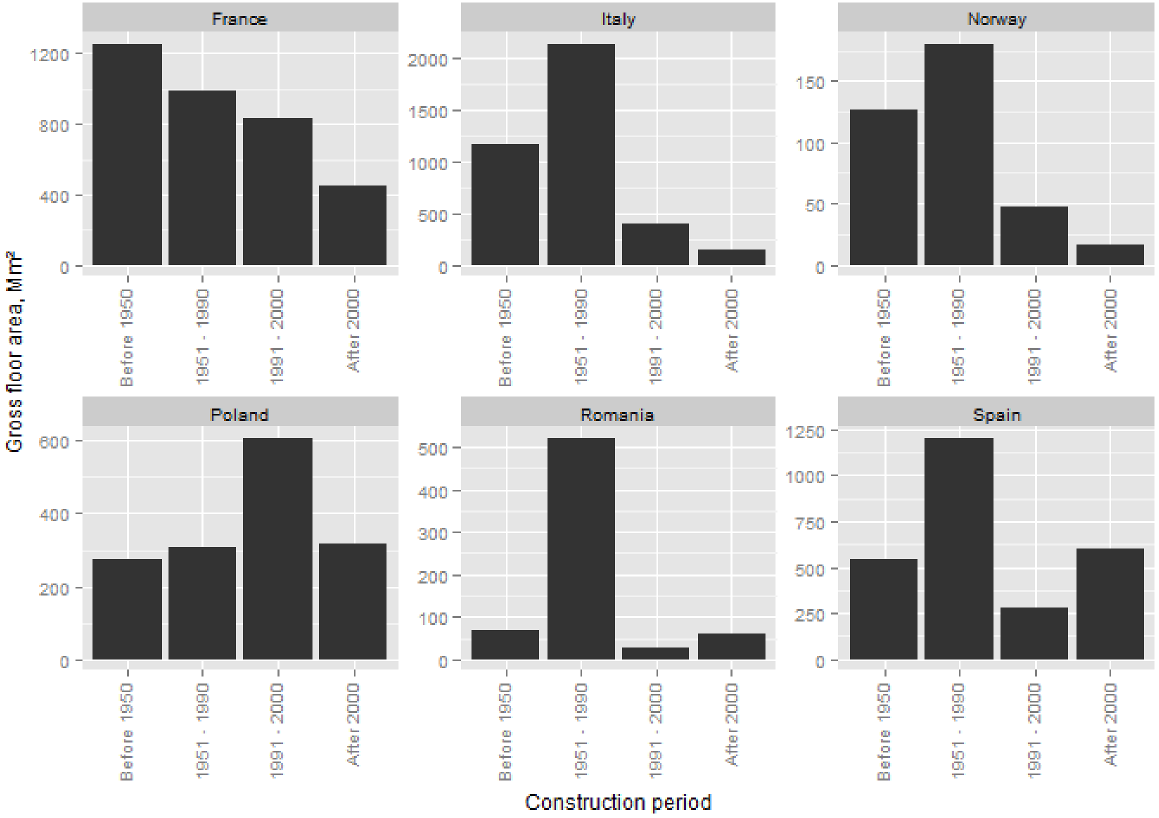


Fig. 11 Gross floor area of the total building sector by construction periods (aggregated) in France, Italy, Norway, Poland, Romania and Spain in 2012

Fig. 12 shows gross floor area by building categories in France, Italy, Norway, Poland, Romania and Spain. Residential buildings make up the highest share of the total building floor area in all investigated countries. The share of the residential buildings on the total building floor area is as follows, 74%, 82%, 78%, 72%, 89%, 79% in France, Italy, Norway, Poland, Romania and Spain, respectively. Apart from Italy and Spain, where the single family houses make up only 22% and 24% on the total building floor area, in other investigated countries, France (51%), Norway (67%), Poland (39%) and Romania (58%), single family houses dominate.

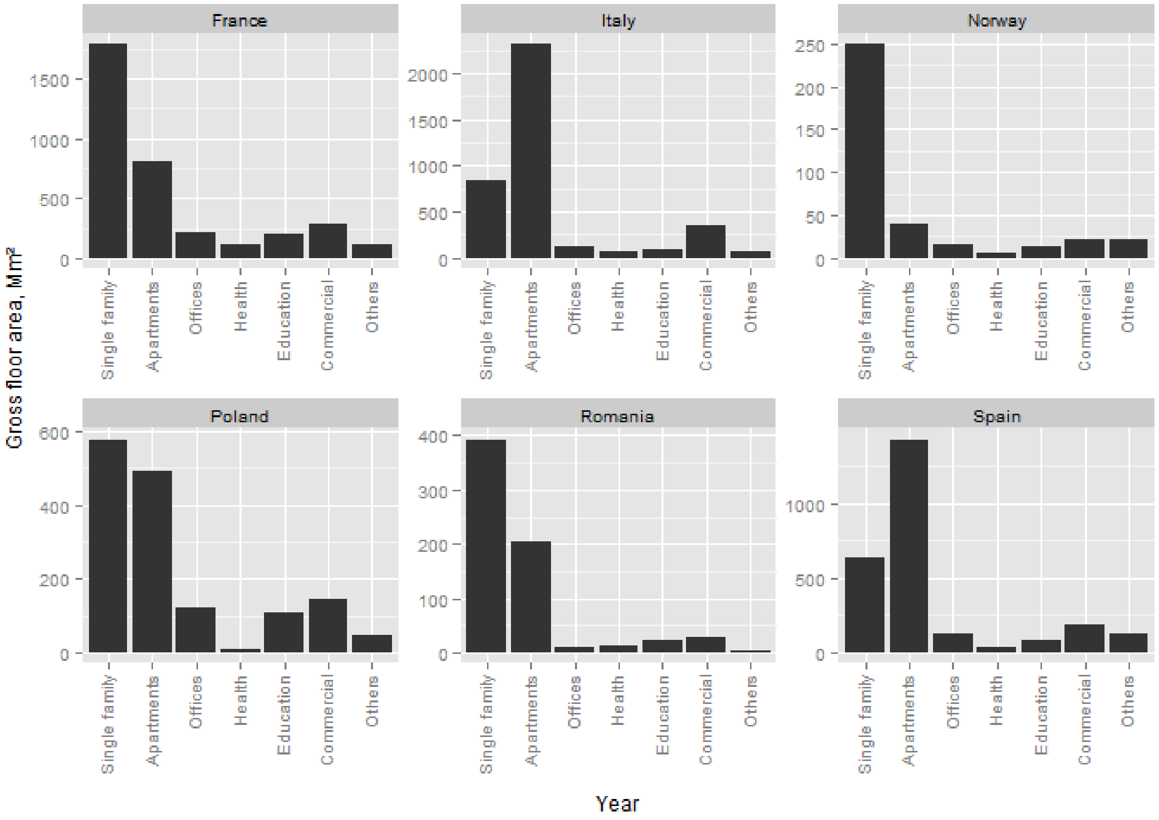


Fig. 12 Gross floor area of the total building sector by building categories (aggregated) in France, Italy, Norway, Poland, Romania and Spain in 2012

Fig. 13 shows gross floor area by energy fuel in France, Italy, Norway, Poland, Romania and Spain. Natural gas is the main source for space heating in France, Italy and Spain. The share of the building floor area supplied by gas is 61% in Italy, 43% in France and 30% in Spain. In these countries, natural gas heating is mainly used in apartment buildings. In Poland, Romania and Norway, natural gas makes up 9%, 25% and 1% of the total gross floor area. District heating is one of the main energy suppliers in Poland and Romania. In Poland, 32% of all buildings are supplied by district heating. After coal which is used in 38% of all building floor area, district heating is the second largest energy supplier. In Romania, 54% of all buildings are heated using biomass. In Norway, 77% of all buildings are heated with electricity.

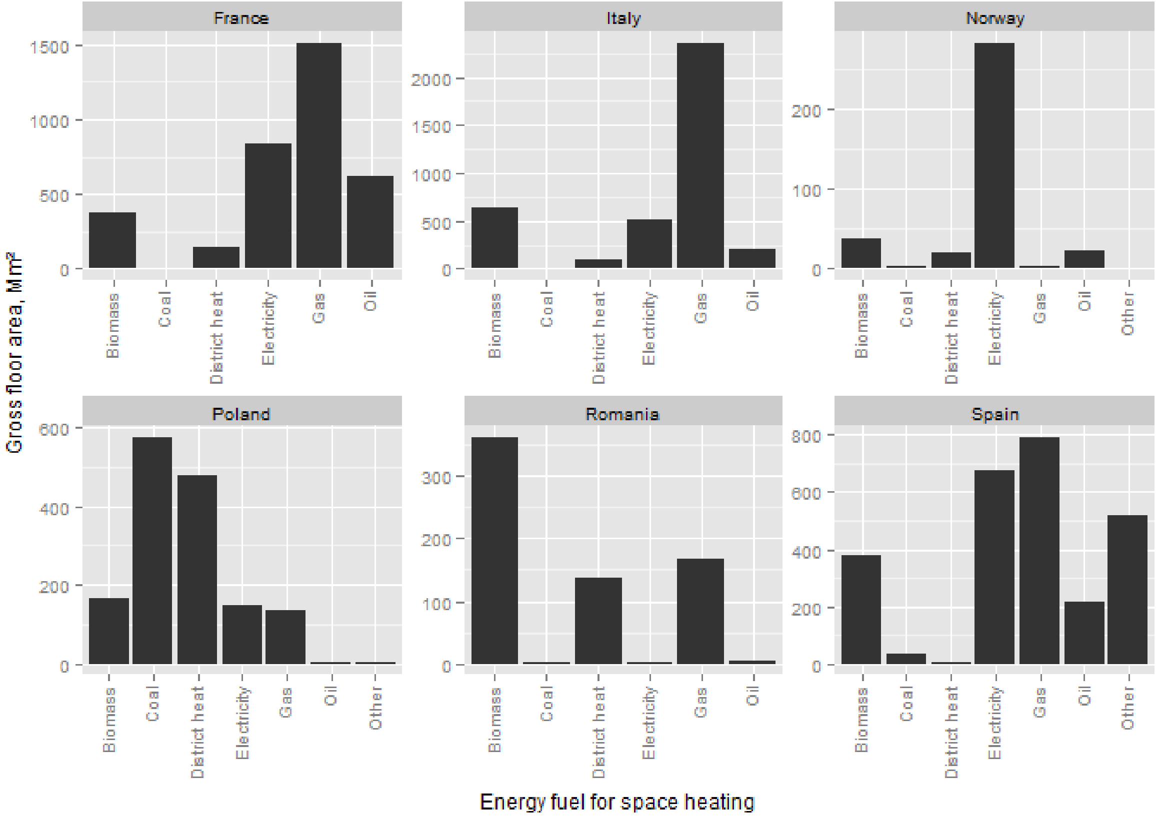


Fig. 13 Gross floor area of the total building sector by energy fuel for space heating (aggregated) in France, Italy, Norway, Poland, Romania and Spain in 2012

4.1.2. Renovation packages

For the Member States, thermal requirements for building renovation are defined in national legislation using different indicators and approaches.

In **France**, there are two different requirements for building renovation, requirements for buildings with the floor area more than 1000 m², and requirements for building with the floor area less than 1000 m². Residential buildings larger than 1000 m² and built after 1948 have to undertake a major renovation in order to reach energy consumption between 80 and 165 kWh/m²/yr (including space heating, cooling, lighting, domestic hot water and equipment). The range depends on the climate zone and the heating fuel. Buildings with the floor area smaller than 1000 m², have to undertake a minor renovation, defined by using the element-by-element thermal regulations concerning insulation, heating, hot-water production, cooling and ventilation equipment. The specific requirements for U-values for the building elements after renovation are defined in RT2012 and are given in Table 2 (Kontonasiou, 2016), (Atanasiu et al., 2014).

In **Italy**, the newest legislative ministerial decree, 26/06/2015, sets the limits of primary energy for heating and the limits of transmittance from different building elements, for building renovation across different Italian climate zones. The requirements must be implemented in buildings with useful surface area bigger than 1000 m² with the exception of cultural heritage and landscape, buildings for industrial, agricultural and artisanal uses. Thermal requirements for existing buildings, dependant on climate zone, are set for walls, roofs, floors, transparent closures and glasses. Table 2 shows the U-values defined in the newest legislation and are weighted according to the number of buildings for each climate zone (Kontonasiou, 2016) (Atanasiu et al., 2014).

In **Norway**, the Technical building regulation TEK10 includes two options on how to fulfil energy performance requirements. They are set for both new building and building renovation. The first option, sets the limits for net energy demand for 13 different building categories including space heating, cooling, DHW and all electricity uses. The second option addresses the components of the building envelope and technical installation. The minimum requirements on U-values are set in TEK10 and are given in Table 2 (Kontonasiou, 2016).

In **Poland**, energy requirements for buildings are set in the Minister of Transport, Construction and Maritime Economy's Ordinance of 2013. This document provides the U-values for the building components and the requirements of non-renewable primary energy demand. They are set for both new building and building renovation (Kontonasiou, 2016).

In **Romania**, thermal requirements for new buildings are set in Regulation C107/2010: there is no mention to requirements for building renovation. The building requirements (for new buildings) refer to minimum thermal resistance R-values and the maximum overall thermal coefficients G-values and U-values for building elements. There is a national rehabilitation program (OUG 18/2009) which is aimed at renovating blocks-of-flats. The buildings being renovated in the frame of this program, have to decrease the annual heating energy consumption by 100 kWh/m². Table 2 gives the U-values of building elements as required in the legislation for new buildings (Kontonasiou, 2016) (Atanasiu et al., 2014).

In **Spain**, the main energy performance requirements for buildings, both new and buildings being renovated are regulated by the Spanish Technical Building Code – CTE (RD 314/2006). For the buildings renovation, there are the following requirements: minimum energy requirements for useful energy demand, performance requirement for technical systems and requirements for minimum solar contributions of domestic hot water (if more efficient than existing system). These requirements must be undertaken if more than 25% of the building envelope is renovated. The requirements differ between different climate zones in Spain. Table 2 gives the average U-value requirements for the building regulation (Kontonasiou, 2016) (Atanasiu et al., 2014).

Table 2 shows U-values of the building elements which are taken from the national building codes in all the investigated countries. The prescriptive-based approach is used in each country. However, as explained above, many countries also define minimum energy performance requirements for building renovation. While by using a prescriptive-based approach, countries can be easy compared with each other, a performance-based approach provides different ways on how to define the minimum energy performance requirements. France and Italy use energy performance requirements expressed in primary energy demand, while Norway and Spain, in useful energy demand. All investigated countries define a wide range of requirements which vary dependent on different climate zones, building types and energy fuels (Table 3).

Table 2 Required U-values of building elements, in the recent national building codes

Country	Floor	Roof	Wall	Window
France	0.27	0.27	0.36	2.1

Italy	0.32	0.27	0.31	1.96
Norway	0.18	0.18	0.22	1.6
Poland	0.2	0.3	0.25	1.3
Romania	0.22	0.22	0.56	1.3
Spain	0.7	0.7	0.7	2.1

Table 3 Minimum energy performance requirements for building renovation (Kontonasiou, 2016)

Country	**Addressed building type**	**Energy performance indicator**	**Value**
France	For major renovation of buildings more than 1000 m² built after 1948	Primary energy demand (kWh/m²/y) for space heating, domestic hot water, ventilation, lighting and air cooling. The range depends on the climate zone and heating fuel	80-165 27-56* (for space heating)
Italy	For major renovation of buildings more than 1000 m²	Primary energy demand (kWh/m²/y) for space heating. The range depends on the climate zone (6 are defined in the legislation) and heating fuel	34-116
Norway	For building renovation (all buildings included)	Overall net energy demand (total useful energy) (kWh/m²/y) including space heating, cooling, DHW and all electricity uses (One climate zone is defined)	125-140 (SFH) 43-48* (for space heating) 115 (MFH) 39* (for space heating)
Spain	For more than 25% of the building envelope	Useful energy demand for space heating ((kWh/m²/y). The range depends on climate zones	15-40
Poland	There are no requirements in terms of minimum energy performance for building renovation		
Romania	There are no requirements in terms of minimum energy performance for building renovation		

*This value was calculated assuming that the energy demand for space heating makes up 34% of the total energy demand (including space heating, cooling, HW, all electricity uses)

Next, I define renovation packages for all countries. The definition is based on the prescriptive-based national energy efficiency requirements expressed in the U-values for building elements (see Table 2). Three different renovation packages; light, medium and deep are defined (see 3.3 explaining the methodology on how these three renovation packages are defined).

Fig. 14 shows the distribution of the specific energy need for space heating in the total building stock for non-renovated buildings and buildings after renovation, by using light, medium and deep renovation packages. Specific energy need for space heating after renovation (light, medium and deep) is calculated using the same methodology, yet the U-values of the building elements are replaced with the U-values of those which have to be achieved, in order to be in line with the building code, as in the case of the “medium” renovation package. Specific energy needs are shown as a box-plot diagram. The median (middle quartile) marks the mid-point of the data and is shown by the line that divides the box into two parts. Each part presents 25% of the total building stock. The diamond indicates the mean value of the total building stock. Specific energy need for space heating per building floor area, is calculated using monthly energy balance approach.

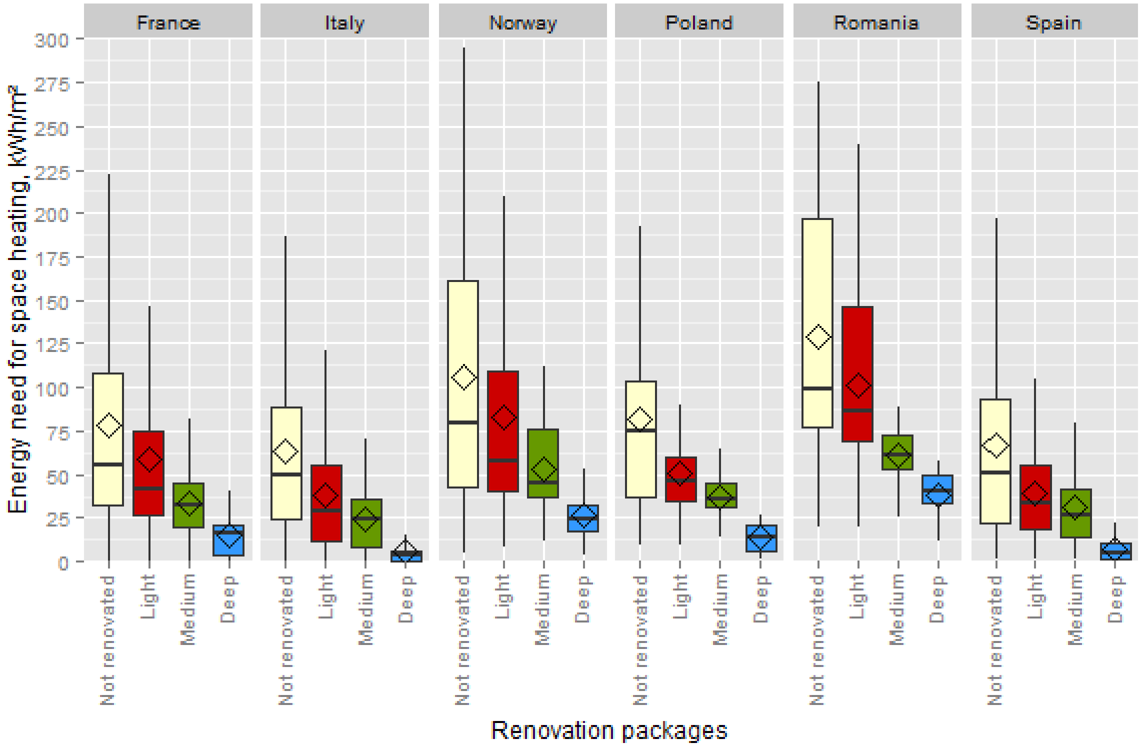


Fig. 14 Distribution of the calculated specific energy need for space heating in the total building stock of France, Italy, Norway, Poland, Romania and Spain, for non-renovated buildings, and after the three renovation packages (light, medium and deep)

As discussed before, in many countries, the national requirements are not restricted by the U-values in the national building codes. In many countries´ national building codes (e.g. France, Italy, Norway, Spain), the requirements are also described using a performance-based approach. In the next step, the calculated energy needs for space heating using the U-values from the national building codes (Table 2) are compared with the minimum energy performance requirements given in the national building code (Table 3).

Energy performance requirements for building renovation in France and Italy are given in primary energy demand, while in Norway and Spain they are given in useful energy demand (Table 3). Primary energy demand is calculated using national primary energy indicators. In France’s and Norway’s building codes, specific yearly energy demand covering space heating, cooling, DHW, lighting and ventilation is given. So, before comparing the results, I have to split the energy demand, to identify the energy demand for space heating. According to (Ürge-Vorsatz et al., 2015), the share of the energy services on the total energy demand is as follows, space heating (32%), domestic hot water (24%), space cooling (2%) and all other electricity uses (58%). Using this composition, the requested primary energy demand for space heating in France and Norway is recalculated. Primary energy demand for space heating is 27.2 – 56.1 kWh/m²/y in France and 42.5 – 47.6 kWh/m²/y in Norway. Fig. 15 shows specific energy demand for space heating calculated for reference residential buildings (Min (Calc.), Max (Calc.), Average (Calc.)) and requirements taken from the national building codes (Min (Code), Max (Code)). Calculated energy demand for space heating takes into account the requirements for major renovation expressed in U-values (see Table 2). In France and Italy, the energy demand for space heating refers to primary energy demand, while in Norway and Spain it refers to useful energy demand. Calculated energy demand, is shown for the reference target buildings applying "medium" renovation package which correspond to major renovation according to the national building code. In almost all investigated countries, the calculated average energy demand for space heating is lower than the maximal energy performance requirements. Only in France, is the average calculated energy demand for space heating 3 kWh/m²/y higher than the requested maximal energy performance requirements.

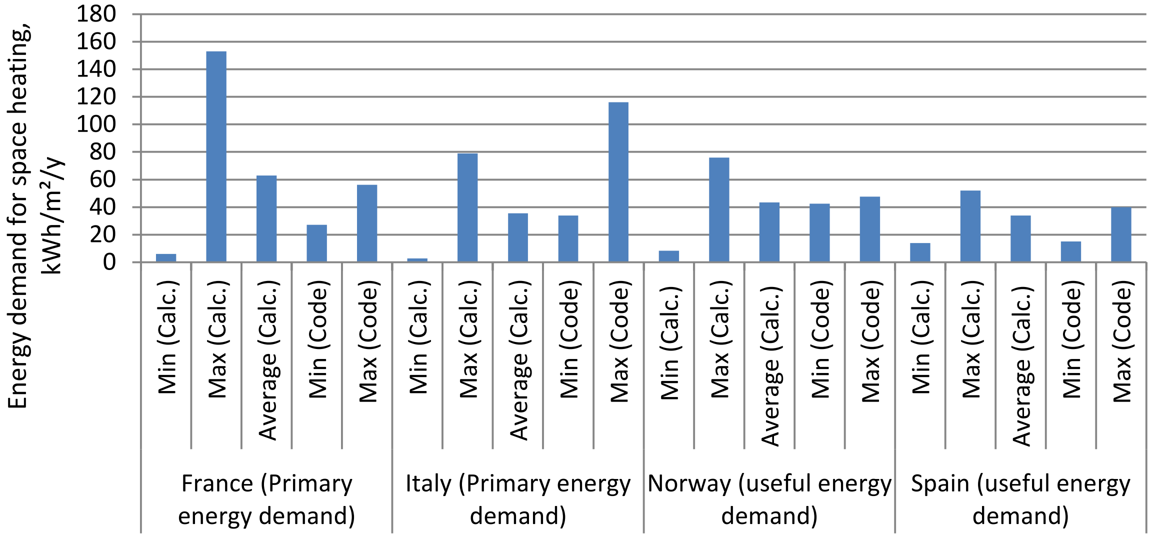


Fig. 15 Calculated specific energy demand for space heating for reference buildings after "medium" renovation and specific energy demand requirements as given in the national building code in France, Italy, Norway and Spain

Fig. 16 shows the mean U-values for three different levels of the residential building envelope renovation and associated average initial investments. Mean U-value of a residential building in a particular country is a result of the building element´s U-value before renovation and the U-value of the selected renovation measure for a building element. Moreover, the surface of the building elements is also taken into account and has an influence on the calculated mean U-value after renovation. The associated average initial investment cost is the result of the selected renovation measure and their investment costs. Moreover, the initial investment costs of the renovation measures vary between the European countries due to the differences in material costs, labour costs and business profit as well as professional and other fees.

Fig. 16 shows that the U-values vary from one country to another. This is due to the differences in the building code requirements for the U-values of the building elements in the European countries. The following parameters also have an influence on the calculated mean U-value of the residential buildings located in the considered countries: U-values of the building elements before renovation, geometry of the buildings, and the share of the single family and apartment buildings in the residential building stock. Fig. 17, Fig. 18, Fig. 19 show average initial investments in three renovation levels for single family houses, apartment houses and service buildings. The average mean values include the initial investments per buildings built in different building periods. It can be seen that the specific investments in the renovation of building envelope per single family houses are higher compared to the apartment buildings. This is due to the geometry of the building.

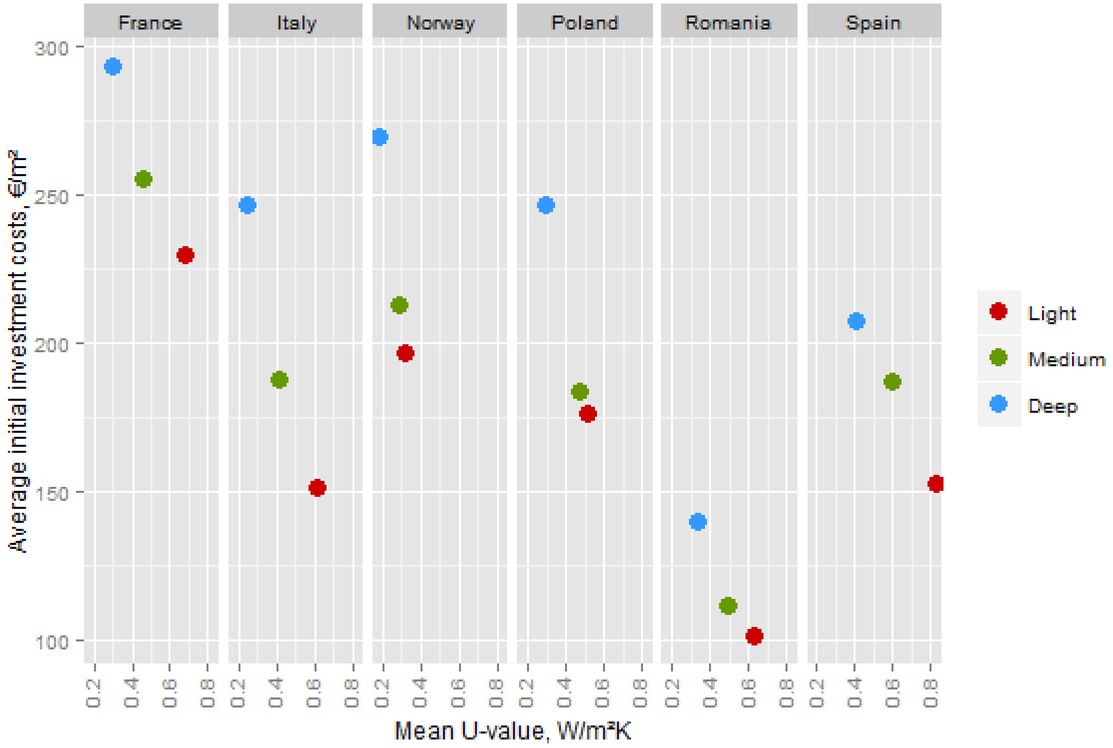


Fig. 16 Mean U-values of the residential buildings for three different levels of building envelope renovation and the associated average initial investments per building gross floor area in France, Italy, Norway, Poland, Romania and Spain

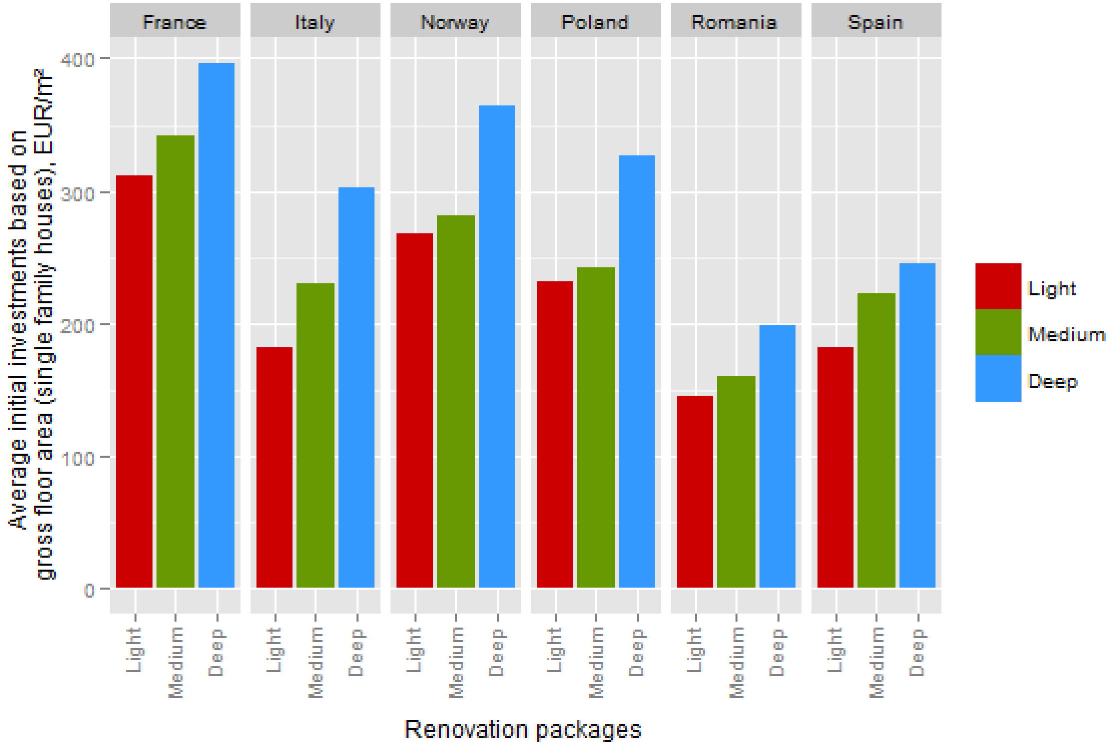


Fig. 17 Average initial investments for single family houses for three different renovation packages; light, medium and deep in the following countries; France, Italy, Norway, Poland, Romania and Spain

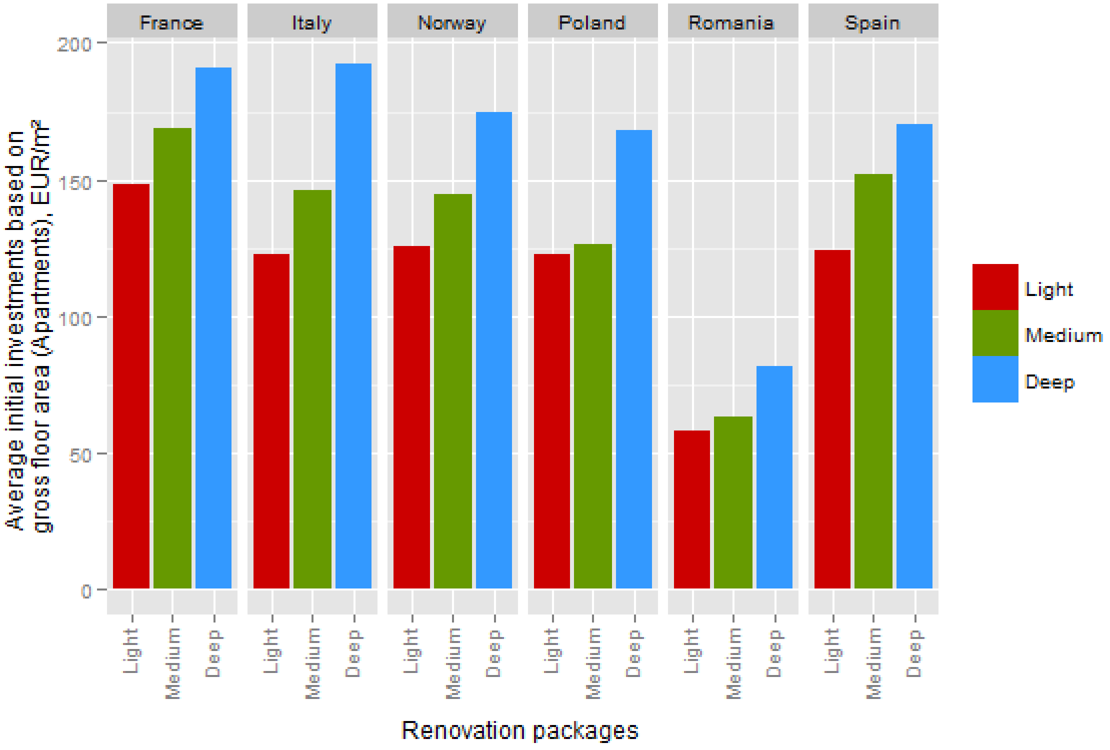


Fig. 18 Average initial investments for apartments for three different renovation packages; light, medium and deep in the following countries; France, Italy, Norway, Poland, Romania and Spain

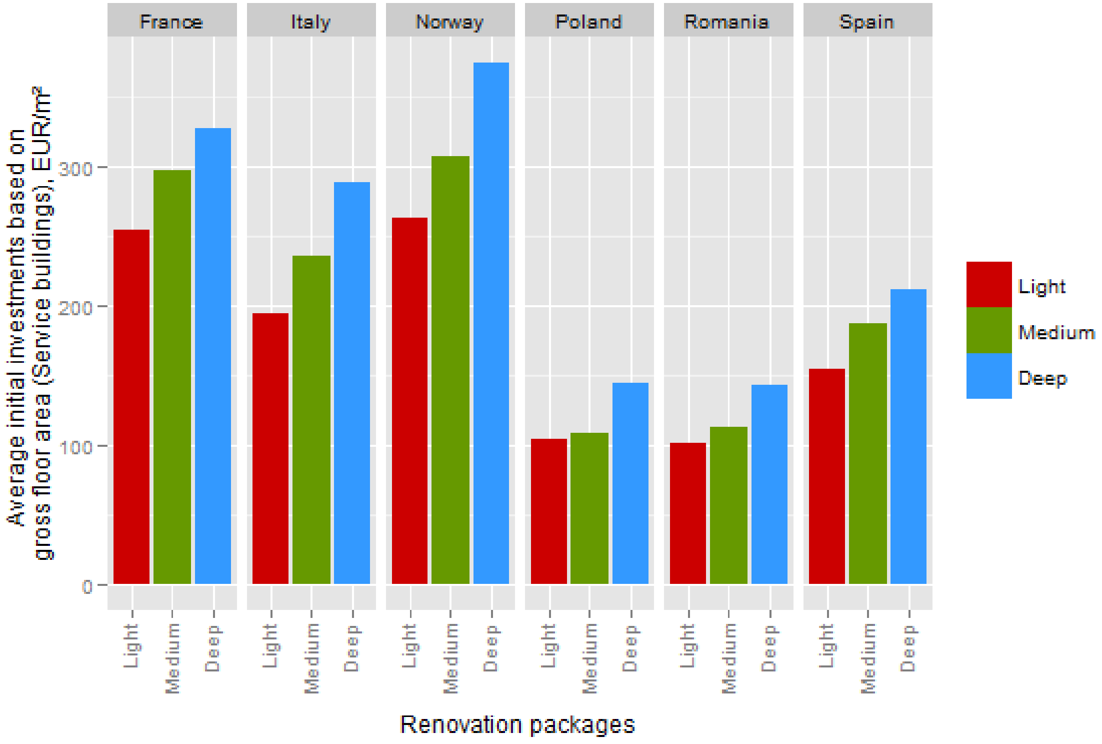


Fig. 19 Average initial investments for service buildings for three different renovation packages; light, medium and deep in the following countries; France, Italy, Norway, Poland, Romania and Spain

4.1.3. Renovation rate

Future renovation rate is calculated using Weibull-distribution. For each investigated county, four different building vintage, before 1950, 1951-1990, 1991-2000 and after 2000 are defined. For each building vintage, the future renovation rate is calculated. Fig. 20 shows cumulated renovation rates for different building vintages from 2012 to 2030. Cumulated renovation rate is 52%, 43%, 19%, and 12% for building built in the following vintages, before 1950, 1951-1990, 1991-2000 and after 2000, respectively. Cumulated renovation rate is used to calculate total renovated building floor area and total final energy demand from 2012 to 2030 in France, Italy, Norway, Poland, Romania and Spain.

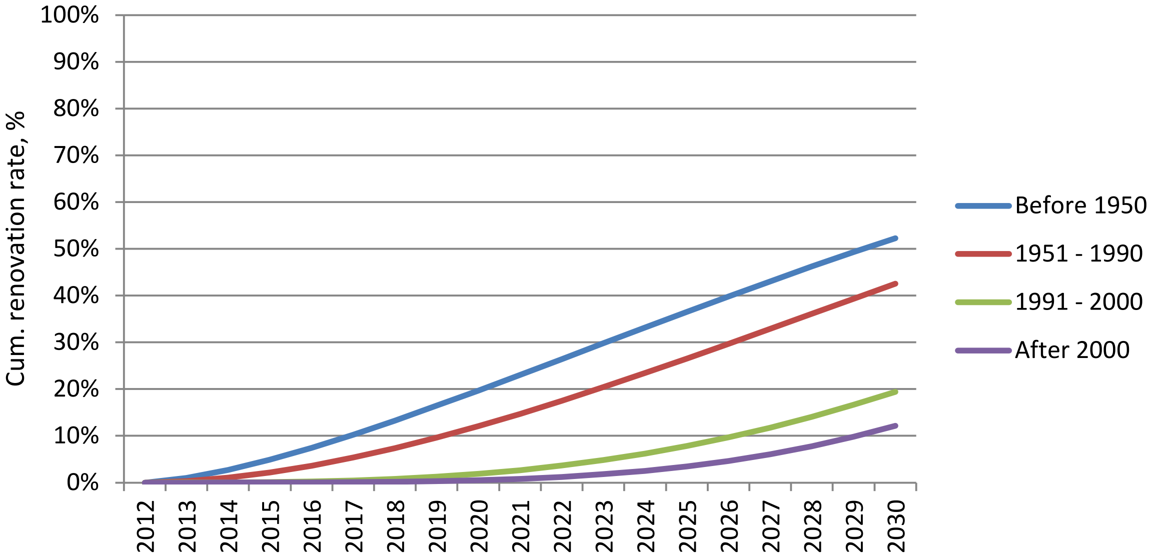


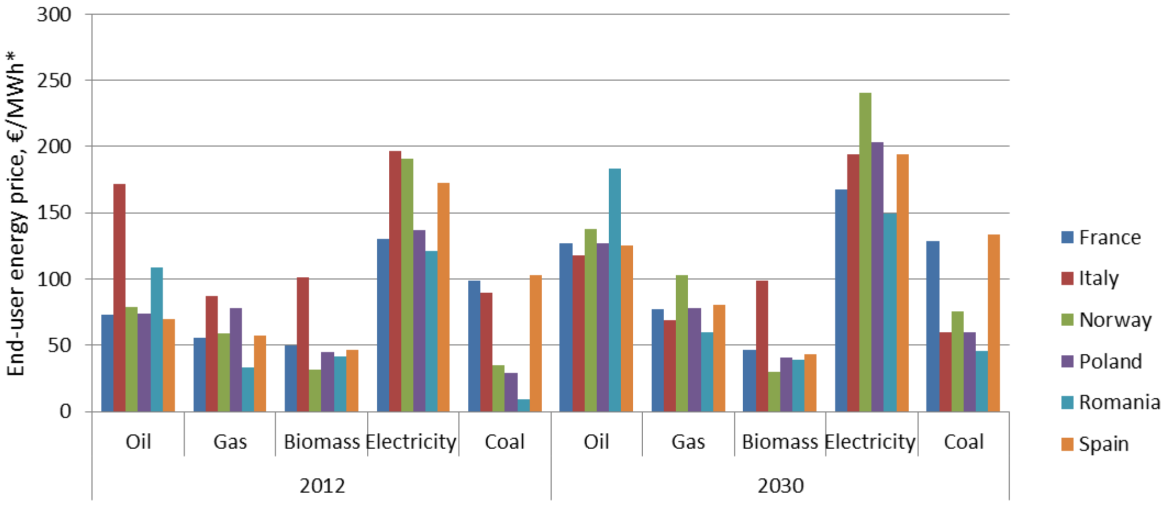
Fig. 20 Cumulated renovation rate for different building vintages used for all investigated countries

4.1.4. Scenario framework

Two different scenarios, the “Business-as-Usual” (BAU) scenario and the “Towards higher energy savings” scenario with different sets of economic conditions are defined. Both scenarios cover a range of economic indicators which have an impact on the cost-effectiveness from an investor´s perspective. Thus the aim of the scenarios, is to investigate the impact on energy savings, by 2030, under different economic conditions. Economic conditions describe different exogenous parameters including subsidies for the deep renovation, CO_2 tax for fossil energy fuels and cost reduction of deep renovation. Parameters used in both scenarios are given in Table 4.

In both scenarios, the calculation takes into account the end-user energy prices which relies on the POLES model of Enerdata (Sebi et al., 2013). The projection of end-use energy prices provided by the POLES model was used in the IEE project ENTRANZE. The end-use energy prices assure harmonized projections for each EU country taking into account energy prices on the international markets and the intensity of carbon commitments and policies (Sebi et al., 2013). POLES model provides two energy price scenarios, “Reference” scenario and “Ambitious Climate” scenario. In this calculation, I use “Reference” energy price scenario which assumes that i.a. already planned climate policies including 20% emission reduction in the European Union by 2020, are taken into account. Fig. 21 shows end-user energy price for different energy fuels in 2012 and 2030 used in the calculation.

In both scenarios, the discount rate is assumed to be 3%. This is a simplified assumption used for all types of buildings. According to Steinbach's and Staniaszek's discussion paper, on discount rates in energy system analysis, discount rates should be differentiated according to different investors (Steinbach and Staniaszek, 2015). The level of discount rates applied to households in different studies range from 3% and 6% while for commercial and industrial investors from 6% to 15% (Steinbach and Staniaszek, 2015).



* Recalculated energy price (originally given in \$2005/toe) with
- USD to EUR currency exchange rate of 1 USD = 0.803 EUR.
- toe to MWh conversion factor 1 toe = 11.63 MWh.
- Prices are recalculated to \$2010/toe using inflation rate from 2006 to 2010 given by Eurostat.

Fig. 21 End-user energy price in 2012 and 2030 used in the calculation for oil, gas, biomass, electricity and coal in France, Italy, Norway, Poland, Romania and Spain

The BAU scenario is a moderate scenario. There are no subsidies for medium and deep renovation. Investments costs of the renovation packages remain unchanged from 2012 to 2030.

In the "Towards higher energy savings" scenario, it is assumed that the European member states make an effort to reduce energy demand in the building sector by supporting implementation of the "deep" renovation package under the statement "Energy efficiency first". There are direct subsidies of 20% for "deep" renovation package in this scenario. Cost reduction in 2030, of "medium" and "deep" renovation packages are 15% and 30% respectively, compared to 2012. These cost reductions were calculated based on the following literature (Manteuffel et al., 2014), (Fernandez Boneta, 2013) and was applied in the report "Renovating Germany´s building stock" (Staniaszek et al., 2015). These learning curves were derived taking into account numerous journal papers and project reports. Additionally, the scenario takes CO_2 tax of 50 €/t CO_2 on fossil energy fuels into account.

Table 4 Variables used in both scenarios

Description	**Modelling variable the "Business-as-Usual" scenario**	**Modelling variable in the "Toward higher energy savings" scenario**
Subsidy for deep renovation of building envelope	0%	20%
Cost reduction of deep renovation of building envelope in 2030 compared to 2012	0%	23%

Cost reduction of medium renovation of building envelope in 2030 compared to 2012	0%	15%
Energy price increase	POLES scenario	POLES scenario
Discount rates	3%	3%
CO2 tax	no	50 €/t CO_2

4.2.Results

In this section, results for two scenarios, Business-as-Usual" and "Towards higher energy savings" are shown. For each scenario, I firstly present country-by-country results using energy saving cost curves. Secondly, I show a cross-country analysis in order to compare countries based on different indicators.

4.2.1. "Business-as-Usual" scenario

Fig. 22 to Fig. 27 show energy saving cost curves for the building sector in France, Italy, Norway, Poland, Romania and Spain. The x-axis indicates cumulated energy savings from 2012 to 2030 for different reference buildings and total building stock. The y-axis indicates cost-effectiveness of investments. Each bar presents the selected least-cost renovation package (light, medium or deep) for a particular reference building. Reference buildings are described by building type, construction period and energy carrier used for space heating (before renovation). Investments in renovation packages are ordered from the cheapest to the most expensive. Profitably renovated reference buildings are those with negative costs.

In **France** (Fig. 22), the calculated final energy demand for space heating in the total building stock was 447 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 31% by 2030. 26% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, single family houses (built before 1950, using oil), single family houses (built between 1991 and 2000, using oil), apartments (built between 1991 and 2000, using electricity) and apartments (built before 1950, using oil). The highest energy savings can be achieved by renovating single family houses (built before 1950, using biomass) followed by single family houses (built before 1950, using gas), single family houses (built before 1950, using oil) and single family houses (built between 1951 and 1990, using gas). The energy savings by renovating these reference buildings are 15.9 TWh, 15.4 TWh, 11.3 TWh and 8 TWh, respectively.

In **Italy** (Fig. 23), the calculated final energy demand for space heating in the total building stock was 294 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 26% by 2030. 38% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, single family houses (built before 1950, using biomass), single family houses (built between 1951 and 1990, using biomass), single family houses (built before 1950, using oil) and apartments (built between 1951 and 1990, using biomass). The highest energy savings can be achieved by renovating apartments (built between 1951 and 1990, using biomass) followed by apartments (1951 – 1990, using gas), apartments (before 1950, using gas) and single family houses (before 1950, using gas). The energy savings by renovating these reference buildings are 13 TWh, 11 TWh, 9.6 TWh and 6.4 TWh respectively.

In **Norway** (Fig. 24), the calculated final energy demand for space heating in the total building stock was 45 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 25% by 2030. 59% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential: education buildings (before 1950, electricity), commercial buildings (before 1950, electricity), health buildings (before 1950, electricity), health buildings (1951-1990, electricity). The highest energy saving can be achieved by renovating single family houses (before 1950, electricity) followed by single family houses (1951 – 1990, electricity), single family houses (before 1950, biomass) and single family houses (1951 – 1990, biomass). The energy savings by renovating these reference buildings are 2.1 TWh, 1.7 TWh, 1.2 TWh and 0.74 TWh, respectively.

In **Poland** (Fig. 25), the calculated final energy demand for space heating in the total building stock was 181 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 22% by 2030. 38% of the total energy savings are through cost effective renovation. The following reference buildings hold the most cost effective potential, single family houses (before 1950, electricity), single family houses (before 1950, gas), commercial buildings (before 1950, biomass), commercial buildings (before 1950, coal). The highest energy savings can be achieved by renovating single family houses (before 1950, coal) followed by single family houses (1951 – 1990, coal), single family houses (1991 – 2000, coal) and single family houses (before 1950, biomass). The energy savings by renovating these reference buildings are 6.6 TWh, 5.3 TWh, 3.5 TWh and 2 TWh, respectively.

In **Romania** (Fig. 26), the calculated final energy demand for space heating in the total building stock was 113 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 25% by 2030. 15% of the total energy savings are through cost effective renovation. The following reference buildings hold the most cost effective potential, health buildings (1951 – 1990, district heat), health buildings (1951 – 1990, gas), single family house (before 1950, gas), and apartments (before 1950, district heat). The highest energy saving can be achieved by renovating single family houses (1951 – 1990, biomass) followed by single family houses (before 1950, biomass), single family houses (1951 – 1990, gas) and commercial buildings (1951 – 1990, gas). The energy savings by renovating these reference buildings are 12.5 TWh, 4.6 TWh, 2.2 TWh and 1.6 TWh, respectively.

In **Spain** (Fig. 27), the calculated final energy demand for space heating in the total building stock was 162 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 23% by 2030. 37% of the total energy savings are through cost effective renovation. The following reference buildings hold the most cost effective potential, health buildings (before 1950, oil), single family houses (before 1950, electricity), offices (before 1950, oil) and education buildings (before 1950, oil). The highest energy saving can be achieved by renovating apartments (1951 – 1990, gas) followed by commercial buildings (before 1950, gas), apartments (1951 – 1990, electricity) and apartments (1951 – 1990, biomass). The energy savings by renovating these reference buildings are 2.8 TWh, 2.4 TWh, 2.3 TWh and 1.9 TWh, respectively.

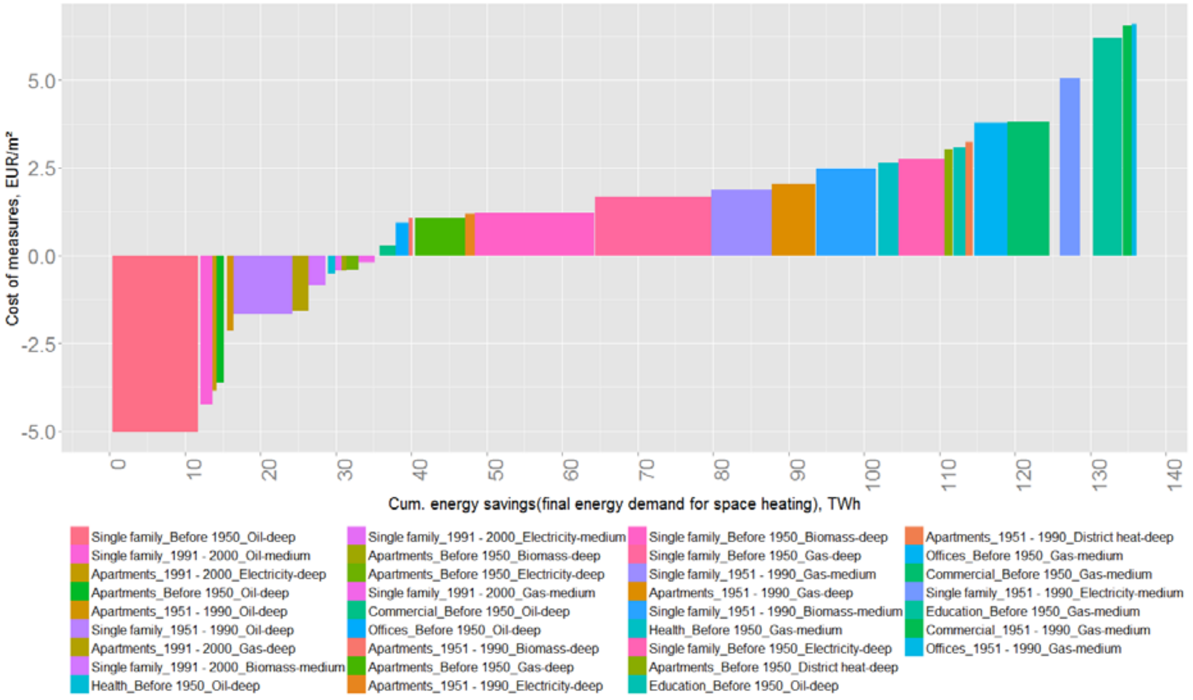


Fig. 22 Cost curve of the energy savings by applying energy efficiency measures in French building sector in the “BAU” scenario. The X-axis shows cumulated energy savings from 2012 to 2030, y-axis – cost effectiveness of investments. Each bar presents reference buildings and the selected least cost renovation package (light, medium or deep)

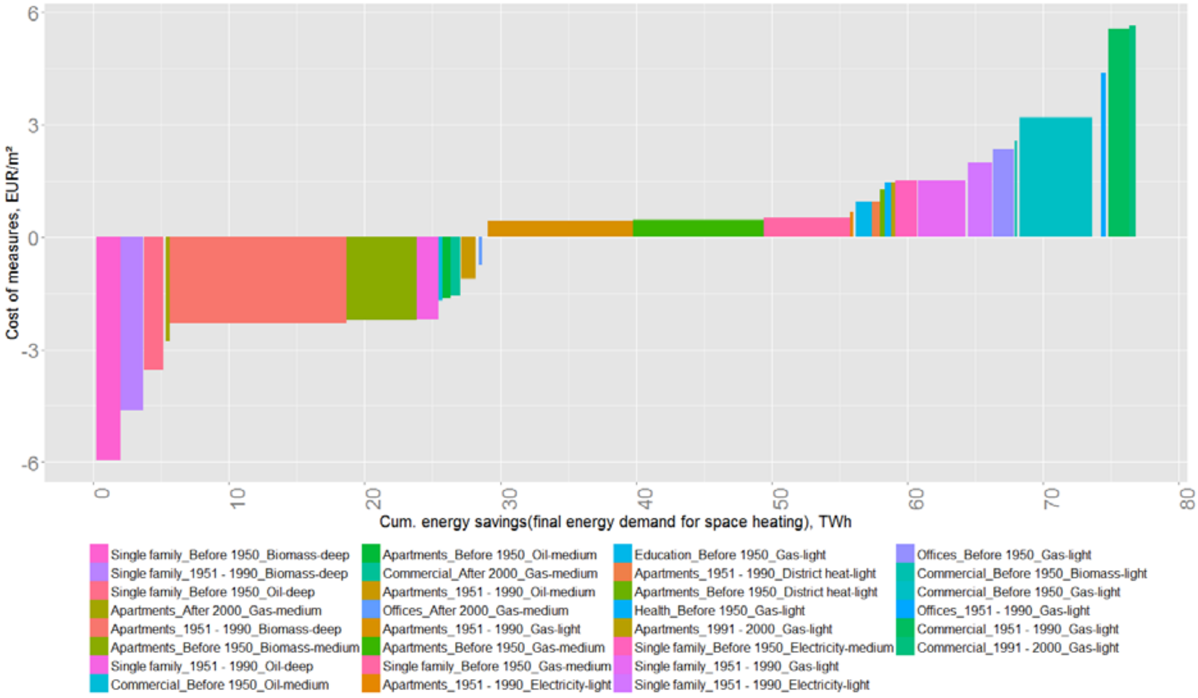


Fig. 23 Cost curve of the energy savings by applying energy efficiency measures in Italy’s building sector, in the “BAU” scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar presents reference buildings and the selected least cost renovation package (light, medium or deep)

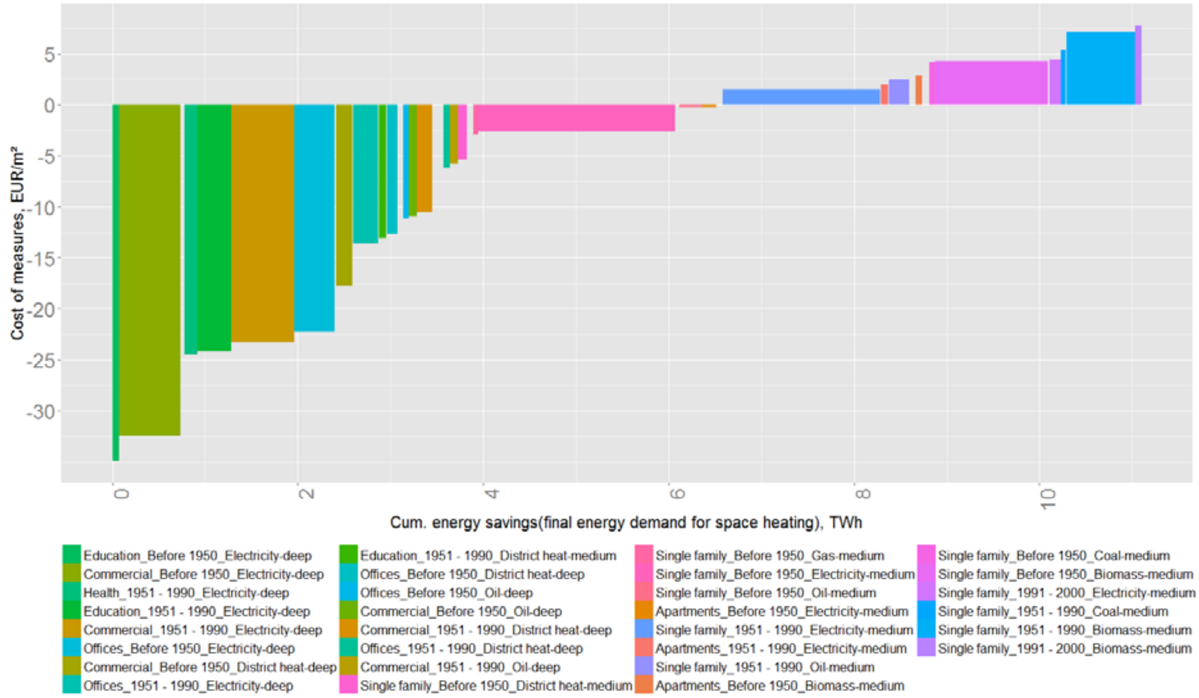


Fig. 24 Cost curve of the energy savings by applying energy efficiency measures in Norway's building sector, in the "BAU" scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar presents reference buildings and the selected least cost renovation package (light, medium or deep)

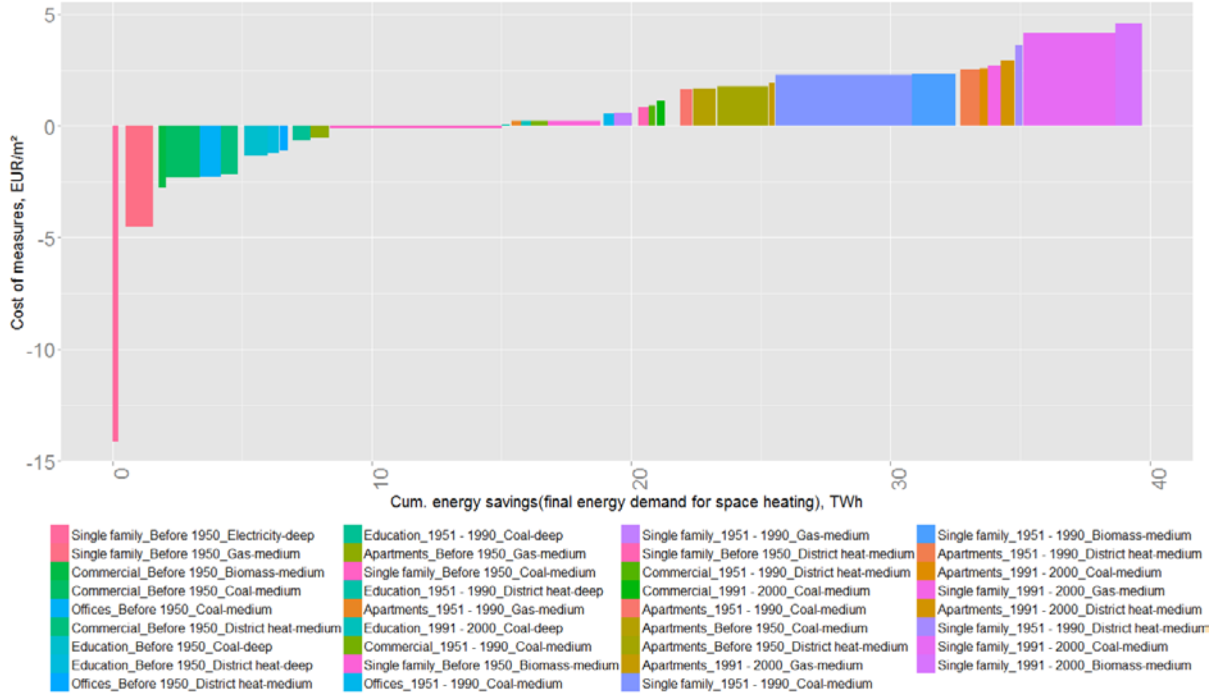


Fig. 25 Cost curve of the energy savings by applying energy efficiency measures in Poland's building sector, in the "BAU" scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar presents reference buildings and the selected least cost renovation package (light, medium or deep)

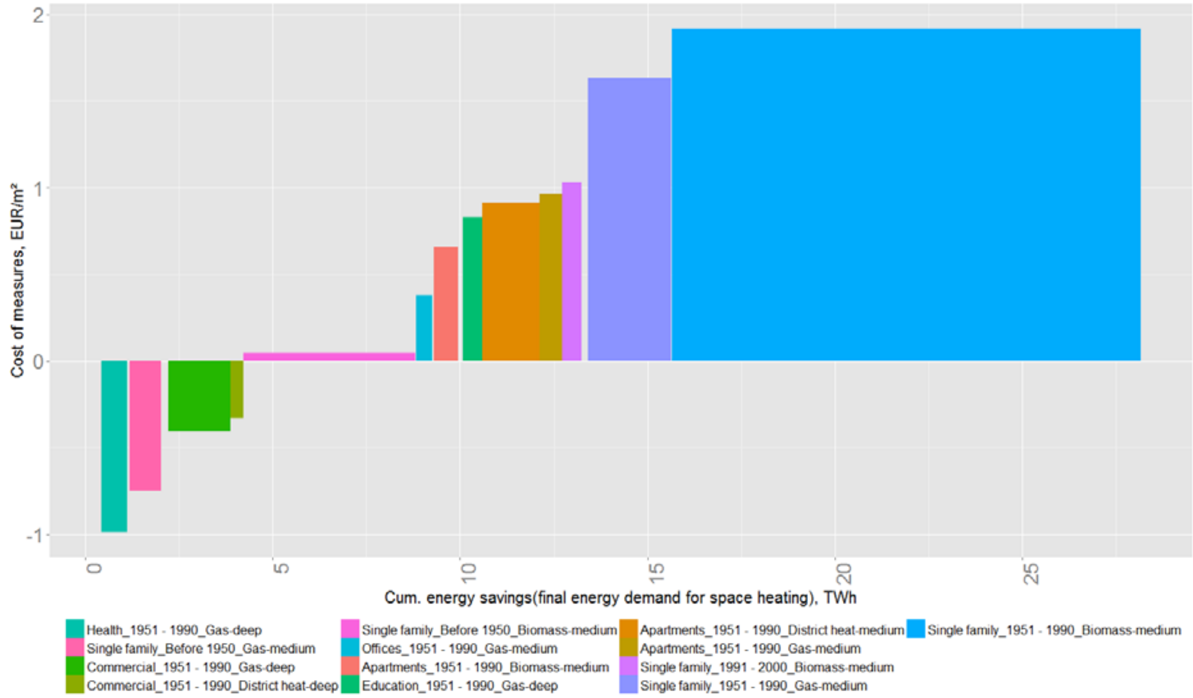


Fig. 26 Cost curve of the energy savings by applying energy efficiency measures in Romania’s building sector, in the “BAU” scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar presents reference buildings and the selected least cost renovation package (light, medium or deep)

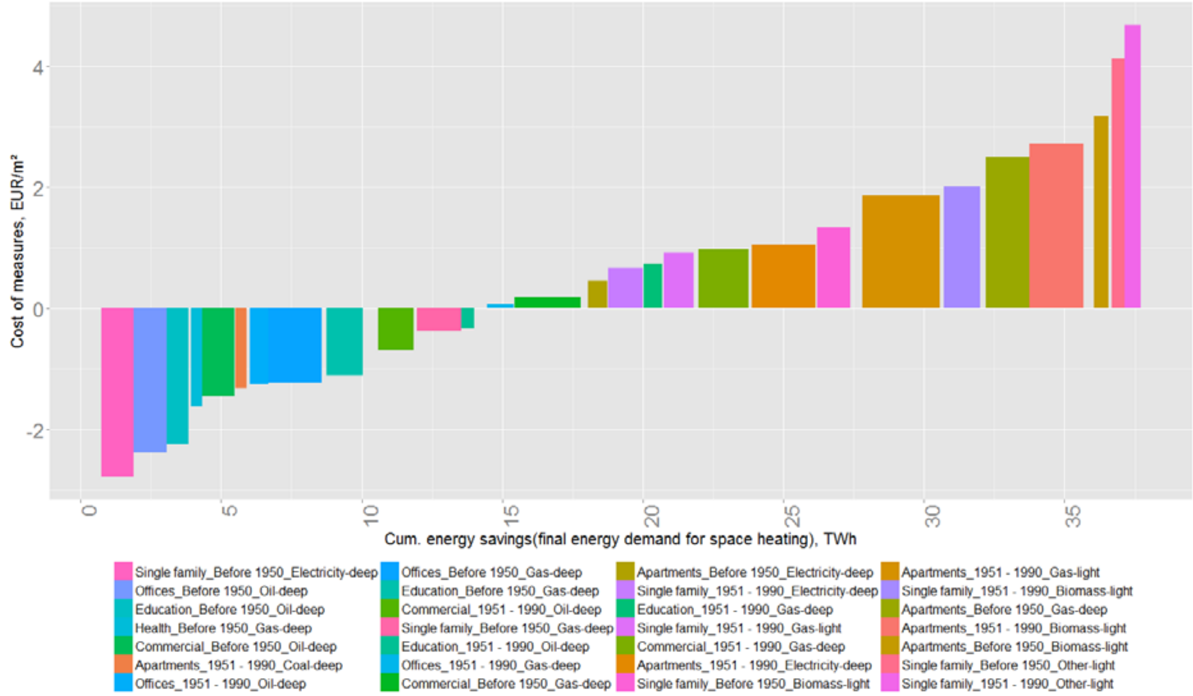


Fig. 27 Cost curve of the energy savings by applying energy efficiency measures in Spain’s building sector, in the “BAU” scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar presents reference buildings and the selected least cost renovation package (light, medium or deep)

Fig. 28 shows the share of profitably renovated gross floor area, on the total renovation gross floor area in 2030 compared to 2012, in all investigated countries. It can be seen that the highest share of the buildings renovated profitably is in Norway (47%), followed by Poland (24%), France (25%), Italy (23%), Spain (21%) and Romania (10%). There are several explanations for these results. Due to the cold climate in Norway, a thermal envelope renovation leads to higher energy savings compared to the countries from other climate regions in Europe. Another influenced indicator is the energy fuel price: The higher the energy fuel price, the higher the cost effectiveness of the investments. The cost effectiveness of investments shows the perspective of the investor under a certain set of economic conditions. It should also be mentioned, that this analysis presents a potential under a certain economic condition without considering barriers which exist in reality such as landlord-tenant dilemma, lack of information on retrofitting options and others.

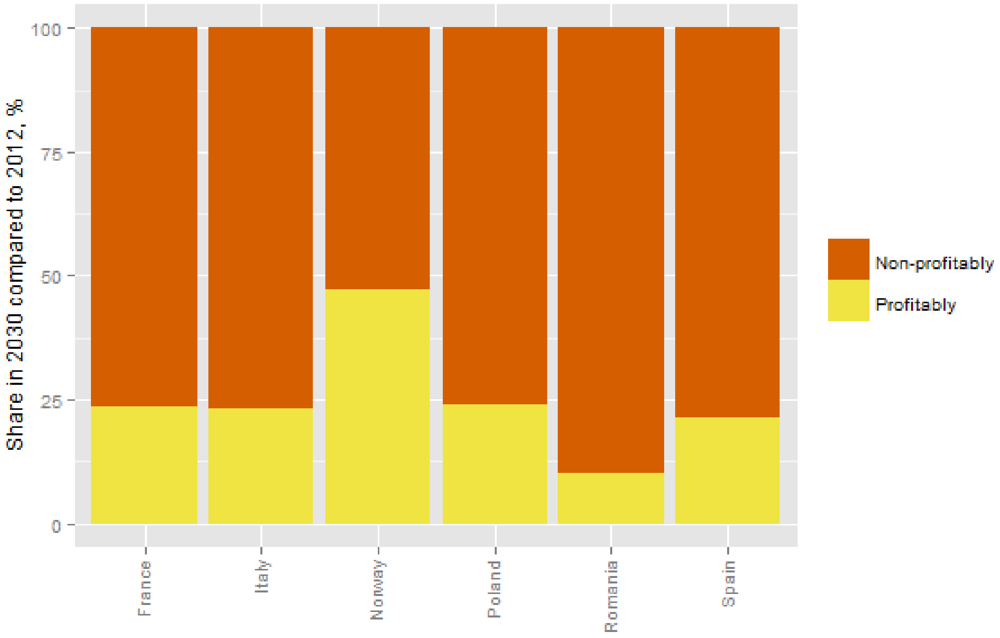


Fig. 28 The share of profitably renovated floor area on the total renovated floor area in 2030 compared to 2012 in France, Italy, Norway, Poland, Romania and Spain in BAU scenario

Fig. 29 shows profitably renovated gross floor area by reference buildings in the period between 2012 and 2030. Reference buildings which have the highest potential, in terms of the total floor area and economic effectiveness, are identified. Almost in all countries, residential buildings have the highest potential to be profitably renovated until 2012. The share of the residential buildings´ gross floor area on the total profitably renovated gross floor area until 2030 is 98%, 96%, 68%, 44%, 45%, 31%, in France, Italy, Norway, Poland, Romania and Spain, respectively. In France, two reference buildings obviously have the highest potential: single family houses built before 1950, and between 1951 – 1990, both heated with oil. The share of these buildings on the total profitably renovated building gross floor area is 37%. Similarly, in other countries, Norway, Spain and Poland, single family houses built before 1950 provide the highest potential. The share of these buildings is 52%, 11%, 28% in Norway, Spain and Poland respectively. However, energy fuel used for space differs between these countries. In Norway and Spain, these buildings are supplied by electricity, whilst in Poland, they are supplied by coal. In Italy, apartment buildings with biomass have the highest share. In Romanian, the highest potential is provided by commercial, health and single family houses which are supplied by gas.

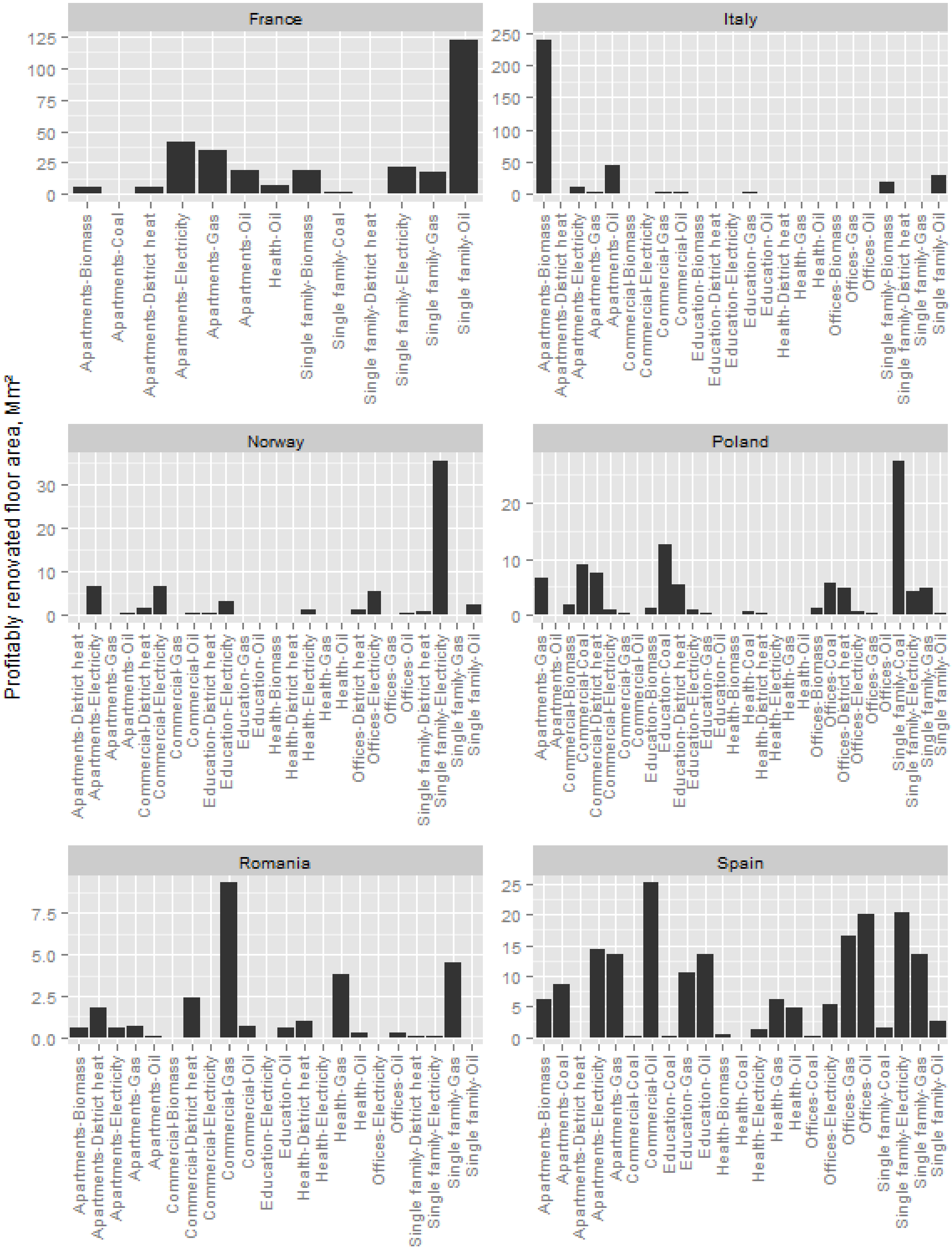


Fig. 29 Profitably renovated floor area for reference buildings renovated from 2012 to 2030, in the BAU scenario, in France, Italy, Norway, Poland, Romania and Spain

Fig. 30 shows the share of renovated building floor area in 2030 compared to the total building gross floor area of 2012. The renovated building floor area is split into the type of renovation packages (light, medium and deep). An additional renovation level was also taken into the calculation namely maintenance renovation. Maintenance renovation measure is a renovation undertaken for aesthetic reasons and is not related to thermal energy savings. The share of renovated building floor area is 36%, 42%, 39%, 40%, 28%, 33% in France, Italy, Norway, Poland, Romania and Spain, respectively. Share of the renovated floor area is influenced by the building vintage and renovation rate, which was calculated using Weibull-distribution. The share of the type of renovation, on the other hand, is driven by the techno-economics of the renovation type. For each reference building, renovation package (maintenance, light, medium or deep) is installed with the highest cost-effectiveness. The cost effectiveness of investments shows the perspective of the investor under a certain set of economic conditions (see chapter scenario framework, 4.1.4). Fig. 30 shows that in Norway, Poland and Romania, the medium package has the highest share. Unlike in Norway, Poland and Romania, in France, Italy and Spain, where the share of medium renovation package is low. In France, deep renovation package makes up the highest share on the total renovated floor area, whilst in Italy, light renovation.

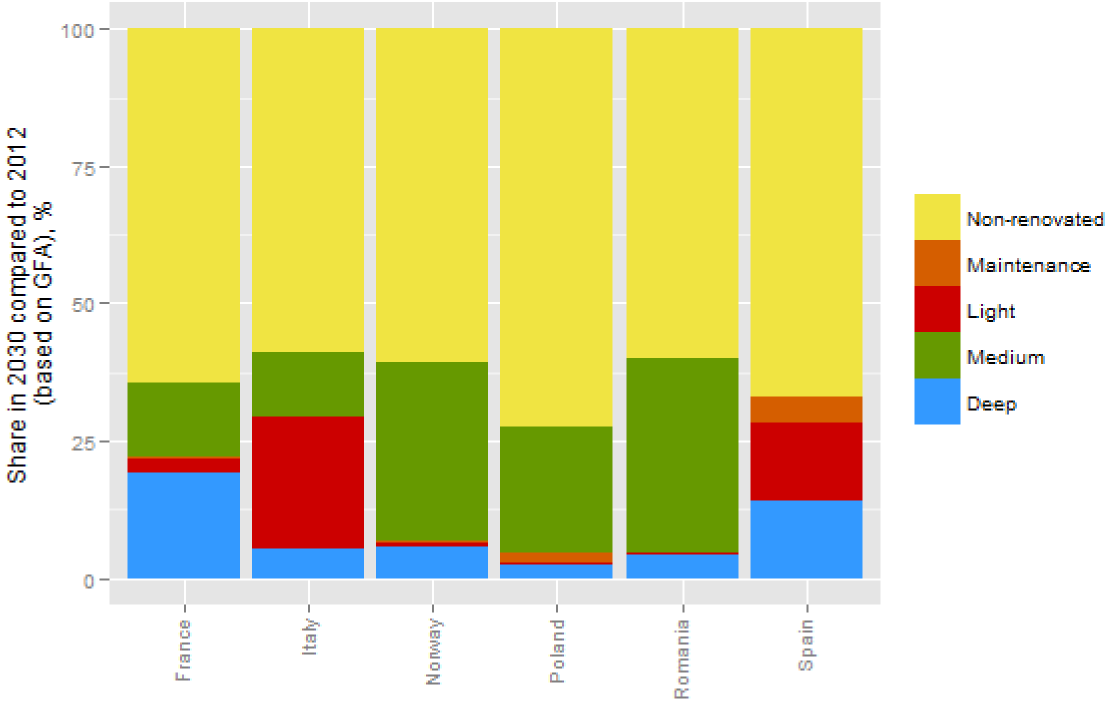


Fig. 30 Share of the renovated building floor areas by renovation level, on the total building floor area in 2030 compared to 2012 in the BAU scenario in France, Italy, Norway, Poland, Romania and Spain

Fig. 31 shows the final energy savings for space heating in the total building stock in 2030 compared to 2012 and average investments per renovated floor area in all the investigated countries. Energy savings for space heating, achieved by renovating building stock from 2012 to 2030, is as follows: 31%, 26.5%, 25%, 22%, 25% and 23%, in France, Italy, Norway, Poland, Romania and Spain, respectively. Total energy saving potential varies slightly between the countries due to the selection of implemented renovation packages (see Fig. 30) and their specific energy savings, which were calculated based on a prescriptive-based approach following the national building code requirements. Moreover, the share of the buildings built before 1950 and between 1951 and 1990 may also have an impact on energy savings. The higher the share of these buildings in the total building stock, the higher the cumulated renovation rate and thus, energy savings. The highest average investments per renovated floor area are in France, followed by Norway. In France, the share of deep renovation is the highest compared to other countries, which is the main reason of the highest initial investments. A high difference can be seen in the investments between Romania and Norway. This is due to the differences in price levels.

Fig. 31 Final energy savings (space heating) until 2030 compared to 2012 and associated average initial investments per renovated floor area in France, Italy, Norway, Poland, Romania and Spain, in the BAU scenario

4.2.2. “Towards higher energy savings” scenario

Fig. 32 to Fig. 37 show energy savings cost curves for the building sector in France, Italy, Norway, Poland, Romania and Spain in the “toward higher energy savings” scenario. The x-axis indicates cumulated energy savings from 2012 to 2030 for different reference buildings and total building stock. The y-axis indicates cost-effectiveness of investments. Each bar presents the selected least cost renovation option (light, medium or deep) for a particular reference building which are ordered from the cheapest to the most expensive. Profitably renovated reference buildings are those with negative costs.

In **France** (Fig. 32), the calculated final energy demand for space heating in the total building stock was 447 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 34% by 2030. 98% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, single family houses (built before 1950, using oil), single family houses (built between 1991 and 2000, using oil), single family houses (built between 1951 and 1990, using oil) and single family houses (built before 1950, using gas). The highest energy savings can be achieved by renovating single family houses (built before 1950, using biomass) followed by single family houses (built before 1950, using gas), single family houses (built before 1950, using oil) and single family houses (built between 1951 and 1990, using gas). The energy savings by renovating these reference buildings are 15.9 TWh, 15.4 TWh, 11.3 TWh and 10.6 TWh, respectively.

In **Italy** (Fig. 33), the calculated final energy demand for space heating in the total building stock was 294 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 40% by 2030. 98% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, single family houses (built before 1950, using biomass), commercial buildings (built between 1951 and 1990, using biomass), single family houses (built before 1950, using biomass). The highest energy savings can be achieved by renovating apartments (built between 1951 and 1990, using gas) followed by apartments (before 1950, using gas), apartments (1951 - 1990, using biomass) and single family houses (before 1950, using gas). The energy savings by renovating these reference buildings are 74 TWh, 56 TWh, 26 TWh and 6.5 TWh, respectively.

In **Norway** (Fig. 34), the calculated final energy demand for space heating in the total building stock was 45 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 29% by 2030. 90% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, education buildings (before 1950, electricity), commercial buildings (before 1950, using electricity), health buildings (before 1950, using electricity), health buildings (1951-1990, using electricity). The highest energy saving can be achieved by renovating single family houses (before 1950, using electricity) followed by single family houses (1951 – 1990, using electricity), single family houses (before 1950, using biomass) and single family houses (1951 – 1990, using biomass). The energy savings by renovating these reference buildings are 2.5 TWh, 2.2 TWh, 1.4 TWh and 0.95 TWh, respectively.

In **Poland** (Fig. 35), the calculated final energy demand for space heating in the total building stock was 181 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 30% by 2030. 96% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, single family houses (before 1950, using electricity), single family houses (before 1950, using gas), commercial buildings (before 1950, using coal), single family houses (before 1950, using electricity). The highest energy saving can be achieved by renovating single family houses (before 1950, using coal) followed by single family houses (1951 – 1990, using coal), single family houses (1991 – 2000, using coal) and apartment buildings (before 1950, using district heating). The energy savings by renovating these reference buildings are 8.1 TWh, 6.8 TWh, 4.9 TWh and 2.7 TWh, respectively.

In **Romania** (Fig. 36), the calculated final energy demand for space heating in the total building stock was 113 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 31% by 2030. Almost 100% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, single family house (before 1950, using gas), commercial buildings (1951-1990, using oil), health buildings (1951 – 1990, using gas) and offices (1951 - 1990, using gas). The highest energy saving can be achieved by renovating single family houses (1951 – 1990, using biomass) followed by single family houses (before 1950, using biomass), single family houses (1951 – 1990, using gas) and apartment buildings (1951 – 1990, using district heat). The energy savings by renovating these reference buildings are 15.5 TWh, 5.5 TWh, 2.7 TWh and 2.2 TWh, respectively.

In **Spain** (Fig. 37), the calculated final energy demand for space heating in the total building stock was 162 TWh in 2012. The cost curve shows the potential to reduce the final energy demand by 32% by 2030. 89% of the total energy savings can be achieved through cost effective renovation. The following reference buildings hold the most cost effective potential, health buildings (before 1950, using oil), education buildings (before 1950, using oil), commercial buildings (before 1950, using oil) and offices (before 1950, using oil). The highest energy saving can be achieved by renovating apartments (1951 – 1990, using gas) followed by single family houses (1951 - 1990, using biomass), apartments (1951 – 1990, using biomass) and apartments (1951 – 1990, using biomass). The energy savings by renovating these reference buildings are 5.2 TWh, 3.6 TWh, 2.9 TWh and 2.4 TWh, respectively.

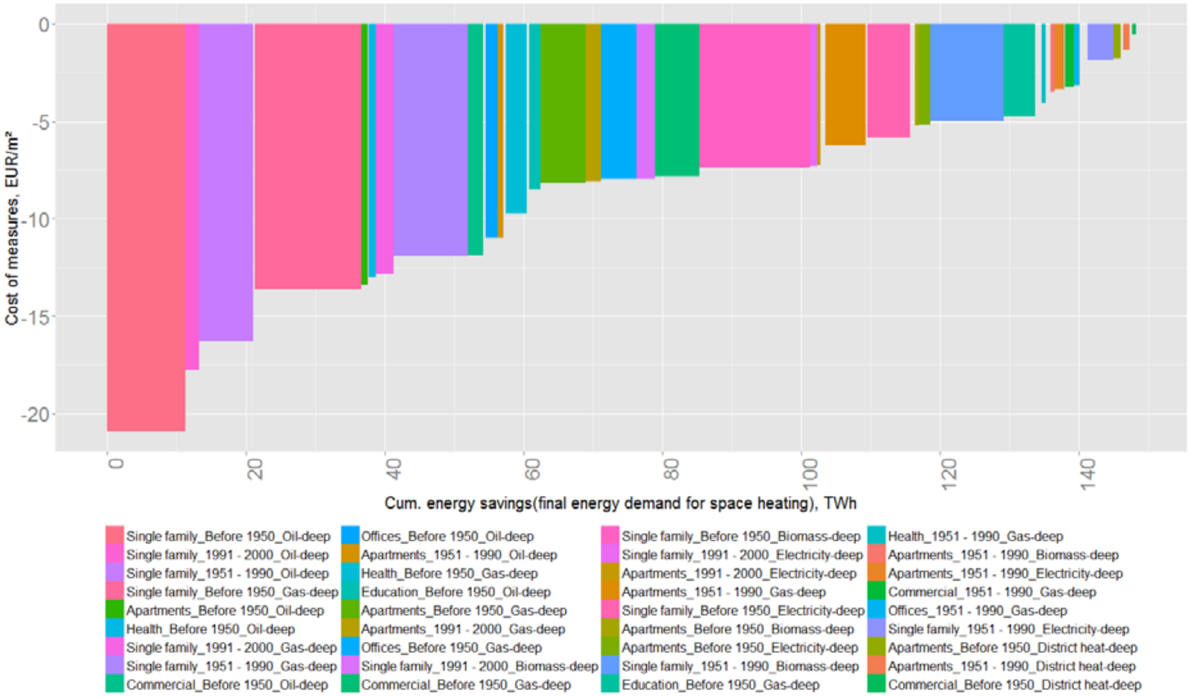


Fig. 32 Cost curve of the energy savings by applying energy efficiency measures in French´ building sector, “Towards higher energy savings” scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar represents a reference building and selected least cost renovation package (light, medium or deep)

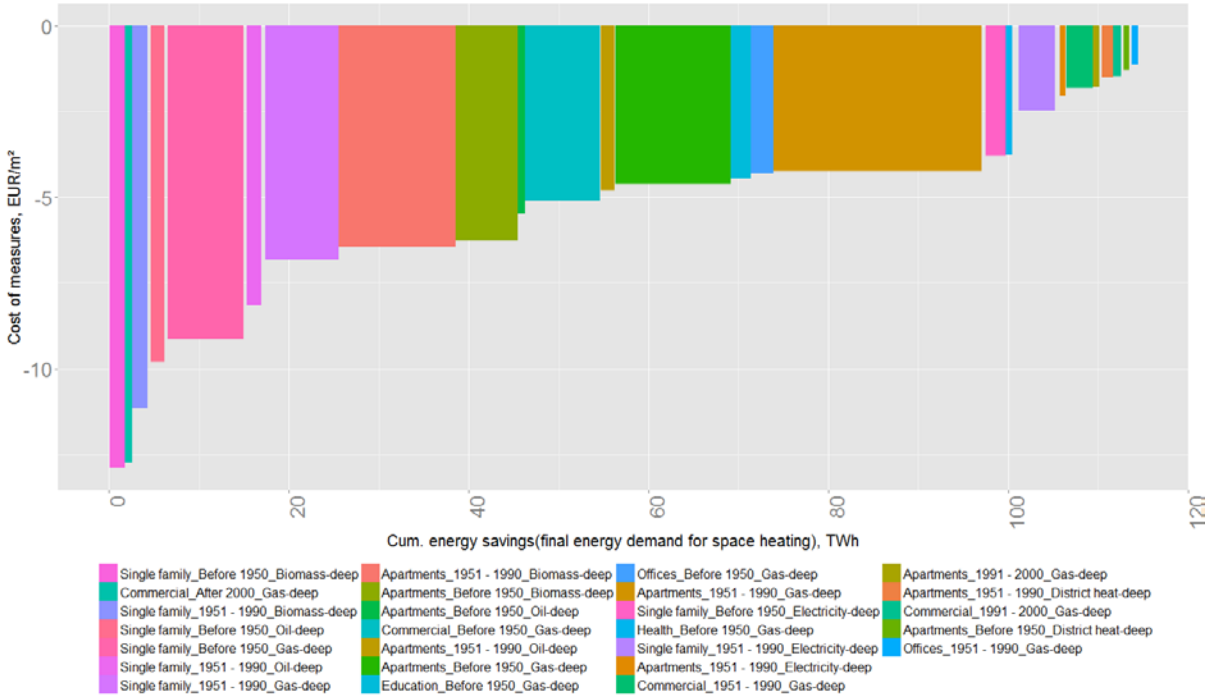


Fig. 33 Cost curve of the energy savings by applying energy efficiency measures in the Italy's building sector, "Towards higher energy savings" scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar represents a reference building and selected least cost renovation package (light, medium or deep)

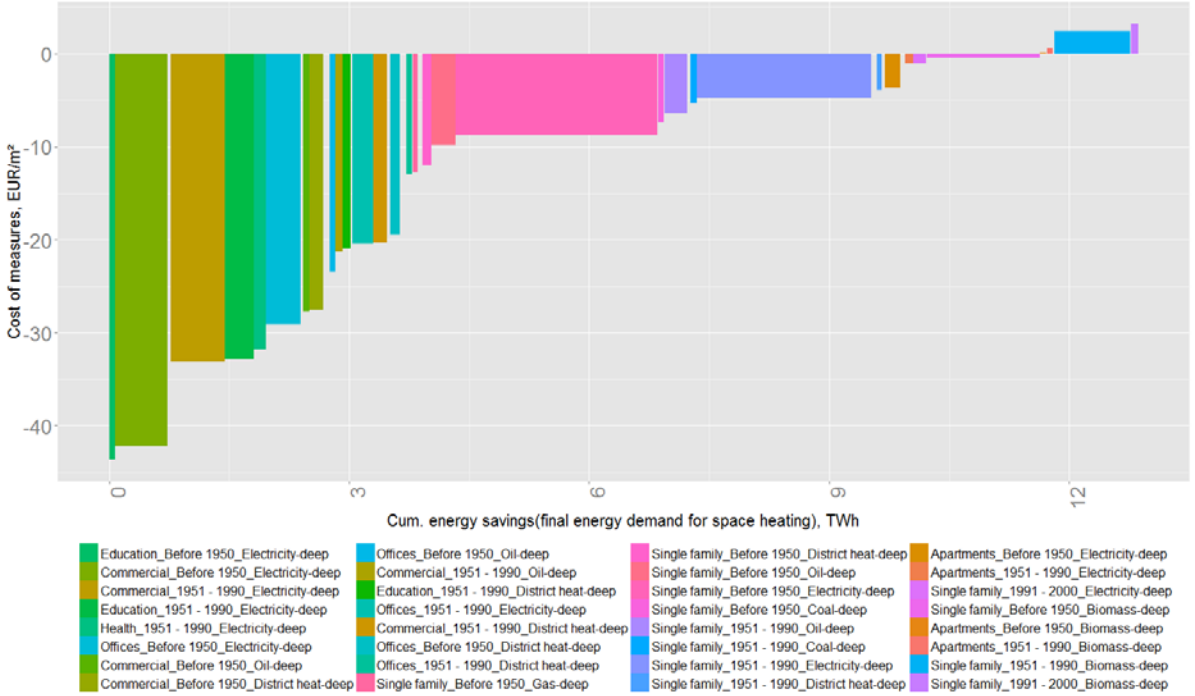


Fig. 34 Cost curve of the energy savings by applying energy efficiency measures in the Norway's building sector, "Towards higher energy savings" scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar represents a reference building and selected least cost renovation package (light, medium or deep)

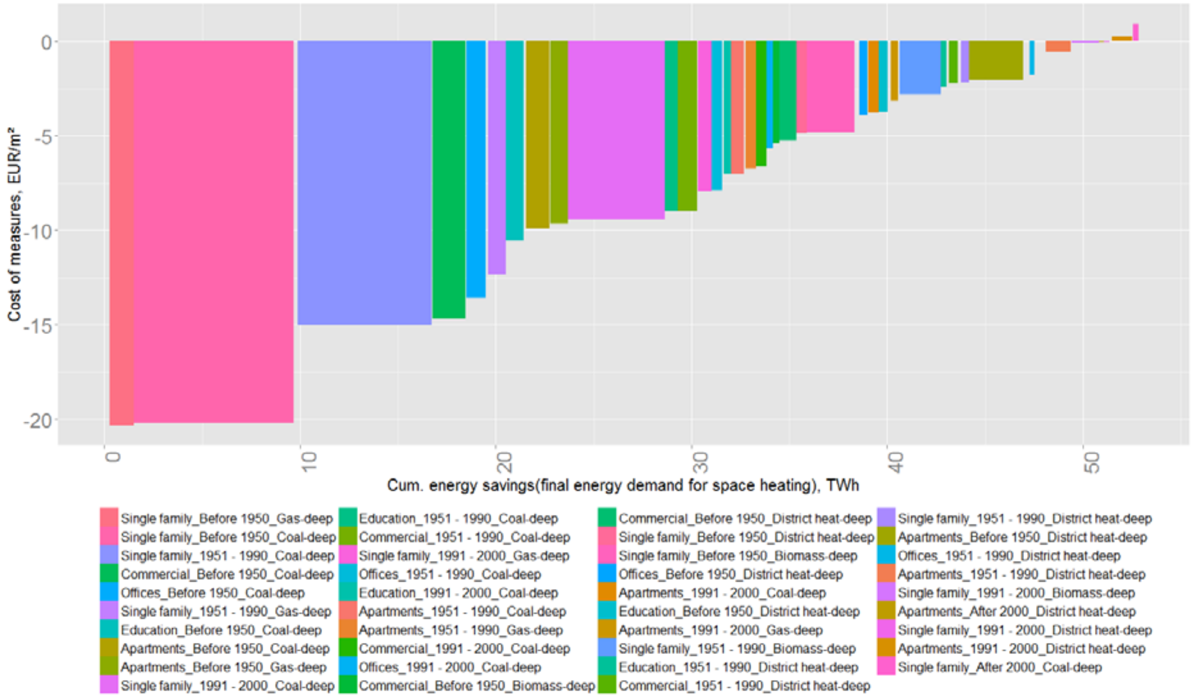


Fig. 35 Cost curve of the energy savings by applying energy efficiency measures in the Poland’s building sector, “Towards higher energy savings” scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar represents a reference building and selected least cost renovation package (light, medium or deep)

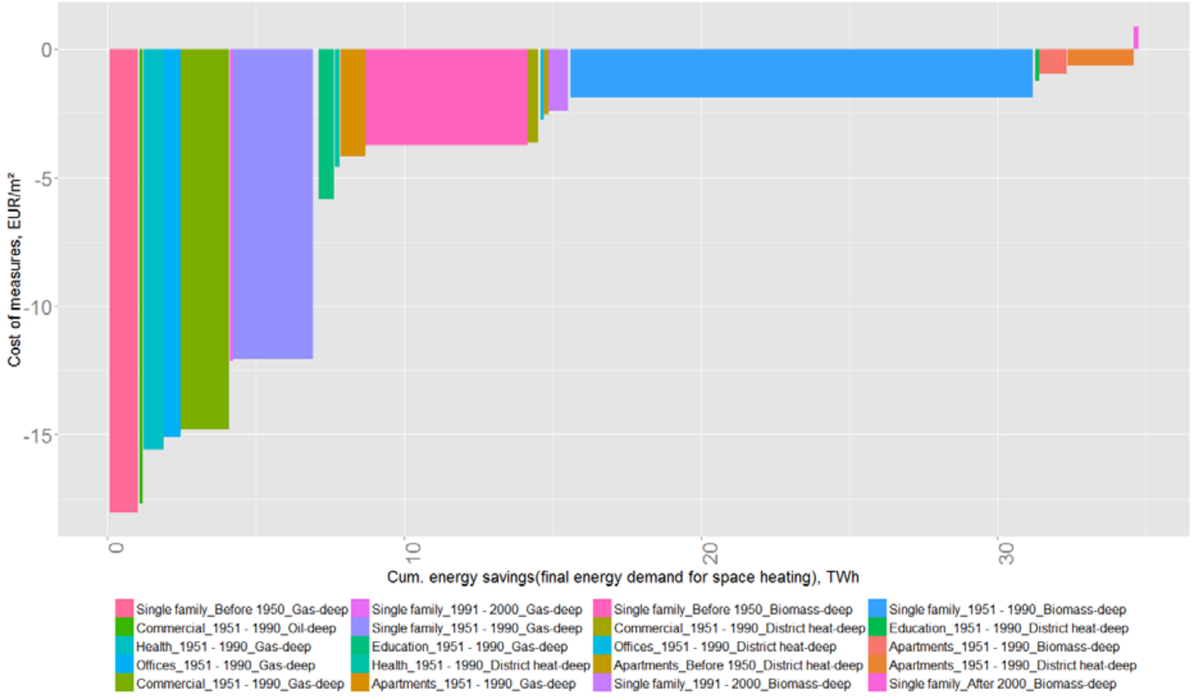


Fig. 36 Cost curve of the energy savings by applying energy efficiency measures in the Romania’s building sector, “Towards higher energy savings” scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar represents a reference building and selected least cost renovation package (light, medium or deep)

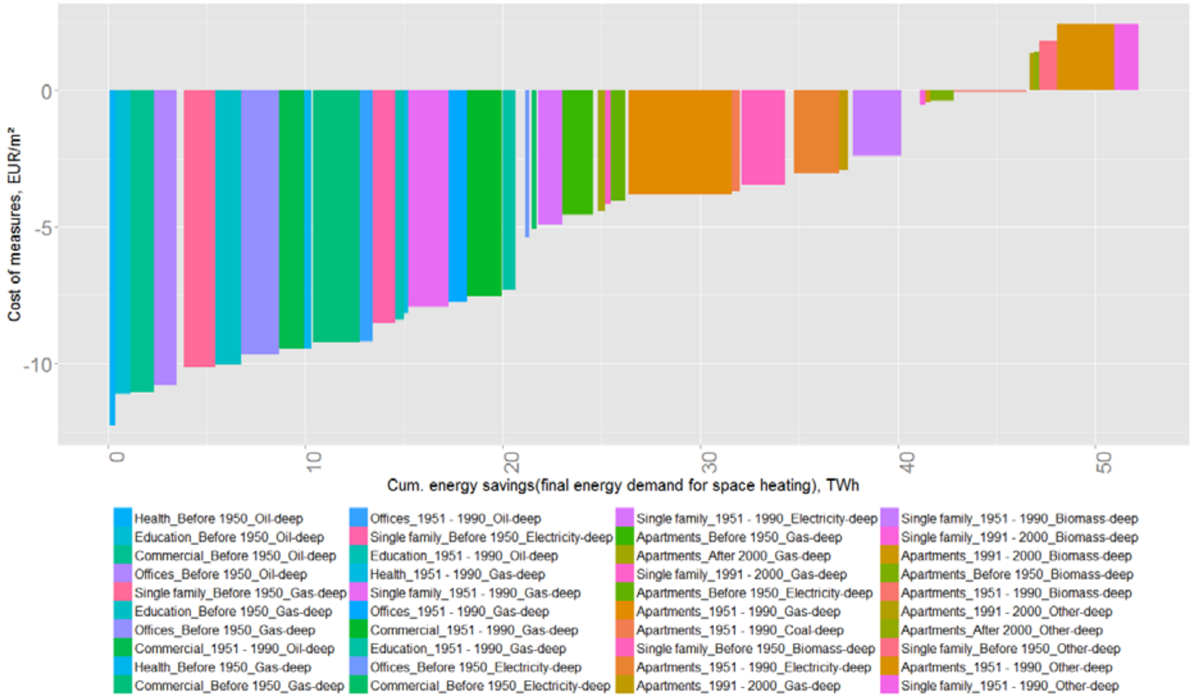


Fig. 37 Cost curve of the energy savings by applying energy efficiency measures in the Spain's building sector, "Towards higher energy savings" scenario. The X-axis shows cumulated energy savings from 2012 to 2030, the y-axis – cost effectiveness of investments. Each bar represents a reference building and selected least cost renovation package (light, medium or deep)

Fig. 38 shows the share of profitably renovated gross floor area, on the total renovation gross floor area in 2030 compared to 2012, in all investigated countries. Unlike in the BAU scenario, almost all the buildings in the "towards higher energy savings" scenario are renovated profitably- in France (97%) followed by Italy (99%), Norway (92%), Poland (86%), Spain (80%) and Romania (99%). The cost effectiveness of investments shows the perspective of the investor under a certain set of economic conditions (see chapter scenario framework, 4.1.4). In the "Towards higher energy savings" scenario there are two parameters influencing the cost of the deep renovation package: investment subsidy and cost reduction resulting, amongst others, from increased sales volumes. Another indicator influencing the costs is the energy fuel price which is increased in this scenario compared to the BAU scenario.

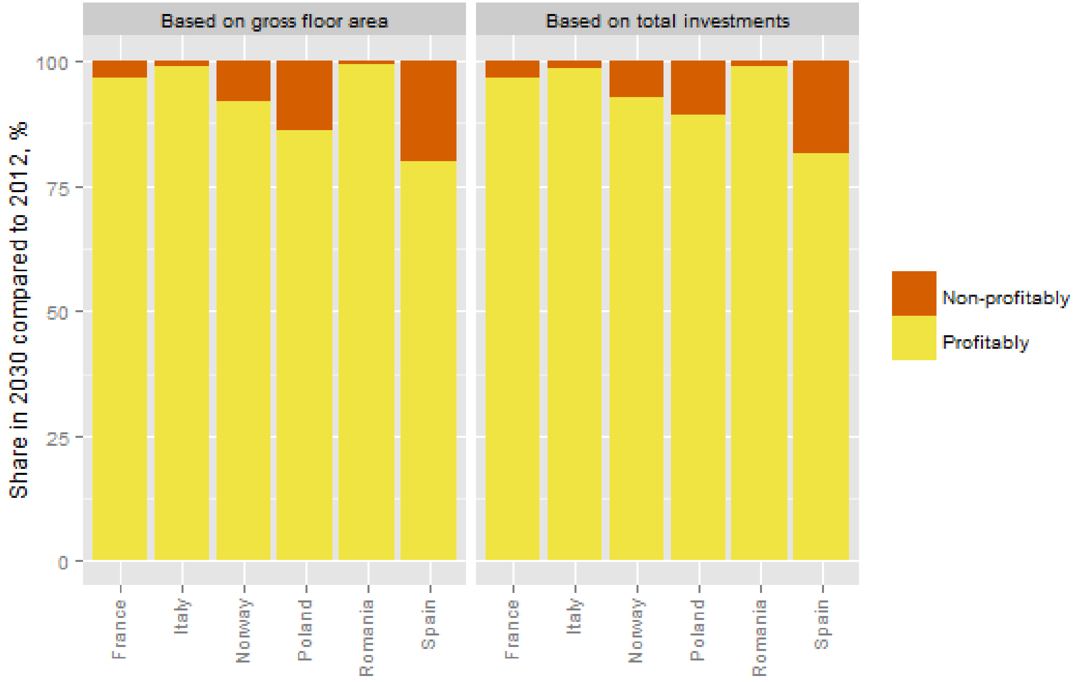


Fig. 38 share of the profitably renovated floor area on the total renovated floor area in 2030 compared to 2012 in France, Italy, Norway, Poland, Romania and Spain in the “Towards higher energy savings” scenario

Fig. 39 shows profitably renovated gross floor area by reference buildings in the period between 2012 and 2030. In almost all countries, residential buildings hold the highest potential to be renovated and thus save energy until 2030. The share of the residential buildings gross floor area on the total renovated gross floor area until 2030, is 76%, 96%, 67%, 44%, 31%, 44% in France, Italy, Norway, Poland, Romania and Spain, respectively. In France, two reference buildings have the highest potential. The two reference buildings are both single family houses built before 1950, but one uses gas and the other electricity as energy fuel for space heating. The share of these buildings on the total profitably renovated building gross floor area is 14%. Similarly as in France, in other countries, Norway, Spain and Poland, single family houses built before 1950 provide the highest potential. The share of these buildings is 56%, 34%, 19% in Norway, Poland, and Spain, respectively. However, the energy fuel used for space heating differs between these countries. In Norway and Spain, these buildings are supplied by electricity, whilst in Poland, they are supplied by coal. In Romanian, the highest potential is provided by commercial, health and single family houses which are supplied by gas.

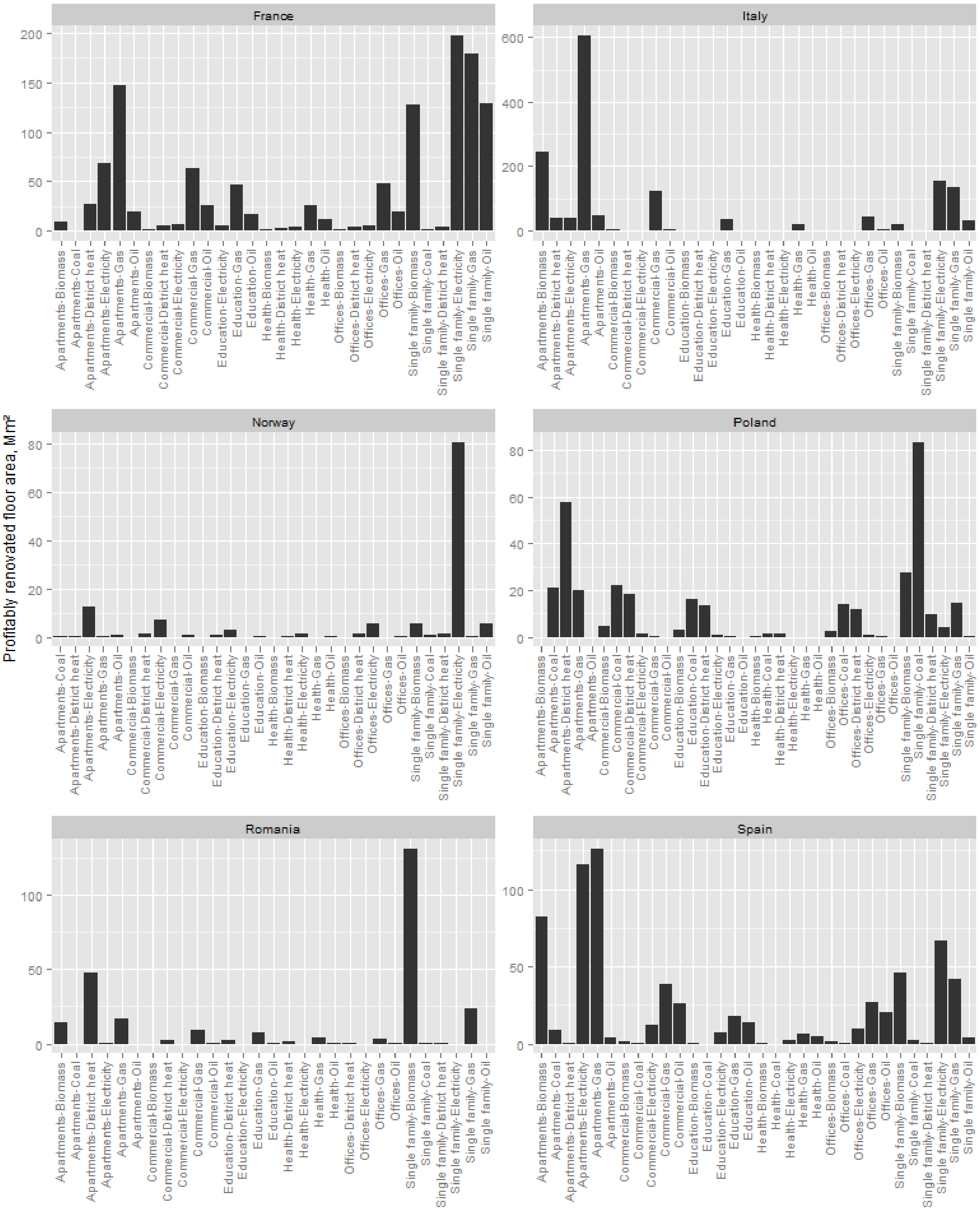


Fig. 39 Profitably renovated floor area by reference buildings renovated from 2012 to 2030 in France, Italy, Norway, Poland, Romania and Spain in the “Towards higher energy savings” scenario

Fig. 40 shows the share of the renovated building floor area on the total building gross floor area in 2030 compared to 2012. The share of renovated building floor area is 36%, 42%, 39%, 40%, 28%, 33% in France, Italy, Norway, Poland, Romania, and Spain, respectively. Share of the renovated floor area is influenced by the building vintage and the renovation rate which was calculated using Weibull-distribution. Implemented type of renovation, on the other hand, is driven by the techno-economics of the renovation type. In this scenario, it is assumed that there is an investment subsidy for deep renovation, and moreover, a cost reduction resulting from increased sales volumes. These factors have an influence that the deep renovation package is the most cost effective and makes accordingly the share of 100% on the total renovated building floor area from 2012 to 2030 in all investigated countries.

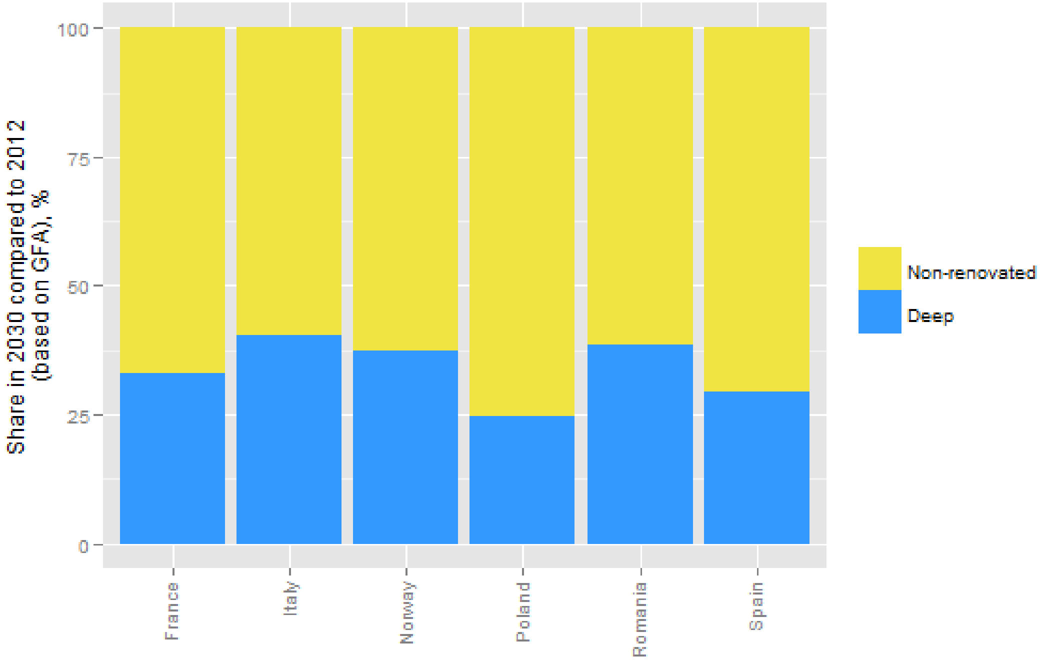


Fig. 40 Shares of the renovated building floor area by renovation level on the total building floor area in 2030 compared to 2012, in France, Italy, Norway, Poland, Romania and Spain, in the "Towards higher energy savings" scenario

Fig. 41 shows the final energy savings for space heating in the total building stock in 2030 compared to 2012 and average investments per renovated floor area in all investigated countries. Energy savings for space heating achieved by renovating building stock from 2012 to 2030 is as follows in the considered countries, 34%, 39%, 28%, 29%, 31% and 32%, in France, Italy, Norway, Poland, Romania and Spain, respectively. In the BAU scenario, the highest energy savings can be achieved by renovating French building stock. This scenario shows that Italian building stock would provide the highest energy saving potential. When it comes to the average investments in the renovation package, it can be seen that investments are smaller than the investments in the BAU scenario. These are total specific investments comprising subsidies and cost reduction. The highest average investments, per renovated floor area are in Norway followed by France, Italy, Spain, Poland and Romania.

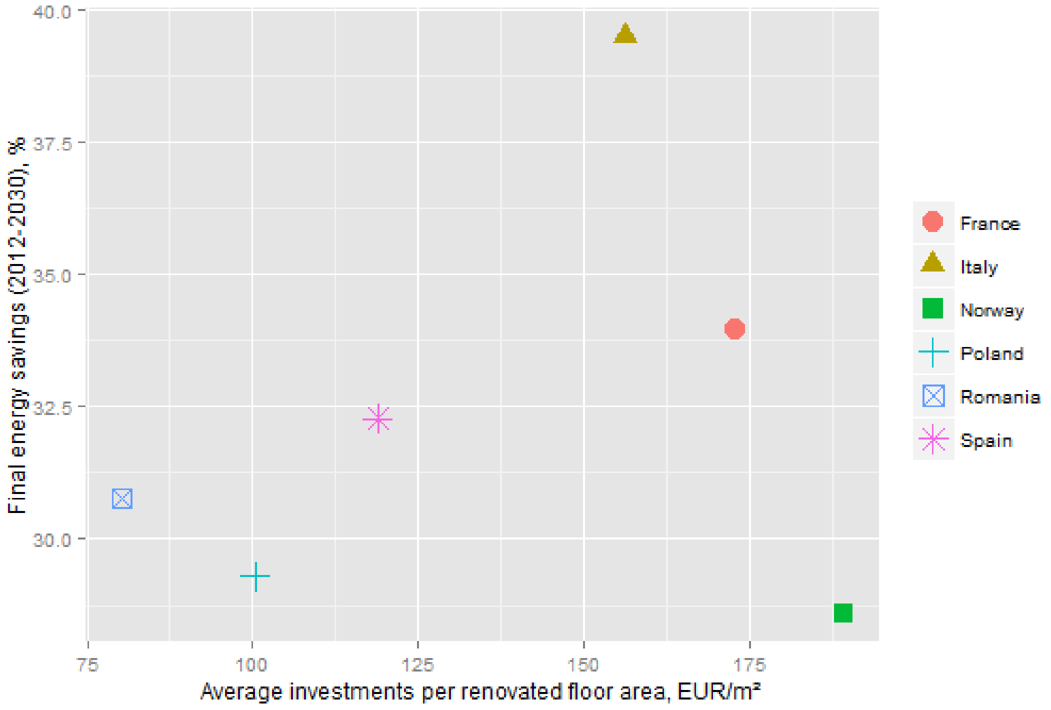


Fig. 41 Final energy savings (space heating) until 2030 compared to 2012 and associated average initial investments per renovated floor area in France, Italy, Norway, Poland, Romania and Spain, in the "Towards higher energy savings" scenario

4.3.Summary and discussion

In this chapter, I calculated final energy savings for space heating until 2030 in the total building stock and provided energy saving cost curves showing the cost of investments and associated energy savings for different reference buildings in France, Italy, Norway, Poland, Romania and Spain. The energy saving cost curves showing investor perspective (using levelized costs per heated building area) were derived. Two different scenarios with different sets of economic conditions were calculated, the BAU scenario and the "Towards higher energy savings" scenario. Calculated energy savings from 2012 to 2030 in the BAU scenario are 31%, 26.5%, 25%, 22%, 25% and 23% in France, Italy, Norway, Poland, Romania, and Spain, respectively, while in the "Towards higher energy savings" scenario, 34%, 39%, 28%, 29%, 31% and 32%, respectively.

The results of the BAU scenario showed that the total energy saving potential varies slightly between the countries. The main identified reasons were the share of implemented renovation packages and their specific energy savings and the share of the buildings built before 1950 and between 1951 and 1990. The highest share of the buildings renovated profitably is in Norway (47%) followed by Poland (24%), France (25%), Italy (23%), Spain (21%) and Romania (10%). The main reasons are the climate and energy fuel prices. Moreover, the results showed that in almost all countries, residential buildings have the highest potential to be profitably renovated until 2030. The highest average investments per renovated floor area are in France, followed by Norway. The reasons are the shares of the deep renovation package and energy price levels of the investments.

When it comes to the "Towards higher energy savings" scenario, it can be seen, that the application of subsidies for deep renovation package, CO_2-tax on fossil energy fuels and cost reduction of deep renovation package make an impact: deep renovation package becomes the lowest cost option for all building types in all investigated countries. The economic conditions defined in each scenario have an impact on the cost-effectiveness of investments and thus the share of the renovation packages. The share of implemented renovation packages has accordingly an impact on the total energy savings. In the BAU scenario due to the lack of political instruments addressing deep renovation package, the higher energy saving potential is lost. Policy instruments such as renovation building standards, subsidies and CO_2 taxes on fossil energy fuels are needed in order to avoid log-in effects.

The limitation of this work:

- The calculations were made by considering only measures of retrofitting including better insulation on building envelope and mechanical ventilation. The calculated energy saving potential is limited because the saving potential due to the installation of renewable energy systems is not considered.
- The results show that the highest energy saving potential can be achieved by renovating residential buildings built before 1950. However, old buildings are often under protection of historical monuments. Renovation of such buildings may incur additional costs due to the special requirements of insulation technology.
- Energy fuel prices play an important role in the cost-effectiveness of the renovation packages. The results might be less ambitious looking at the today’s oil and gas prices.
- Other barriers which were not take into consideration, and which might reduce calculated energy saving potential, are as follows:
    - Imperfect and lack of information which prevents consumers investing in energy efficiency measures.
    - Absence of markets. There is no energy efficiency market, as it is difficult to sell energy efficiency as a product, however, energy efficiency services and energy performance contractors can fill this gap.
    - Split incentives (classic example of the landlord/tenant relationship).
    - Transaction and hidden cost.

5. Case Study II: Policy based energy demand scenarios to 2050

This chapter aims at showing energy demand for space heating and hot water and associated CO_2-emission reduction to 2050 in the building sector in France, Italy, Norway, Poland, Romania and Spain. The second case study provides policy based energy demand scenarios and analyses their consistency with Paris COP21 decarbonisation targets. The main drivers of energy saving, the renovation rate, the renovation depth, the energy performance of the new buildings, and renewable energy installation, are assessed. The scenarios are modelled by using a bottom-up, techno-socio-economic approach in Invert/EE-Lab model (Müller, 2015), (Invert/EE-Lab, 2017).

Two different scenarios are derived, a current policy scenario and an ambitious policy scenario. Both scenarios are driven by different policy measures. The following policy measures and programmes were presented and described in the investigated countries; (I) building codes for building renovation and new buildings, (II) financial support programmes for technical measures of retrofitting including insulation of envelope and renewable energy technologies, (III) renovation obligation of public buildings according to the Energy Efficiency Directive (EED), (IV) RES-H use obligation according to the Renewable Energy Directive (RED) and (V) compliances with regulatory policies.

To model energy demand scenarios until 2050 the following method steps are carried out:

(I) Disaggregated data on the building stock in the investigated countries are collected.
(II) Data on existing policy measures and programmes are collected and policy packages are built.
(III) Four renovation packages; light, medium, deep and deep plus, related to the building envelope and on site renewable energy technologies are defined.
(IV) Current and future energy demand for space heating and hot water is calculated with the building simulation tool Invert-EE/Lab.
(V) Current and future CO_2-emissions are calculated using the data on the energy demand by energy carrier and national CO_2-emission factors
(VI) In order to assess the consistency of the derived policy based scenarios with the Paris agreement, indicators for this assessment are carried out.

This chapter is partly based on the following publications: (Toleikyte et al., 2016), (Bointner et al., 2016), (Kranzl et al., 2017)

5.1.Input data

The key input data used in this chapter is described in the previous section. The following input data set is taken into calculation:

- Building stock description (see section 4.1.1)
- Definition of the renovation packages (see section 4.1.2)
- Cost data of renovation options (see section 4.1.2) and heating systems (cost data on the heating systems were collected within the European project ENTRANZE (Fernandez Boneta, 2013).

5.1.1. Policy instruments and packages

Future final energy demand is affected by existing policies including energy performance requirements, financial instrument and obligations for renewable sources in the buildings. These policies were surveyed in the project ZEBRA2020 for different European countries and implemented in the model Invert-EE/Lab. The ZEBRA2020 project investigates European, national and regional policies addressing energy efficiency effort implemented in the building sector (Kontonasiou, 2016).

Building codes for new buildings and building renovation

Energy performance of the buildings can be described using different indicators (see chapter 3.3). The European Member states describe the energy performance of buildings (renovation and new) using two different approaches, a prescriptive-based approach and a performance-based approach. In the scenario calculation, I use the prescriptive-based approach. This means that the U-values of building elements and characteristics of mechanical ventilation are investigated.

The following standards for new building constructions are defined:

- buildings built according to the national building code,
- buildings built better than building code and
- buildings built according to the national nZEB definition or better than nZEB definition.

The first category “Buildings built according to the national building code” reflects the building standards which were used in 2012 and until the time when the nZEB standard is in force. The definition “buildings built better than building code” describes buildings which have better energy performance but don´t achieve the requirements of nZEB. “National nZEB definition or better than nZEB” definition describes the requirements set in the European Directive on energy performance of buildings (Council Directive 2010/31/EU, 2010). Following Article 9 of this directive, each Member State has to define nZEB (nearly zero energy building) and enforce it on new buildings from 2021.

For the building renovation, four different renovation packages, light, medium, deep and deep plus are defined. Each package covers renovation of floor, roof, wall and window. The deep and deep plus renovations additionally implement the installation of the mechanical ventilation. The methodology to define renovation packages are descripted in chapter 3.3.

Financial and fiscal support policies/programmes

All investigated countries provide programmes to support energy performance of buildings and to increase installation of the renewable energy systems in the buildings. Table 5 shows on-going programmes in all investigated countries and total budget as the sum over all on-going programmes listed in this table. In Invert/EE-Lab, the financial policies are implemented using direct grants and subsidies. It can be seen, that in reality, next to direct grants and subsidies, other economic instruments such as preferential loan schemes, Value Added Tax, tax incentives or tax rebates are used. In Invert-EE/Lab, the total budget is split into the budget for building renovation and new building construction (for residential buildings and other buildings) as well as the budget for heat supply systems. By analysing the national on-going programmes, the budgets were spit accordingly (see Table 5).

Table 5 National on-going programmes to support energy performance of buildings and installation of renewable energy systems

Country	**Programmes (Programme name, type of program and covered measures)**	**Budget implemented in the modelling**
France	Zero-rated eco-loan (soft loans for major renovation works including envelope and equipment); The property tax exemption (tax exemption for new buildings and building renovation including envelope and equipment); Lowe VAT for renovation work (tax exemption for major renovation works including envelope and equipment); The sustainable development account: preferential loans for energy savings (preferential loans and soft loans for equipments); Eco-loan for social housing (soft loan for building envelope renovation); Energy transition tax credit (personal income taxes reduction for renovation including envelope and equipment).	Building envelope (households and other buildings): 287.5 mln € and 50 mln € Heating systems: 287.5 mln € and 50 mln €
Italy	Piano Casa (tax deductions and increases in permissible volumes for building envelope for new buildings and building renovation); Piano Casa 2 (tax deduction for all type of measures related to the energy savings); Thermal Account (cost subsidy for building envelope and renewable energy systems); Detrazioni fiscali 65%. Tax deduction for energy efficiency improvement actions (tax deductions for building envelope and renewable energy systems); Guarantee funds and promotion of TPF (Third-Party Financing) models (guarantee fund to public buildings, especially schools and hospitals; building envelope and district heating and cooling networks).	Building envelope (households and other buildings): n.a. Heating systems: n.a.
Norway	Støtte til energieffektive nybygg – Support for energy-efficient new buildings (grants for building envelope, highly efficient technical systems); Støtte til eksisterende bygg – Support for existing buildings (grants for building envelope, highly efficient technical systems); Støtte til oppgradering av bolig – Support for upgrading residences (grants for building envelope, energy supply systems others than electricity); Enovatilskuddet - The Enova Grants (grants for energy consulting and specific single measures covering building envelope and heating systems); Grunnlån – Basic Loan (preferential loan for new buildings and major renovation covering building envelope); Tilskudd til tilstandsvurdering – Grants for appraisal of need for repair/renovation (grants for building envelope); Energy improvement (grants (mainly) and preferential loan for renewable energy supply).	Building envelope (households and other buildings): 157 mln € and 157 mln € Heating systems: 162.11 mln € and 161.45 mln €
Poland	Thermo-modernization Fund (thermo-modernization and the repairs of existing buildings); Operational Program Infrastructure and Environment (POIE) (subsidies for complex energy modernization of public buildings and residences including building envelope and renewable systems; Improving energy efficiency. Subsidies for loans to build energy-efficient homes	Building envelope (households and other buildings): 26.28 mln € and 10.75 mln € Heating systems: 29.04 mln € and 10.75 mln €

Country	Programmes (Programme name, type of program and covered measures)	Budget implemented in the modelling
	(grants for building envelope and renewable systems); Improvement of energy efficiency LEMUR – energy efficient public utility buildings (subsidies for building envelope and renewable systems).	
Romania	The national program on increasing the energy performance of housing blocks (grants for building envelope and Installation of RES systems); The program of thermal rehabilitation of residential buildings financed by bank loans with Government guarantee (soft loans for building envelope and installation of RES systems); Thermal Rehabilitation Programmes with funding from the Regional Operational Programme (grants for building envelope and rehabilitation of the heating system); The project "Improving energy efficiency in low-income households and communities in Romania" (grants for building envelope and installation of RES systems); Program Casa Verde for individuals (grants for technical equipment including heating, ventilation systems, RES in buildings, etc.); Program Casa Verde for public bodies (grants for renewable energy systems); Clădire verde Cluj-Napoca municipality (tax reduction for linked to an energy performance certificate e.g. BREEAM, LEED).	Building envelope (households and other buildings): 180 mln € and 10.8 mln € Heating systems: 24 mln € and 4 mln €
Spain	PAREER-CRECE: Aid Programme for Energy Rehabilitation in Existing Buildings (Energy Efficiency National Fund promoted by IDAE) (subsidies, preferential loans for building envelope and renewable systems); JESSICA-F.I.D.A.E.: Fund for financing projects in energy efficiency and renewable energy of non-residential buildings (JESSICA fund promoted by IDAE) (preferential loans for building envelope and renewable systems); PIMA Sol: Environmental Action Plan is an initiative designed to reduce greenhouse gas (GHG) emissions and also to improve efficient use of energy and resources in the Spanish Tourist sector (banking fund promoted by MAGRAMA) (preferential loans); 2013-2016 National Plan for the promotion of rental housing, building refurbishment and urban regeneration (subsidies); ICO Companies and Entrepreneurs: Economic financing for refurbishment of dwellings and buildings (funded and promoted by ICO Credit Line) (preferential loans); FES-CO2: Carbon Fund for a Sustainable Economy to promote Clima Projects (promoted by MAGRAMA) (grants for building envelope and renewable systems); Tax and VAT reductionPersonal income taxes reduction (tax reduction) and Fiscal incentive (VAT reduction); building envelope and renewable systems.	Building envelope (households and other buildings): 250 mln € and 80 mln € Heating systems: 280 mln € and 107 mln €

Renovation obligation of public buildings according to the EED

According to the Energy Efficiency Directive (EED), Article 5 (Council Directive 2012/27/EU, 2012), every year, central governments in EU member states must carry out energy efficient renovations on at least 3% (by floor area) of the buildings they own and occupy. This instrument is implemented in Invert-EE/Lab as an obligation instrument leading to the 3% of yearly renovation of publicly occupied buildings. The following building categories were assumed to be publicly occupied: public offices, education buildings and health buildings.

RES-H use obligations according to the RED

Renewable Energy Directive (RED), Article 13 (Council Directive 2009/28/EC, 2009) requests that the member states integrate renewable energy generation in buildings as part of the specific minimum requirements in their building codes. Only a few EU member states have implemented RES requirements into their current building regulations so far (Kranzl et al., 2014c). All member states have to make “nearly zero energy building” a standard for new buildings by 2020. A nearly zero energy building is defined in the Energy Performance Building Directive (EPBD-recast) (Council Directive 2010/31/EU, 2010) as follows “(…) *a building that has a very high energy performance (…). The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*”. A certain minimum share of energy demand supplied by renewable energy sources is implemented from 2021 in all building categories in case of building renovation and new building construction.

5.1.2. Scenario framework

Two different scenarios are defined which are driven by different policy measures. The first scenario is titled as **current policy scenario** and the second, **ambitious policy scenario**. The current policy scenario is driven by the existing policies including energy performance requirements, financial instruments and obligations for renewable energy sources while the ambitious policy scenario is based on more intensive policies which lead to higher renovation rates and depths, more efficient new building construction, a higher share of renewable energy and corresponding CO_2-emissions and energy savings.

Table 6 Policy description used in current and ambitious policy scenarios

Policies	**Current policy scenario**	**Ambitious policy scenario**
Building codes for building renovation	National building code requirements (building codes for building renovation 2012). Based on the regulations, three renovation packages are defined: • Medium (Building code 2012) • Light (lack of compliances, U-values are increased by 30% compared to the building codes) • Deep renovation (U-values are reduced by 30% compared to the building code and mechanical ventilation is installed)	Full compliance with building codes (due to the coaching measures and professional training). There is no light renovation package. The following renovation packages are implemented: • Medium (Building code 2012) • Deep renovation (U-values are reduced by 30% compared to the building code and mechanical ventilation is installed) • Deep plus (higher energy performance achievements compared to deep renovation)
Building codes for new buildings	For the new building construction, the policy requirements implemented in the period 2012 and 2020 and from 2021 to 2050 are distinguished. From 2012 to 2020, the current policies are in force and from 2021 to 2050, the EPBD 2010 is implemented and the new building standard follows the nZEB requirements. From 2012 to 2021: • Building code, 2012 : requirements for the new building construction defined in the national building code in 2012 • Better than building code, 2012: higher energy performance achievements compared to the building code in 2012 (U-values are reduced by 20% compared to the building code) • Much better than building code, 2012 (U-values are reduced by 50% compared to the building code) From 2022 to 2050: • Building code, requirements for nZEB (U-values	Building standard 2012 is updated in 2017 and higher energy performance of new construction are required. The national nZEB requirements are also stronger in this policy scenario.

Policies	Current policy scenario	Ambitious policy scenario
	are reduced by 15% compared to the building code, 2012) • Better than building code, 2022 (U-values are reduced by 20% compared to the building code, 2022 • Much better than building code, 2022 (U-values are reduced by 50% compared to the building code, 2022)	
Financial and fiscal support policies/programmes	Existing programmes are implemented and available by 2050. Financial and support programmes are implemented for energy efficiency investments and for use of renewable energy sources.	Public budget for these support instruments is increased by 50% compared to the current policy scenario.
Increase of renovation rate	3% yearly renovation rate in central government buildings	3% yearly renovation rate in central government buildings
RES obligation	Minimum share of energy demand supplied by renewable energy sources: 20% from 2021 for all building categories, building renovation and new building construction.	Increase of the minimum share of energy demand supplied by renewable energy sources
Compliances	Compliance is checked only for new buildings.	Compliances is checked for new buildings and building renovation

5.1.3. COP21 agreement: indicator assessment

In order to assess the consistency of the derived policy based scenarios with the Paris agreement, indicators for this assessment were carried out. The main indicator is CO_2-emission reduction from the base year to 2050. The CO_2-emission reduction is a result of the energy demand reduction for space heating and hot water, applied mix of technologies and energy carrier. The main problem to investigate the CO_2-emission reduction is on how to deal with the GHG-emission factors for electricity and district heating. Within the European project Commonenergy, CO_2-emission conversion factors for electricity from 2012 until 2050 for all European countries were developed and applied for the shopping centres (Toleikyte et al., 2017b), (Gantner, 2016). CO_2-emission conversion factors were calculated using a reference scenario provided by the European Commission in “EU Energy, Transport and GHG Emissions Trends to 2050. Reference scenario 2013” (European Commission, 2013a).

However, since the analysis is purely focus on the building stock as such, I calculate CO_2-emission reduction assuming constant emission factors for district heating and electricity in order not to distort results by assuming decreasing emission factors. Additionally, I calculate CO_2-emission reduction assuming dynamic emission factors for electricity. Thus, three different indicators are investigated:

- CO_2-emission reduction assuming constant emission factors for district heating and electricity
- CO_2-emission reduction assuming dynamic emission factors for electricity
- CO_2-emission reduction excluding electricity and district heating

Table 7 shows CO_2-emissions factors used in the calculation.

Table 7 CO_2-emission factors for different energy fuels and countries

Energy fuel	**CO_2-emission factor, base year 2012 tCO2/MWh**	**CO_2-emission factor, tCO2/MWh$_e$ (for electricity in 2050, dynamic) (Toleikyte et al., 2017b), (Gantner, 2016)**
Coal	0.34	/
Gas	0.202	/
Oil	0.272	/
Renewable (biomass, solar, PV)	0	/
District heat	0.17	/
Electricity (France)	0.079	0.039
Electricity (Italy)	0.49	0.356
Electricity (Norway)	0.047	0.047
Electricity (Poland)	1.04	0.608
Electricity (Romania)	0.67	0.67
Electricity (Spain)	0.42	0.42

5.2.Results

5.2.1. Drivers for energy savings

The main drivers for energy savings and CO_2-emission reduction are renovation rate, renovation depth and heating system deployment. Moreover, future energy demand is also depending on the new building stock and its energy demand. In this section, three main scenario results are shown: the share of building renovation by renovation packages, the share of new building construction by energy performance standards and finally, the share of energy fuels.

Fig. 42 shows total cumulated floor area of renovated buildings by renovation packages in 2013, 2020, 2030, 2040 and 2050 compared to 2012 in all investigated countries. Renovation packages include maintenance (building envelope renovation without energy savings, e.g. painting of façade), light, medium and deep packages in the current policy scenario and medium, deep and deep plus in the ambitious policy scenario. Total cumulated renovation rate in 2030 in the current policy scenario is 27%, 41%, 31%, 25%, 37% and 34% in France, Italy, Norway, Poland, Romania and Spain, respectively. Total cumulated renovation rate in 2050 in the current policy scenario is 80%, 89%, 81%, 83%, 89% and 81% in France, Italy, Norway, Poland, Romania and Spain, respectively. In many countries, maintenance makes up the highest share of the total cumulated renovated floor area in 2030 and 2050. The cumulated renovation rate without maintenance in 2050 is 45%, 40%, 42%, 57%, 39% and 38% in France, Italy, Norway, Poland, Romania and Spain, respectively. In France and Italy, the light renovation package comprises the largest distributions of the total renovated building floor area while in Norway, Poland, Romania and Spain, the medium renovation package. Ambitious policy scenario which implements policies supporting deep and deep plus renovation and ensuring compliances with regulatory policies shows different composition of the renovation packages compared to the current policy scenario. The cumulated renovation rate without maintenance in 2050 in ambitious policy scenario is 58%, 61%, 71%, 65%, 74% and 72% in France, Italy, Norway, Poland, Romania and Spain, respectively. In Norway, the deep renovation package comprises the largest distributions of the total renovated building floor area while in France, Italy, Poland, Romania and Spain, the medium renovation package.

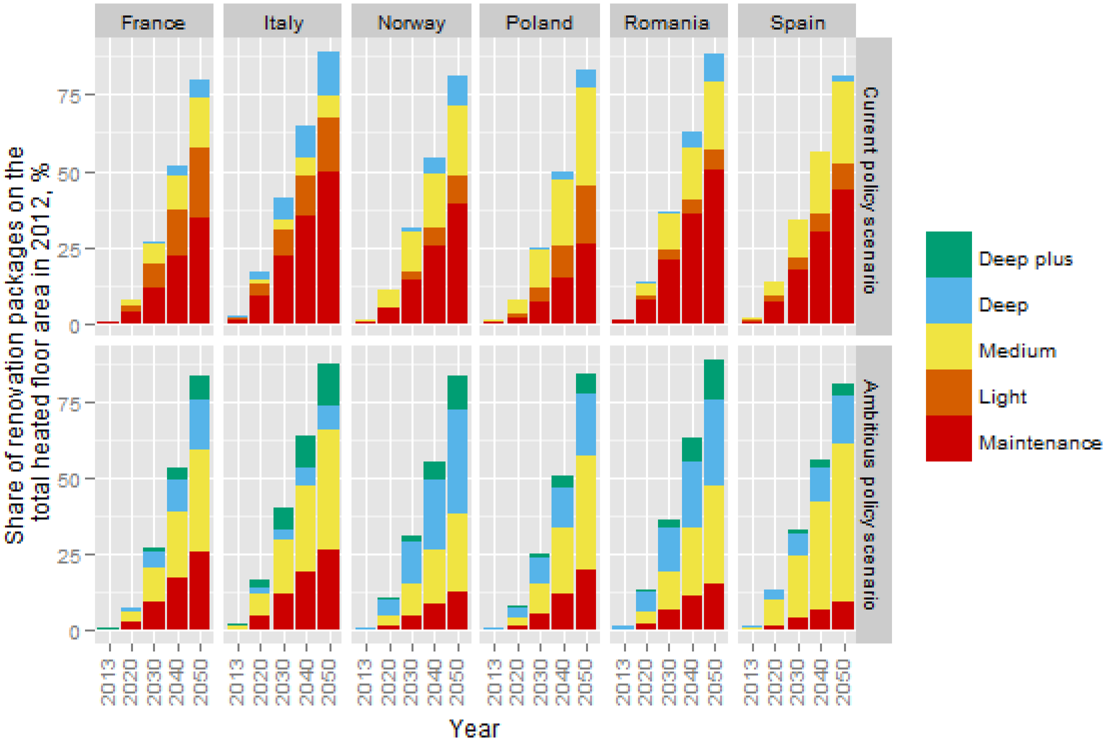


Fig. 42 Total cumulated building floor area by renovation packages in 2013, 2020, 2030, 2040 and 2050 compared to 2012 in France, Italy, Norway, Poland, Romania and Spain. Current and ambitious policy scenarios

Fig. 43 shows the share of the energy carrier on the total energy demand for space heating and hot water in the total building stock from 2013 to 2050 in both scenarios in France, Italy, Norway, Poland, Romania and Spain. In France, Italy, Poland and Spain, fossil fuel-based heating systems make up a significant share of the total energy demand for building space heating in 2012. Natural gas is the most common energy fuel in these countries. The share of natural gas on the total final energy demand for space heating and hot water was 44%, 61%, 2%, 20%, 30% and 37% in France, Italy, Norway, Poland, Romania and Spain respectively. Both scenarios show a decrease of natural gas demand in almost all countries. Unlike in these countries, in Norway, the highest share of the buildings is supplied by electricity. Renewable energy, biomass, solar and ambient, contribute to final energy demand in 2012 by 63%, 69%, 14%, 60%, 32% and 67% in France, Italy, Norway, Poland, Romania and Spain respectively. Both scenarios show an increase share of the renewable energy until 2050. The key drivers are policies supporting renewable heating systems and its economic feasibility.

In France, the share of fossil-fuel-based heating systems, especially natural gas is, significant in 2012. The fossil-fuel-based heating systems are slowly replaced with the renewable systems. The share of non-delivered energy (i.e. solar and ambient energy) is increasing over time from around 3% of final energy demand in 2012 to around 33% in current policy scenario and 35% in ambitious policy scenario in 2050.

In Italy, the share of fossil-fuel-based heating systems, especially natural gas and oil is significant in 2012. The share of non-delivered energy (i.e. solar and ambient energy) is around 5.8% of final energy demand in 2012, to around 26% in current policy scenario and around 30% in ambitious policy scenario in 2050.

In Norway, according to § 14-7 of the current Technical Building Regulations, it is not permitted to install a boiler of fossil oil to accommodate the basic energy load for space and water heating. From 2017, the prohibition of oil boilers is extended to all installations for fossil fuels sector for both, basic and peak load. On the other hand, energy supply by direct-acting electricity is no longer explicitly limited. These are the main reasons of the decrease of the fossil-fuel-based heating systems from 2012 to 2050. The share of non-delivered energy (i.e. solar and ambient energy) is around 7% of final energy demand in 2012 and around 25% and 27% in the current policy and ambitious policy scenarios respectively.

In Poland, there are no direct requirements in the building codes referring to the required share of renewable energy systems (RES). Additionally, current politics are supporting coal industry and stopping the RES. According to the national experts, there will be a law defining the quality of the coal supplied heating systems, and coal will not be forbidden in the building sector. These are the main reasons of the slowly decrease of the fossil-fuel-based heating systems from 2012 to 2050 in Poland. The share of non-delivered energy (i.e. solar and ambient energy) is around 1% of final energy demand in 2012 and around 6.7% and 13% in the current policy and ambitious policy scenarios respectively.

In Romania, the share of fossil-fuel-based heating systems, natural gas, oil and coal makes up around 35% of the total energy demand for space heating and hot water in 2012. The share of non-delivered energy (i.e. solar and ambient energy) is around 0.5% of final energy demand in 2012 to around 16% in current policy scenario and 20% in ambitious policy scenario in 2050.

In Spain, the share of fossil-fuel-based heating systems, natural gas, oil and coal makes up around 40% of the total energy demand for space heating and hot water in 2012. The share of non-delivered energy (i.e. solar and ambient energy) is around 2.5% of final energy demand in 2012 to around 40% in current policy scenario and 50% in ambitious policy scenario in 2050.

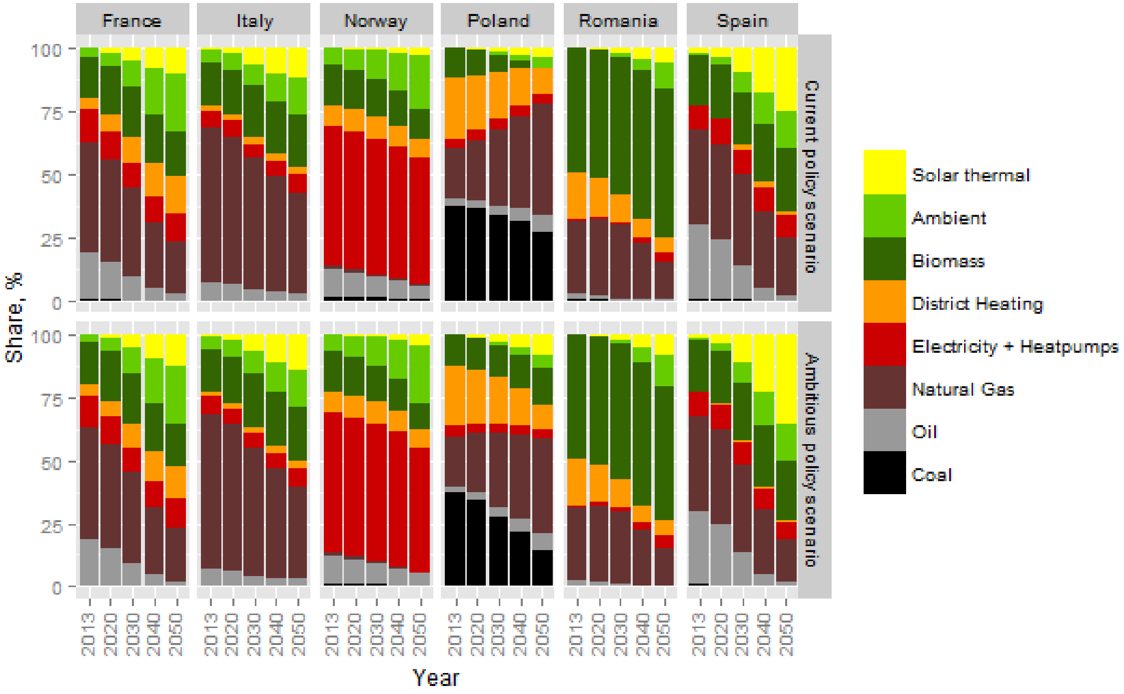


Fig. 43 Share of the energy carrier on the total energy demand for space heating and hot water in the total building stock from 2013 to 2050 in France, Italy, Norway, Poland, Romania and Spain. Current policy scenario and ambitious policy scenario

5.2.2. Energy demand and CO_2-savings scenarios

Fig. 44 shows scenario results in all investigated countries for the following parameters: reduction of the final energy demand for space heating & hot water, primary energy demand and CO_2-emissions. The reduction of the CO_2-emissions, final energy demand and primary energy demand varies from 27% to 70%, 27% to 61% and from 11% to 48% respectively from 2012 and 2050 in the investigated European countries within the current policy scenario. In the ambitious policy scenario, which implements more stringent measures and additional financial instruments on existing buildings, reduction of the CO_2-emissions, final energy demand and primary energy demand from 2012 to 2050 is as follows: 36% to 81%, 37% to 70% and from 17% to 60%, respectively.

The reduction potential in the building sector varies strongly from one country to another. The scenario's energy savings and CO_2-emission reduction is very much dependent on the status quo situation in this complex sector. There are several key drivers for the energy savings and CO_2-emission reduction (1) current energy performance of buildings (2) renovation rates and depth (3) the current role of different energy carriers (4) policy packages (5) energy prices and (5) the reduction in CO_2-intensity of electricity generation. It should be mentioned that the CO_2-emission factors for electricity are kept constant in this study.

Although the ambitious scenario includes more stringent policy instruments compared to the current policy scenario, the CO_2-reductions reach a level of around 80% only in the most ambitious cases. However, the climate targets clearly indicate that reductions in the building sector beyond 80-90% will be required. This shows that an achievement of agreements like that from COP21 require higher policy ambitions, going beyond the assumptions of ambitious policy scenarios developed in this project together with policy makers.

In France, the reduction of the CO_2-emissions from 2012 and 2050 is around 64% in the current policy scenario and around 71% in the ambitious policy scenario. The reduction of the primary energy demand is around 50% and 59% in the current and the ambitious policy scenarios respectively.

In Italy, the reduction of the CO_2-emissions from 2012 and 2050 is around 61% in the current policy scenario and around 68% in the ambitious policy scenario. The reduction of the primary energy demand is around 55% and 62% in the current and the ambitious policy scenarios respectively.

In Norway, the reduction of the CO_2-emissions from 2012 and 2050 is around 58% in the current policy scenario and around 62% in the ambitious policy scenario. The reduction of the primary energy demand is around 42% and 62% in the current and the ambitious policy scenarios respectively.

In Poland, The reduction of the CO_2-emissions from 2012 and 2050 is around 59% in the current policy scenario and around 61% in the ambitious policy scenario. The reduction of the primary energy demand is around 52% and 59% in the current and the ambitious policy scenarios respectively.

In Romania, the reduction of the CO_2-emissions from 2012 and 2050 is around 60% in the current policy scenario and around 62% in the ambitious policy scenario. The reduction of the primary energy demand is around 50% and 60% in the current and the ambitious policy scenarios respectively.

In Spain, the reduction of the CO_2-emissions from 2012 and 2050 is around 70% in the current policy scenario and around 80% in the ambitious policy scenario. The reduction of the primary energy demand is around 60% and 71% in the current and the ambitious policy scenarios respectively.

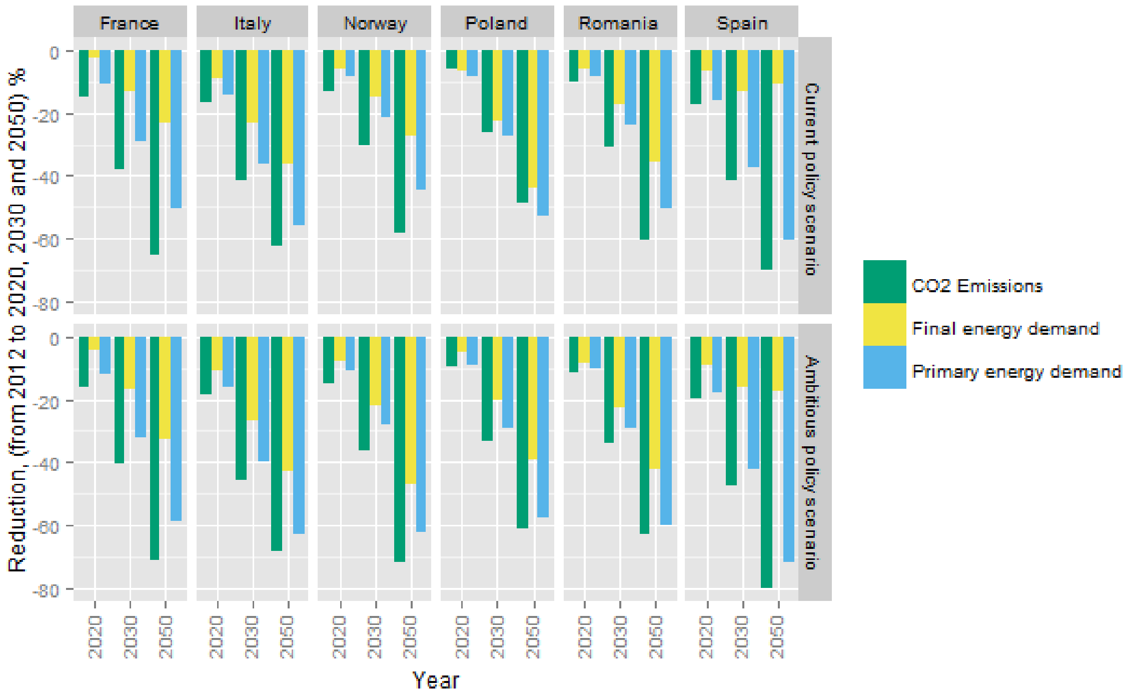


Fig. 44 Reduction of the final and primary energy savings for space heating and CO_2-emissions from 2012 to 2030 in the building sector in the BAU scenario in France, Italy, Norway, Poland, Romania and Spain

5.2.3. Consistency with the COP21 agreement

Fig. 45 shows CO_2-emission reduction from 2012 to 2050 in two investigated scenarios and three different indicators:

- Constant: CO_2-emission reduction assuming constant emission factors for district heating and electricity
- Dynamic: CO_2-emission reduction assuming dynamic emission factors for electricity
- Excl.elect&DH: CO_2-emission reduction excluding electricity and district heating

It can be seen that only few countries achieve levels of more than 85–90 % CO_2-savings to 2050. Looking at the constant CO_2-emission factors for electricity and district heating, none of the country can achieve sufficient CO_2-savings (>80%). With respect to the indicator showing CO_2-emission reduction excluding electricity and district heating, only Spain can achieve levels of more than 85-90% CO_2-emissions savings. And it can be achieved by implementing more ambitious policies compared to the currently existing policies.

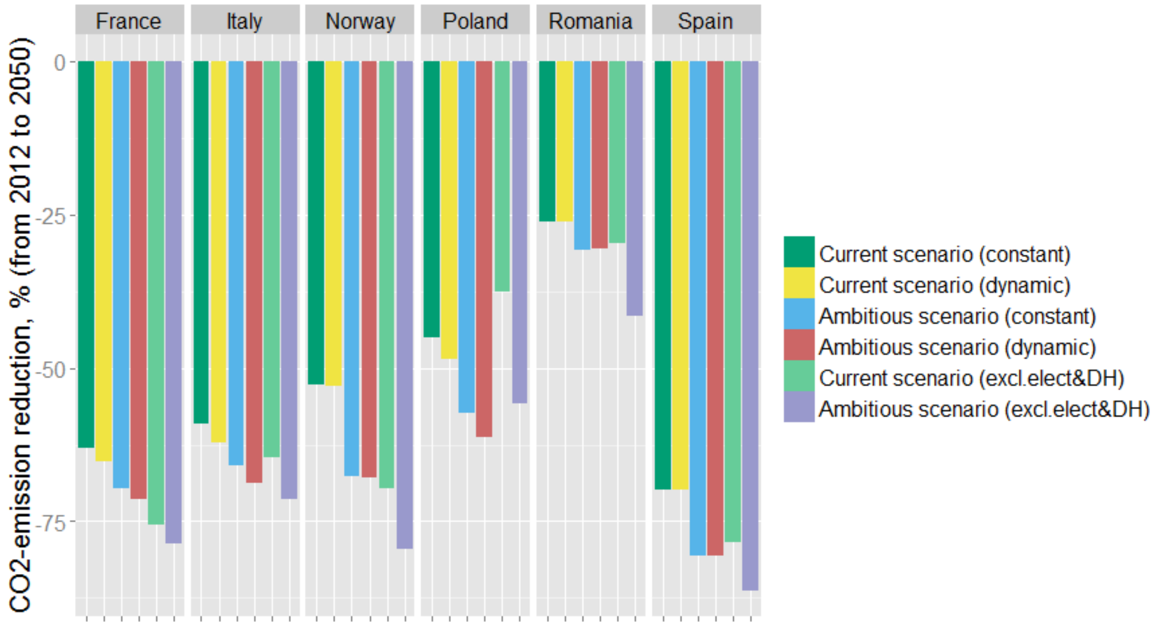


Fig. 45 CO2-emission reduction from 2012 to 2050 showing three different indicators for two scenarios, current and ambitious

5.3.Summary and discussion

In this chapter, the final and primary energy demand for space heating & hot water as well as CO_2-emissions in the total building stock was calculated for France, Italy, Norway, Poland, Romania and Spain.

The results show that in France, Italy, Poland and Spain, fossil fuel-based heating systems make up a significant share of the total energy demand for building space heating in 2012. Natural gas is the most common energy fuel in these countries. Both scenarios show a decrease of natural gas demand in almost all countries. The reduction of the CO_2-emissions, final energy demand and primary energy demand varies from 27% to 70%, 27% to 61% and from 11% to 48% respectively from 2012 and 2050 in the investigated European countries within the current policy scenario. In the ambitious policy scenario, which implements more stringent measures and additional financial instruments on existing buildings, reduction of the CO_2-emissions, final energy demand and primary energy demand from 2012 to 2050 is as follows: 36% to 81%, 37% to 70% and from 17% to 60%, respectively.

One of the main drivers is the future renovation rate. The total cumulated renovation rate from 2012 to 2050 in the current policy scenario is 80%, 89%, 81%, 83%, 89% and 81% in France, Italy, Norway, Poland, Romania and Spain, respectively. In many countries, maintenance makes up the highest share of the total cumulated renovated floor area in 2030 and 2050. The cumulated renovation rate without maintenance in 2050 is 45%, 40%, 42%, 57%, 39% and 38% in France, Italy, Norway, Poland, Romania and Spain, respectively. The ambitious policy scenario which implements policies supporting deep and deep plus renovation and ensuring compliances with regulatory policies, shows different composition of the renovation packages compared to the current policy scenario. The cumulated renovation rate without maintenance in 2050 in ambitious policy scenario is 58%, 61%, 71%, 65%, 74% and 72% in France, Italy, Norway, Poland, Romania and Spain, respectively.

The current energy performance of buildings has a strong impact on achievable energy savings and cost of building renovation. Thus, the higher the current efficiency of the building stock, the more expensive is a further improvement is and the stronger the political incentives have to be.

The role of different energy carriers shows its importance. In almost 50% of the investigated countries, fossil fuel-based heating systems make up a significant share of the total energy demand for building space heating in 2012. Natural gas is the most common energy fuel. 50% of the energy demand for space heating is supplied by the natural gas in France, Italy, Poland and Spain. The scenario shows a decrease of natural gas demand in almost all countries. In the current policy scenario, the share of natural gas demand is 35% from the total energy demand for space heating in 2050. The key drivers are policies supporting renewable heating systems and its economic feasibility. Renewable energy makes up a high share of the total energy demand for space heating in Romania. Building related CO_2-emissions are correspondently low in 2012 and this is the main reason that high CO_2-emission savings cannot be achieved in this country. Coal, which is mainly used in Poland, will only slowly run out in the investigated scenarios. Poland̕s current policies are supporting the coal industry which correspondingly keeps coal as an important fuel for the future space heating in this country.

The analysis on the consistency with COP21 agreement shows, that only few countries achieve levels of more than 85–90 % CO_2-savings to 2050. Looking at the constant CO_2-emission factors for electricity and district heating, none of the country can achieve sufficient CO_2-savings (>80%). With respect to the indicator showing CO_2-emission reduction excluding electricity and district heating, only Spain can achieve levels of more than 85-90% CO_2-emissions savings.

In the European roadmap for moving to a competitive low carbon economy in 2050 it is stated that electricity will play a central role in the low carbon economy. This might be a crucial condition also for the decarbonisation of the European building sector. Thus, these results call for a) an ambitious shift towards low-carbon electricity generation and b) in the light of climate change mitigation a binding United Nations CO_2-emission reduction agreement.

The main limitation of this study is as follows:

The literature review showed that climate will play an important role for the future energy demand in the building sector. In this analysis, the future energy demand was calculated under one future climate scenario taking the outdoor temperature forecast into account (based on Fleiter et al., 2017). However, a sensitivity analysis should be carried out using different climate scenarios.

Moreover, the literature review showed an increase in future energy demand for space cooling especially in the southern European countries. While considering the future building energy demand, cooling is an important part which should be taken into political discourse. Since cooling is supplied by electricity, the transition towards low-carbon electricity generation remains even more important.

6. Case Study III: Cost curves for the Lithuanian building sector

This chapter aims to calculate potential energy savings for space heating and hot water until 2030, for the Lithuanian residential building sector, by implementing energy efficiency solutions. Policy recommendations are derived by showing which buildings and energy efficiency measures should be addressed in order to determine the full energy saving potential in the most effective way. Different cost curves for energy savings potential are applied, and these curves show an investor perspective and overall economic perspective.

6.1.Input data

6.1.1. Building stock

In Lithuania, as in other European transition countries, apartment buildings built between 1960 and 1990 comprise the largest distribution of total building stock (Martinot, 1997), (Ürge-Vorsatz et al., 2006). These buildings have a high energy demand for heating and hot water preparation. The lack of basic energy efficiency requirements at the time of construction is the main reason that these buildings have such low energy performance. Typical of these constructions are cement blocks and concrete panels (Ürge-Vorsatz et al., 2006). After 1950 in the USSR and other eastern European countries, housing construction rapidly increased in order to improve living standards of citizens and to rebuild buildings destroyed during the Second World War (Smith, 2010). Nowadays these apartment buildings make up a significant part of the current residential building stock in Lithuania. The total gross floor area of a residential building, including single-family houses and apartment buildings, was approximately 128 mm² in 2012. The number of apartment buildings and single family buildings was 480,000 in 2012. Single-family houses make up 51% on the total residential building floor area, while apartment buildings represent 49%. Buildings built between 1961 and 1990 make up the largest share of the total residential building gross floor area, with 58.4%.

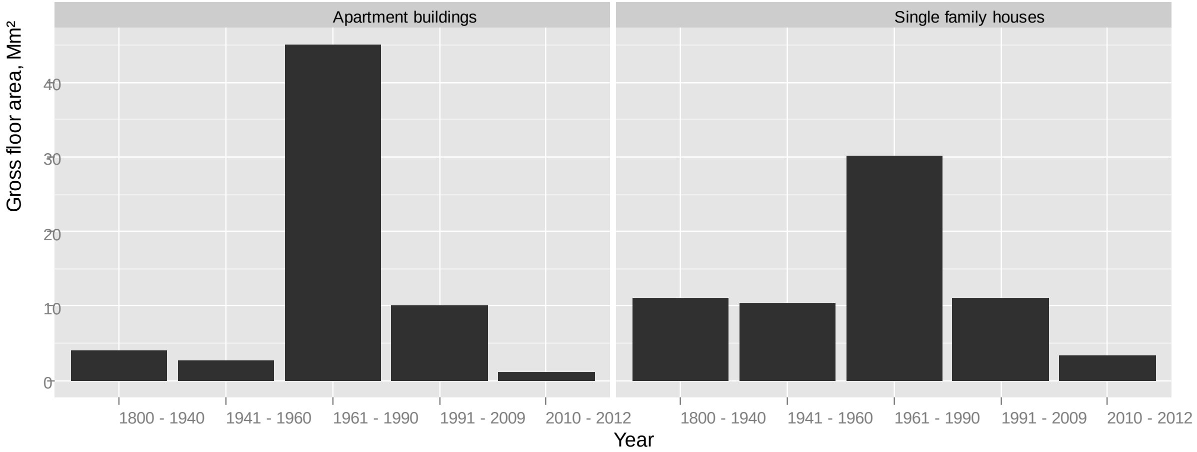


Fig. 46 Gross floor area of residential building stock shown by building periods and building types (based on 2012 data). Data sources: State Enterprise Centre of Registers, Lithuania (Valstybės įmonė registrų centras, 2014) and project ENTRANZE (ENTRANZE, 2016)

Building´s energy need for space heating was calculated for each building class with Invert-EE/Lab. The following data was used for this estimation; building geometry, transmission and ventilation properties, climate data, occupation behaviour and comfort requirements. This data was collected in the European project ENTRANZE (ENTRANZE, 2016). The U-values of building´s elements were determined for each building class. In Lithuania, buildings built in a particular period can be related to a particular building's energy performance class (see Table 8). There are 7 building's energy performance classes, G, F, D, C, A, A+ and A++. The Lithuanian report to European Commission on energy performance requirements outlines different buildings into a particular energy performance class (European Commission, 2013b). Energy performance classes are defined using U-values of the building´s elements (see Table 8).

Table 8 U-values of the building´s elements of buildings built in different periods and U-values requirements of the new buildings. U-values for different buildings are defined in the Lithuanian Certification of energy performance (European Commission, 2013b) and in the Technical Regulation of Construction STR 2.01.09:2005 (Ministry of Environment of the Republic of Lithuania, 2005)

Building element	**U-values of the building´s elements [W/m²K]**						
	G (building s built between 1800 – 1940)	**F (building s built between 1941 – 1960)**	**D (SFH/MFH) (building s built between 1990 – 2009)**	**C (buildings built prior to 2014)**	**A (buildings built from 2016)**	**A+ (Buildings built from 2018)**	**A++ (Buildings built from 2021. It is official Lithuanian nZEB definition)**
Roof	1.02	0.85	0.24/0.25	0.16	0.1	0.09	0.08
Floor (ground)	0.852	0.71	0.33/0.48	0.25	0.14	0.12	0.1
Floor (basement)	0.852	0.71	0.31/0.39	0.25	0.14	0.12	0.1
Wall	1.524	1.27	0.48	0.2	0.12	0.11	0.1
Windows	3	2.5	1.82/1.81	1.6	1	0.85	0.7

Of the total gross floor area of Lithuanian residential buildings, 45% are supplied by district heating. District heating is the main energy source of space heating and domestic hot water. Heat boilers with biomass supplied 43% of the total residential building floor area. Other energy carriers make up only a small proportion, with gas, coal, electricity and oil occupying 6%, 5%, 0.2% and 0.01%, respectively (Valstybės įmonė registrų centras, 2014), (ENTRANZE, 2016).

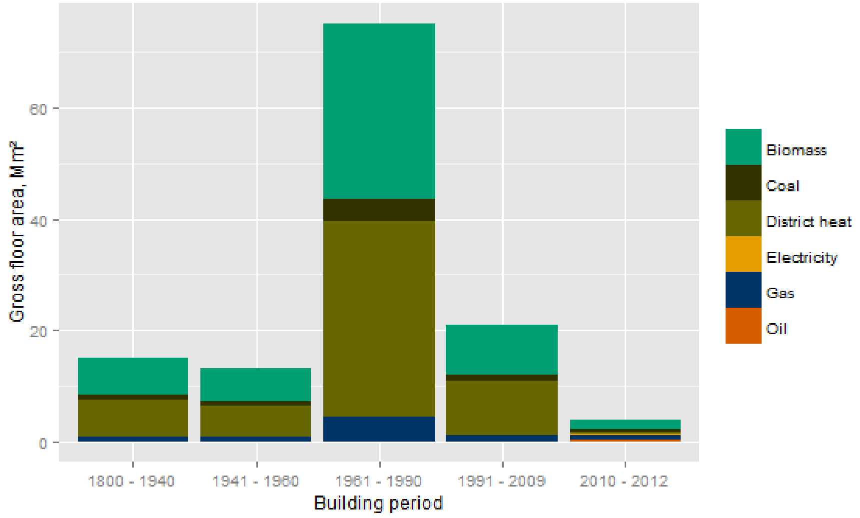


Fig. 47 Gross floor area of residential building stock by building periods and supplied energy in 2012. Data sources: State Enterprise Centre of Registers, Lithuania (Valstybės įmonė registrų centras, 2014) and project ENTRANZE (ENTRANZE, 2016)

6.1.2. Energy efficiency solutions

Fifteen renovation options were defined. The renovation options include the improvement of the building envelope and installation of a non-grid connected heating system (heat pump) as well as the installation of solar thermal panels for hot water. Improving energy efficiency on the building envelope is outlined by the respective class of energy performance of the building. The Construction Technical Regulation STR 2.01.09:2012 "Energy Performance of Buildings. Certification of Energy Performance" (Ministry of Environment of the Republic of Lithuania, 2005) defines the U-values of the building elements after renovation in order to achieve a particular class of energy performance of the building. Building classes start with class D as the lowest and end with class A++ renovations, which indicate very high energy performance with very low energy consumption. To calculate energy performance on the renovated buildings, a prescriptive-based approach is used. The U-values of building elements before renovation and after renovation are defined. Energy performance of buildings before and after renovation is calculated using Invert-EE/Lab model. Descriptions of the renovation option used in the calculation and associated U-values of the building elements are given in Table 9.

Table 9 Renovation options from 1 to 15 including energy efficiency improvements of the building envelope and installation of decentralized heating system

Renovation index	Renovation options	Description
1-5	D, C, A, A+, A++	Improving energy efficiency of the building envelope (D, C, A, A+, A++) and increasing control efficiency of heating system and domestic hot water supply system (U-values of building elements, [W/m²K], D: U_{window}= 1.81, U_{wall}=0.48, U_{roof}=0.25; U_{floor}= 0.39; C: U_{window}= 1.6, U_{wall}=0.2, U_{roof}=0.16; U_{floor}= 0.25; A: U_{window}= 1.0, U_{wall}=0.12, U_{roof}=0.1; U_{floor}= 0.14; A+: U_{window}= 0.85, U_{wall}=0.11, U_{roof}=0.09; U_{floor}= 0.12; A++: U_{window}= 0.7, U_{wall}=0.1, U_{roof}=0.08; U_{floor}= 0.1)
6-10	D, C, A, A+, A++ (each in combination with heat pump)	Improving energy efficiency of the building envelope (D, C, A, A+, A++) and installation of non-grid connected heating system (heat pump, ground, COP=4)
11-15	D, C, A, A+, A++ in	Improving energy efficiency of the building envelope (D, C, A, A+, A++),

Renovation index	Renovation options	Description
	combination with heat pump and solar thermal system	installation of non-grid connected heating system (heat pump, ground, COP=4) and installation of solar thermal panels for hot water

The specific investment costs of the renovation options were calculated using data from the Lithuanian report to European Commission on energy performance requirements (European Commission, 2013b). This report provides data on the initial investment costs per saved energy while implementing different renovation options and non-grid connected heating systems for 36 reference buildings of different constructions (European Commission, 2013b). To assess the specific investment cost of the renovation options for building types used in my thesis, the following calculation steps were carried out:

- Energy savings for space heating for all renovation options and for all investigated building classes were calculated.
- Data from the Lithuanian report to European Commission on energy performance requirements (European Commission, 2013b) on specific energy savings and associated investment costs were collected.
- Cost functions were derived to identify the specific costs of saved energy after implementing all investigated renovation options for the different type of buildings. Final initial specific investment cost of the building renovation is a function of the specific energy savings for space heating and associated investment costs. The costs are shown in the cost diagrams. Fig. 48 and Fig. 49 show cost of energy efficiency solutions for apartment buildings and single family houses.
- Final initial specific investment cost of the gas heating system, heat pump and solar thermal panels is a function of heated floor area and associated specific costs (Fig. 65 - Fig. 69 in Appendix A. Cost figures).

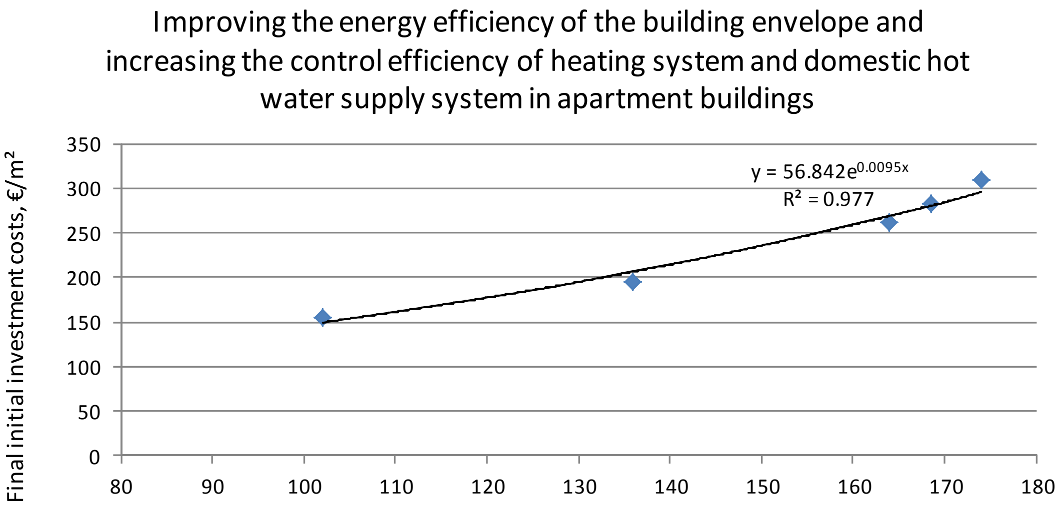


Fig. 48 Investment costs in relation to energy savings for space heating and domestic hot water in apartment buildings (own calculations based on data from (European Commission, 2013b))

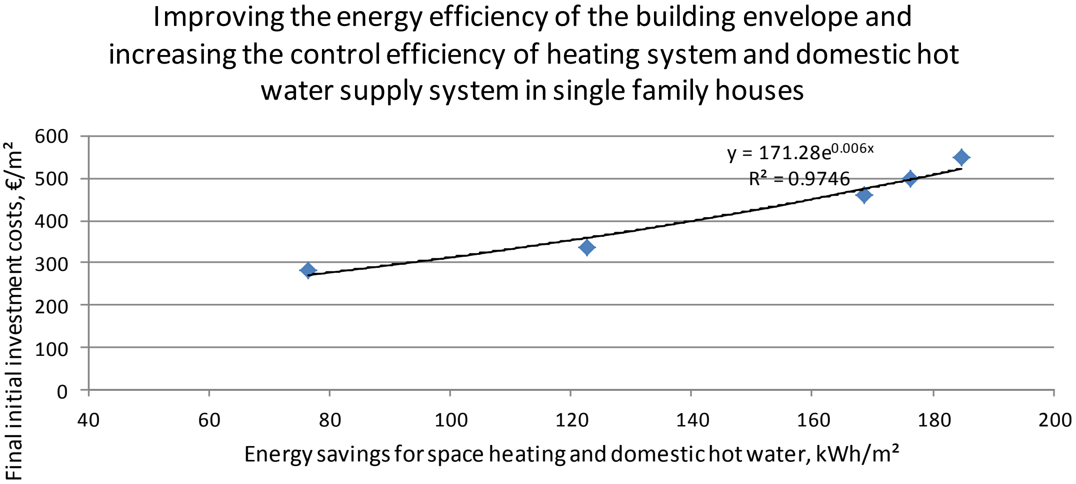


Fig. 49 Investment costs in relation to energy savings for space heating and domestic hot water in single family buildings (own calculations based on data from (European Commission, 2013b))

6.1.3. Economic parameters

Energy fuel prices for district heating, gas and biomass in 2012 were 0.09 €/kWh, 0.05 €/kWh and 0.03 €/kWh respectively (prices include value-added taxes [VAT]) (European Commission, 2013b). These prices were set using the statistics provided by the Lithuanian National Commission for Energy Control and Prices. Lithuanian report to European Commission on energy performance requirements also provides energy fuel price developments from 2012 to 2030. The fuel prices increase from 2012 to 2030 by 54%, 67% and 28% for district heat, gas and biomass, respectively. The trend of the future price development was linked to the energy price trends provided by the European Commission. The discount rate used in this calculation is 3%.

6.2. Results

6.2.1. Techno-economics of the energy efficiency solutions

By using a monthly balance method, specific energy need for space heating for each building type was calculated (Fig. 50). Specific energy need for space heating with 248 kWh/m² is the highest in the single family house built between 1800 and 1940. The calculation shows that the specific energy demand in an apartment building built between 1941 and 1960 is 120 kWh/m^2/year. An apartment building built between 1961 and 1990 demands app. 110 kWh/m^2/year.

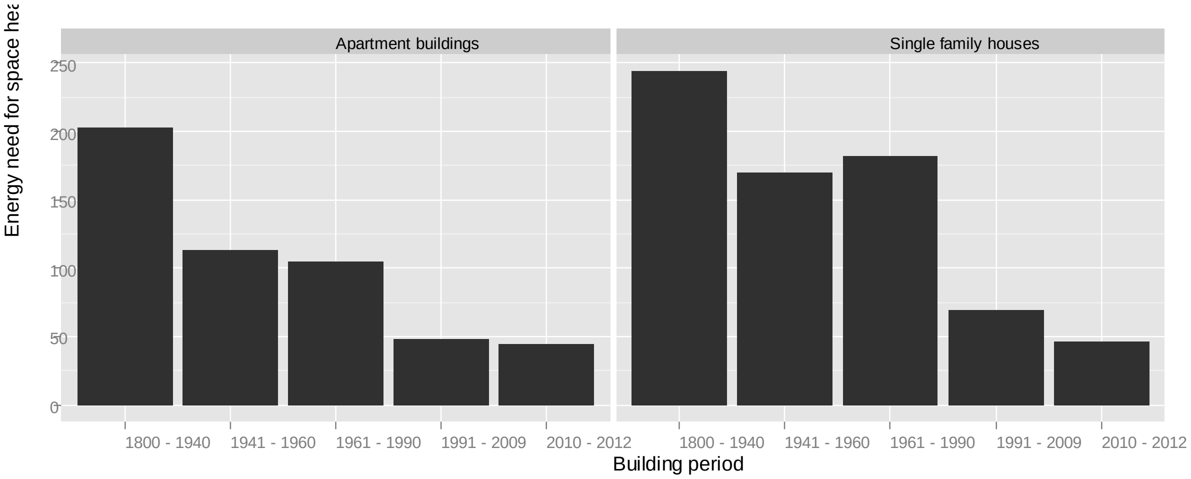


Fig. 50 Energy need for space heating (effective) for different building types of the Lithuanian building stock

The costs of investments were calculated for each building type implementing all considered energy efficiency solutions. Fig. 51 and Fig. 52 both look at apartment buildings (MFH) and single family buildings (SFH) built between 1941 and 1960, supplied by district heating, gas and biomass. They show the cost of conserved energy and cost-effectiveness of investments in the energy efficiency options (y-axis) and specific energy savings for space heating and hot water achieved by these options (x-axis). The costs were calculated using the discount rate of 3% and a calculation lifetime of 30 years. The calculation using the cost of conserved energy shows slightly different results compared to the calculation using levelized costs.

The calculations using cost of conserved energy, show that the cheapest investments can be achieved for apartment buildings which use biomass as energy fuel for space heating. The cost of conserved energy in investments of this building type vary from 0.05 €/kWh to 0.08 €/kWh. The lowest cost option would be to implement building class C, changing the heating system from biomass boilers to heat pumps. The most expensive energy efficiency solution for this building type is implementing building class A++, this would involve changing the heating systems to heat pumps and installing solar systems. The same apartment building which is supplied by district heating and gas have a slightly higher cost of conserved energy in energy efficiency solutions, compared to buildings with biomass heating, due to the efficiency of the heating system and corresponding lower energy savings.

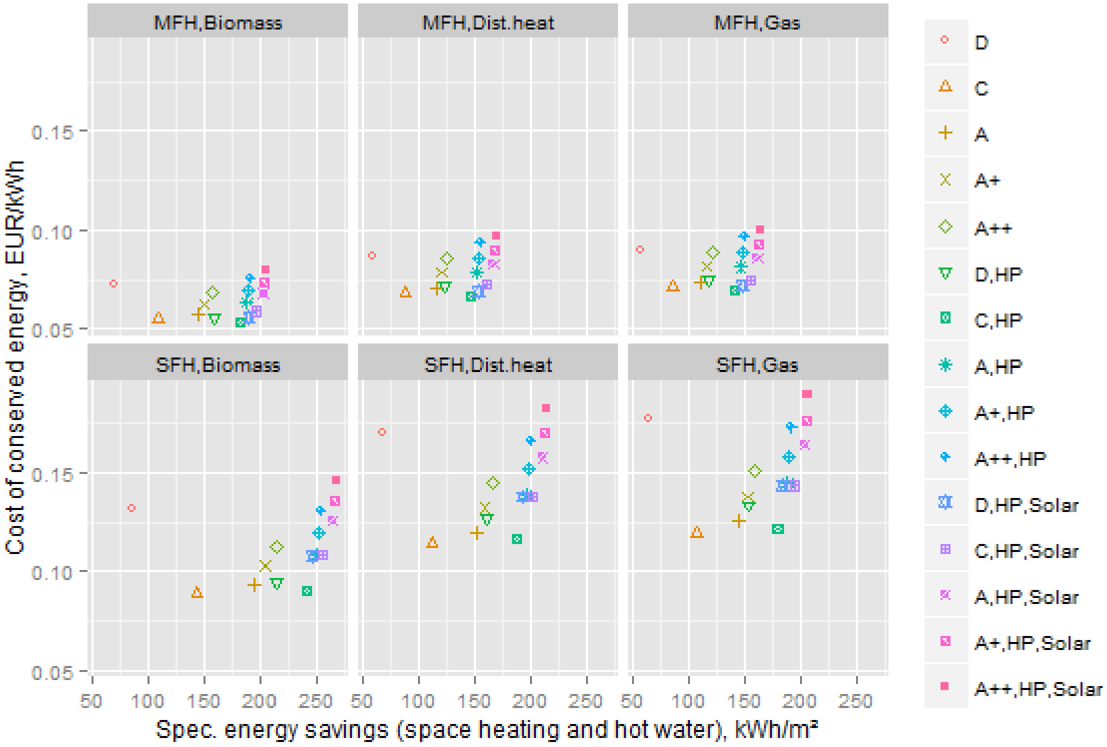


Fig. 51 Specific energy savings (x-axis) and cost of conserved energy of investments (y-axis) in different energy efficiency solutions for different types of buildings

When it comes to the levelized costs, the estimation shows different results. In this case, buildings using biomass heating are related to the highest cost of investments compared to the buildings supplied by district heating and gas. The energy fuel price has an impact on the cost-effectiveness. The biomass price is low compared to the price of district heating and gas heating.

The highest cost-effectiveness of the investments in energy efficiency options can be achieved in the apartment buildings supplied by the district heating. The lowest cost option for this type of building is investing in building class A. Levelized costs in energy efficiency solutions achieving energy performance classes A, A+ and A++ are negative, varying from -5.6 €/m² to -4.3 €/m². Specific yearly energy demand for space heating and hot water before renovation is 180 KWh/m² in this type of apartment building (built between 1941 and 1960, supplied by district heating). Specific energy savings for space heating and hot water by achieving the following building classes, A, A+ and A++ are 115 kWh/m², 120 kWh/m² and 125 kWh/m², respectively.

The same building class (Apartment building, 1941-1960) using gas and biomass fuels shows higher levelized costs compared to the buildings with district heating. This is due to the fuel prices, which were in Lithuania in 2012, 0.09 €/kWh, 0.05 €/kWh and 0.03 €/kWh (average fuel price including VAT) for district heat, gas and biomass respectively. The least cost option for the apartment building with gas and biomass is building class C. The levelized costs are 0.08 €/m² and 1.6 €/m² for buildings with gas and biomass, respectively. The specific final energy savings are 85 kWh/m² and 108 kWh/m² for buildings with gas and biomass, respectively.

The highest energy savings can be achieved using A++ renovation and installing non-grid connected heating system, heat pump and solar thermal panels. Single family houses built between 1941 and

1960, supplied by district heating can be renovated in a cost-effective way, achieving energy performance class C. The levelized costs per saved energy are -0.64 €/m². Specific energy savings for space heating and hot water by achieving these building classes are 112 kWh/m². These results show that apartment buildings can be renovated in a more cost-effective way than single family houses. The main reason is the specific initial investment costs which correlate to the size of the building. Consequently, the specific initial investment costs are higher for the single family houses. Levelized costs are high and energy savings are low in apartment and single family houses built after 1991. Thus, the newer are the buildings are the higher are the levelized costs due to the low energy savings.

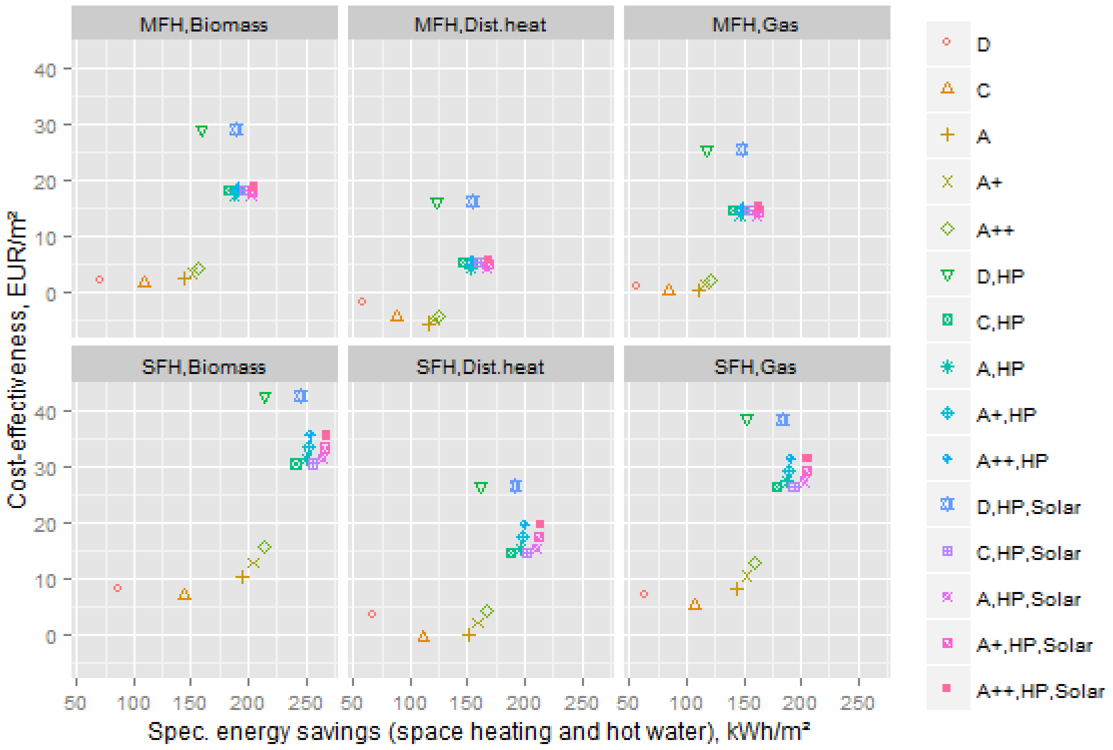


Fig. 52 Specific energy savings (x-axis) and cost-effectiveness (y-axis) of investments in different energy efficiency solutions for different types of buildings

6.2.2. Energy saving cost curves

The final energy demand for space heating and hot water in the residential building stock was 7.7 TWh in 2012. The development of the final energy demand to 2030 is based on the renovation rate and selected renovation options. The calculated cumulated renovation rate up to 2030 varied from approximately 50% for the buildings built between 1800 and 1940 to 7.5% for the buildings built after 2010 (see Table 10).

Table 10 Cumulated renovation rate in 2030 compared to 2012 and yearly renovation rate for different type of buildings built in different building periods

	Single family houses					**Apartment buildings**				
	1800 - 1940	**1941 - 1960**	**1961 - 1990**	**1991 - 2009**	**2010 - 2012**	**1800 - 1940**	**1941 - 1960**	**1961 - 1990**	**1991 - 2009**	**2010 - 2012**

Share of renovated buildings by 2030, %	52%	43%	31%	12%	7%	49%	36%	31%	12%	7%
Renovation rate, %	3.1%	2.5%	1.8%	0.7%	0.4%	2.9%	2.1%	1.8%	0.7%	0.4%

In a further step, I calculated the total energy saving potential to the year 2030 for the entire residential building stock using two different cost curves, the cost curve showing the building investors ‘perspective and the energy saving cost curve showing overall economic perspective.

The cost curve showing the building investors ‘perspective selects the most cost-effective renovation option for each investigated reference building. The cost curve showing overall economic perspective, selects the renovation options for each building which are related to the highest energy savings.

Fig. 53 and Fig. 54 present the energy savings using the cost curves which show the building investors ‘perspective. It shows that the final energy demand can be reduced by 2030, either by 61%, if the energy efficiency solutions are based on the costs of conserved energy (Fig. 53) or by 56%, if the energy efficiency solutions are based on levelized costs (Fig. 54). Legend description of both figures is given in Appendix B. Building types.

Fig. 53 shows cumulated energy savings from 2012 to 2030 in all investigated building types (x-axis) and the cost of conserved energy of the investments in the selected renovation option (y-axis). Each bar represents building type and selected lowest cost renovation option

The results show that investments in apartment buildings (built during years 1800-1940, 1941-1960 and 1961-1990) that are supplied by biomass heating (the three first bars), implement efficiency class C and change the heating system would be most cost-effective, leading to a total final energy savings of 9%. The highest energy savings can be achieved by renovating apartment buildings that were built between 1961 and 1990 and are supplied by district heating (8 bar, Fig. 53). The total final energy savings were calculated as 685 GWh or 9% by 2030 with the selected renovation option of energy efficiency class C and with the replacement of the heating system. However, the three cheapest investments have initial investments that are higher than energy costs because of biomass price. For this reason, from the investors’ point of view, these investments do not save costs. Fig. 54 shows the selected energy efficiency measures that use the levelized costs and thus show the investors’ perspective. The results show that the most cost-effective options are investing in apartment buildings (built in years 1800-1940, 1941-1960 and 1961-1990) that are supplied by district heating. The costs per heated area vary from -12.3 €/m² to -4.4 €/kWh for these building types. The results show that 24% of the total energy savings by 2030 can be achieved in a cost-effective way.

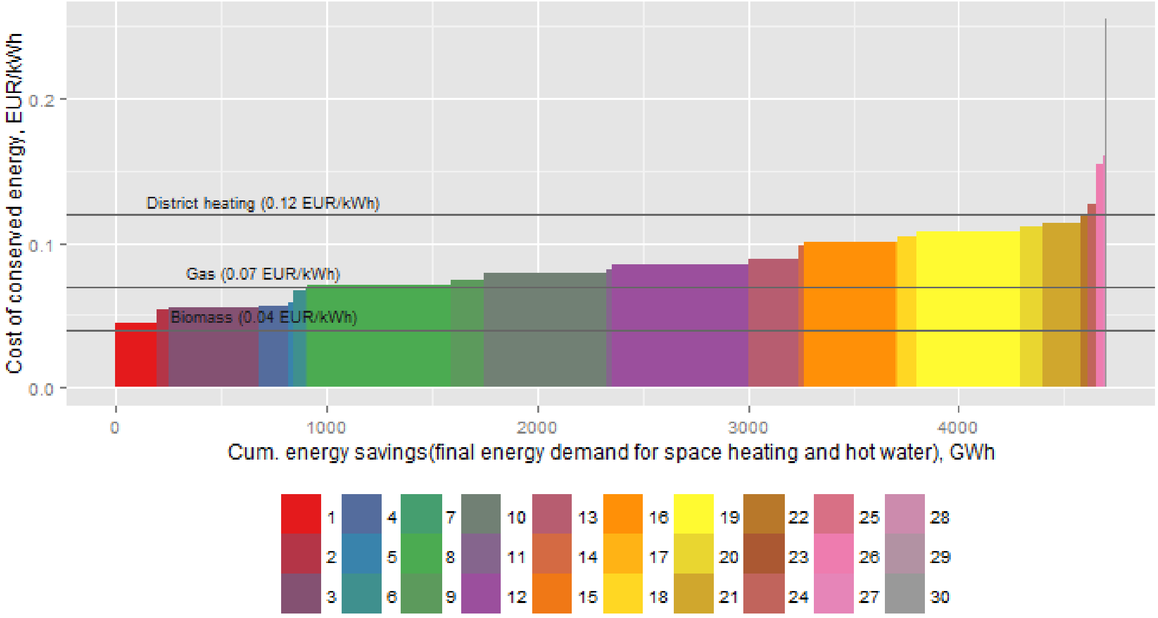


Fig. 53 Energy saving cost curve showing the building investors ‘perspective using cost of conserved energy

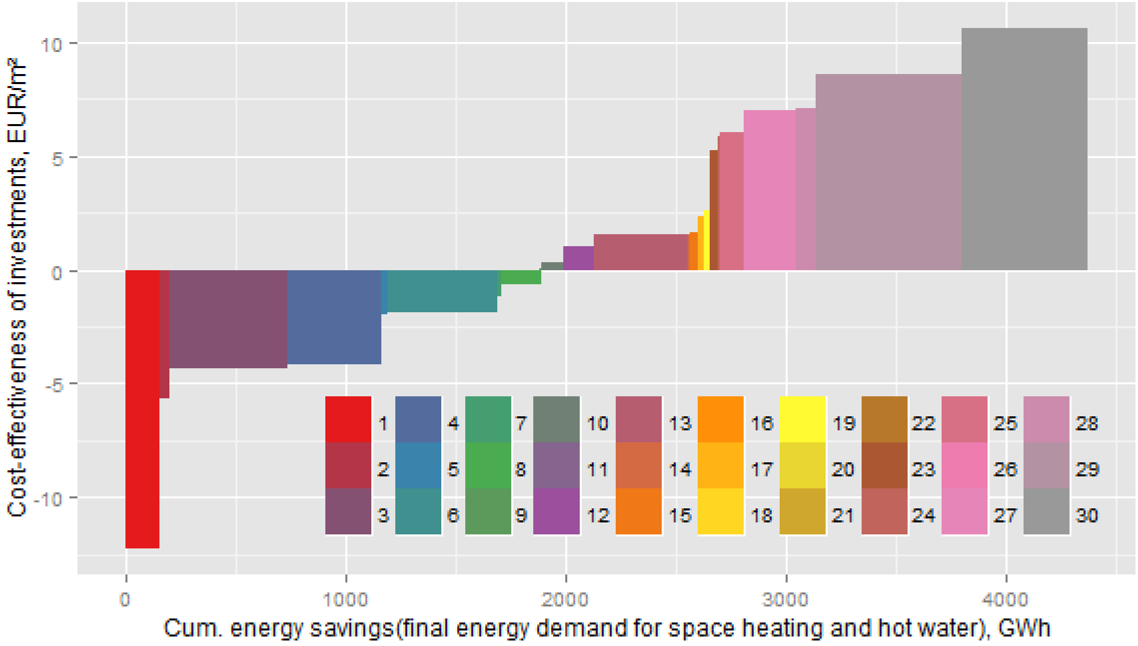


Fig. 54 Energy saving cost curve showing the building investors ‘perspective using levelized cost per heated floor area

The cost curve approach using the lowest cost option neglects many energy efficiency solutions which would result in higher energy savings and additional investments. Moreover, by using this type of cost curve, we encourage lock-in effects by neglecting energy efficiency solutions which would lead to higher energy savings. Therefore, to avoid these effects, we utilized the adapted cost curve to show a societal and overall economic perspective.

All building types and implemented measures were ordered based on their cost-effectiveness. Yet renovation option for the corresponding building type was selected, which has the highest energy savings. This cost curve might show the renovation options for particular building type which are selected in order to achieve energy savings targets.

Fig. 55 shows building types and energy efficiency options which were identified to achieve 30% of the total energy savings by 2030. The results show that energy efficiency class A++ implemented in apartment buildings (built in years 1941-1960 and 1961-1990) and supplied by district hearing are the most cost-effective measures and can save 620 GWh from 2012 to 2030. Energy efficiency class A in single-family houses (built 1800-1940 and 1961-1990) supplied by district heating are the most cost-effective energy efficiency improvements. When one selected building type is considered, it can be seen that investment in renovation option with higher energy savings is still cost-effective and leads to higher energy savings.

Lowest-cost option, from an investor's point of view, was proved to be the selection of energy performance class A for apartment buildings built between 1961 and 1990 and supplied by district heating. However, the lowest-cost option for the same building is energy performance class A+ if I consider the energy saving cost curve showing overall economic perspective. The levelized costs of investments in renovation to achieve A and A++ energy performance classes are -4.3 €/m² and -3.1 €/m², respectively. Total energy savings for space heating and hot water by 2030 are 530 GWh and 572 GWh after implementation A and A++ energy performance classes.

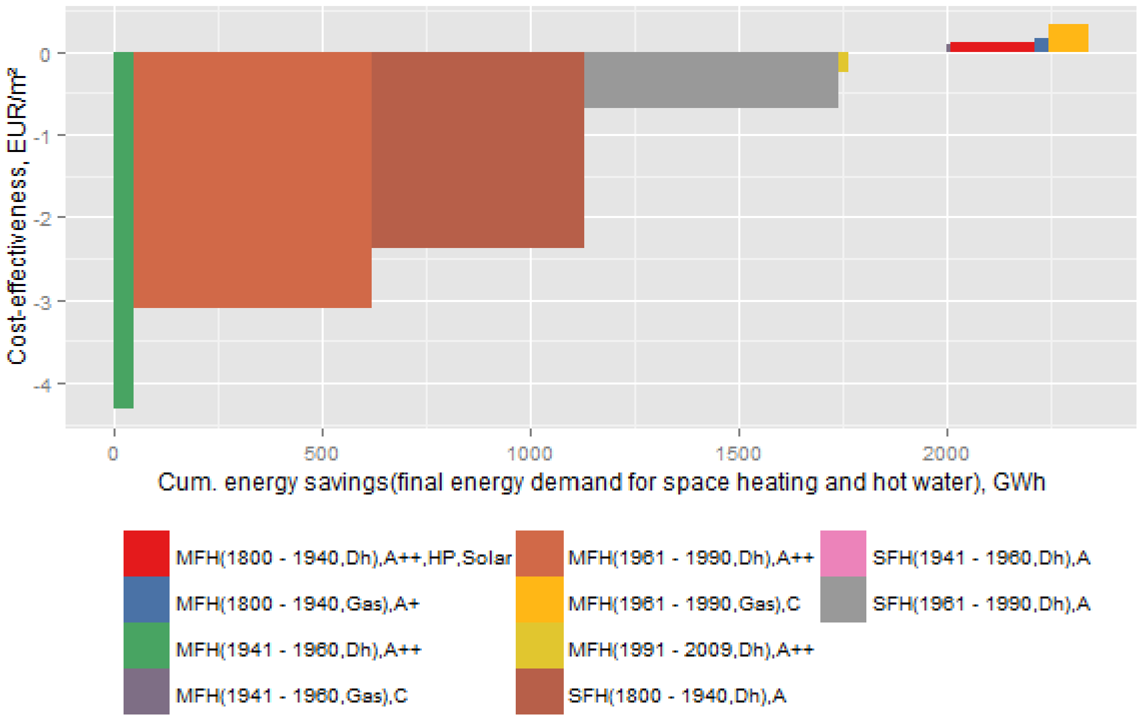


Fig. 55 Energy saving cost curve showing the lowest-cost renovation options to achieve a certain energy saving target (overall economic perspective)

6.2.3. Policy recommendations

Policy recommendations can be derived based on the calculation results. The calculations were carried out for the Lithuanian residential building sector, and so policy recommendations address this country specifically. However, policy recommendations can be directly applied to other European transitions economies due to their similarities in building stock, policies and costs. Moreover, the methodology can be applied to other European countries using country specific input data on the building stock and costs.

The results show that renovating old apartment buildings that are supplied by district heating are clearly the most cost-effective option. The very low energy performance of these buildings, their size and accordingly relatively low specific investment costs as well as high district heating prices makes them an ideal investment. It seems that an investment in energy efficiency solutions is a very good option for homeowners to save money. However, there are several barriers stopping renovation activities. One of the barriers is the compensation on fuel prices. These calculations were made by using the standard district heating price. By having a lower district heating price, investments in energy efficiency measures are not cost-effective. This instrument is a barrier for the implementation of energy efficiency measures. Instead of using subsidies for heating costs, subsidies for building thermal renovations could be provided to address low-income homeowners and residential buildings with low energy performances. Possible examples of how to select the buildings receiving financial support from the state for thermal renovation are:

- Buildings of a minimum EPC with G and lower,
- Buildings whose total cost of heating is 25% or more of its value
- Buildings whose total cost of heating takes up a high share of the resident’s income.

The second outcome shows that there is a need to promote building owners’ investments in deep renovation measures (energy performance class A+ and A++) in order to maximise the full energy saving potentials and ensure the transition of the Lithuanian building stock towards nZEBs. The outcome of these investments would be environmentally, socially and economically beneficial. Although investments in A+, A++ renovation are cost-effective for different types of buildings, the up-front investments are often disliked by investors. For this reason, to trigger the uptake of deep renovations, the following legislative, economic and communicative suggestions are presented:

- Provide building owners and investors with tailored advice. The Energy Performance Certificates (EPCs) aim at providing information on the energy performance of a building for its owners. At present, EPCs are required for buildings that are being renovated and new buildings in Lithuania. These EPCs could be ditributed for all buildings in order to provide information and tailored advice about the full range of renovation options available and their benefits.
- Provide financial products that address deep renovation (A++ or nZEB renovation). Provide low-interest loans to housing associations or grants with various rates dependent on the expected energy savings.
- Promote market uptake of deep renovation with information campaigns and demonstration projects to inform investors and housing associations.

6.3.Summary and discussions

In this chapter, total energy saving potential by year 2030 for space heating and hot water was calculated in the Lithuanian residential building stock. Two different approaches of deriving cost curves were presented; the cost curve showing the building investors ‘perspective and the energy saving cost curve showing overall economic perspective. Both led to different findings.

The final energy demand for space heating and hot water in residential building stock was 7.7 TWh in 2012. By using the cost curve showing the building investors ‘perspective, cost-effectiveness of different energy efficiency options was assessed for different building types, and the lowest-cost option for each building type was selected. Two different indicators were used to select the lowest-cost option; cost of conserved energy and levelized costs. By using the first indicator, 61% of the energy savings for space heating and hot water can be achieved from 2012 to 2030, whilst using the second indicator would result in savings of 56%. The use of the cost of conserved energy for selecting the lowest-cost options led to higher energy savings compared to the use of the levelized costs. However, the cost of conserved energy did not show the lowest-cost option from the investor point of view.

By using the lowest-cost option approach the lock-in effect might occur by neglecting energy efficiency solutions, which can lead to higher energy savings and small additional costs for investors compared to the lowest-cost option. For this reason, I used the second cost curve showing overall economic perspective. This approach shows the renovation options with the highest energy savings for the total building stock to achieve the target energy savings. To achieve energy savings of 30% from 2012 to 2030, the following investments were found to be the most cost effective: energy efficiency class A++ for apartment buildings (1941-1960 and 1961-1990) that are supplied by district heating, followed by efficiency class A for single-family houses (1800-1940 and 1961-1990) that are supplied by district heating.

The second approach shows that to achieve energy savings targets, attention should be paid to the refurbishment of old apartment buildings built before 1990 and supplied by district heat because these buildings provide the highest energy savings; by renovating these buildings, the most money can be saved. Moreover, implementation of energy efficiency solutions which lead to high energy savings (energy performance class A+ and A++) should be promoted because these solutions are correlated with high additional energy savings and relatively low additional investments compared to energy performance classes C and A, which were chosen to be the lowest-cost option from the investor’s point of view in the first approach. This is important in order to avoid the lock-in effect.

The results call for (I) policies to support building renovation that address buildings with low energy performance instead of subsidising energy prices and (II) policies promoting deep renovation (A+, A++) in order to avoid lock-in effects and ensure the transition of Lithuanian building stock towards nearly zero-energy buildings (nZEBs).

7. Case Study IV: Modelling of energy demand of shopping centres

This chapter aims to calculate final current and future energy demand in the shopping centre’s building stock is calculated using a bottom-up approach. The European shopping centres are categorised based on the building period, building size and types of shops in the building. Energy demand for space heating, space cooling, lighting, ventilation, refrigeration and appliances is calculated. Modelling of the future energy demand is based (I) on the development of the shopping centre building stock, taking into account the renovated floor area and new building construction and (II) on the specific energy demand savings achieved by applying new technologies for space heating and cooling, appliances, lighting and refrigeration.

The specific energy demand for space heating and cooling is calculated using monthly energy balance approach by applying building simulation tool Invert-EE/Lab. Energy demand for lighting, ventilation, refrigeration and appliances is calculated by taking the typical power load in each shop and multiplying it with the specific power duration.

Four different scenarios are derived showing the impact of the most important drivers such as renovation rates and implemented energy efficiency solutions. The chapter provides recommendations on how to increase the use of energy efficiency measures in European shopping centres, thus assisting the sector to contribute to the European 2030 climate and energy targets addressing the following stakeholders, owner/tenants, real estate investors and policy makers.

This chapter is partly based on the following publications: (Bointner et al., 2014), (Toleikyte and Bointner, 2016), (Toleikyte et al., 2017a)

7.1.Input data

7.1.1. Disaggregation of building stock

Starting with the investigation of the energy demand modelling in the shopping centre, it should be defined what a shopping centre is. There currently exist a wide number of different shopping centre size, forms and functions (Bointner et al., 2014). To model the energy demand of a shopping centre building, the definitions should provide clarity about the retail units inside the shopping center, the size of the shopping centre, the location and type. According to Clifford M. Guy, 1998, a shopping centre building can be classified by type of goods, shopping trip purposes, by size and type of stores and by store ownership. A shopping centre is also defined as a building type in EPBD-recast 2010/31/EU (Council Directive 2010/31/EU, 2010). According to EPBD-recast, shopping centre buildings belong to the class of wholesale and retail trade buildings. International Council of shopping centres (ICSC) which aims to advance the shopping center industry in over 100 countries by providing publications and statistics on shopping centre development, defines a shopping centre as *"a scheme that is planned, built and managed as a single entity, comprising units and communal areas, with a minimum gross leasable area*[1] *(GLA) of 5,000 square meters"* (International Council of Shopping Centers, 2005).

The shopping centre building stock is categorised into small, medium, large and very large buildings. This categorization is based on the International Council of Shopping Centres (ICSC) statistics which divides European traditional shopping centres into four scheme sizes: very large (80,000 m² and above), large (40,000–79,999 m²), medium (20,000–39,999 m²) and small (5,000–19,999 m²) (International Council of Shopping Centers, 2005). These categories are then disaggregated into three building periods, buildings built before 1990, 1991-2002 and buildings built 2003-2012. In total, 12 shopping centre categories are defined for each country (EU28 and Norway) (see Fig. 56). All shopping centres in EU-28 and Norway were aggregated into four shopping centre types including three building construction periods:

- Small (before 1990; 1991 – 2002; 2003 – 2012);
- Medium (before 1990; 1991 – 2002; 2003 – 2012);
- Large (before 1990; 1991 – 2002; 2003 – 2012);
- Very large (before 1990; 1991 – 2002; 2003 – 2012).

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[1] *Gross leasable area (GLA) is the amount of floor area available to be rented and designed for tenant occupancy*

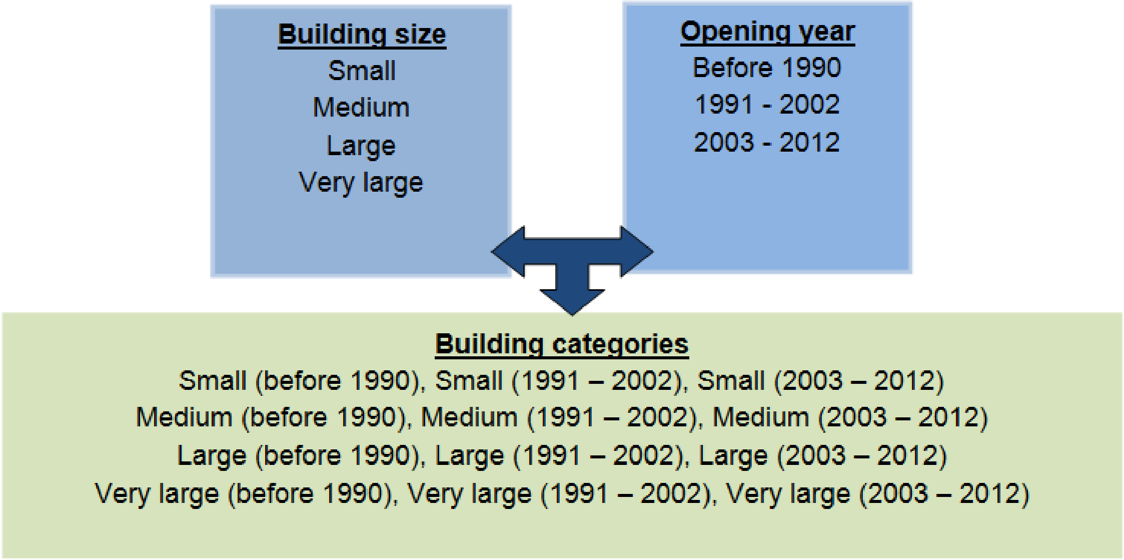

Fig. 56 Building categories as combination of the building size and opening year

The typical composition of the shops within the different shopping centres categories is analysed. This analysis is crucial for a bottom-up calculation of the energy demand in the shopping centres because shopping centres have many differentiated functions such as food refrigeration, marketing of products and improved comfort. According to Schönberger et al., 2013, the composition of the energy consumption varies from one retailer to another, non-food retailers, have a different share of energy use compared to food retailers. Five different shop categories and their share of the floor area on the shopping centre categories are defined (Bointner et al., 2014):

- retail stores (including clothing, hobby and home shops),
- common areas,
- medium stores (including supermarkets),
- restaurants (inc. cafes and food courts) and
- other services (inc. warehouse, service rooms).

Table 11 shows the shopping centre store composition within the building categories. It can be seen that in small shopping centres, the share of the supermarkets is higher compared to large and very large shopping centres while in large and very large shopping centres, the share of restaurants, cafes and food courts is higher compared to small and medium shopping centres. Thus, the large and very large shopping centres typically offer more entertainment, for example restaurants and cafes.

Table 11 Shopping centre store composition share of shops on the total shopping centre floor area (Bointner et al., 2014)

Building categories	**Shop types**				
	Retail stores: clothing, hobby, home	**Common area**	**Medium stores, big size stores, super-markets**	**Restaurant, cafes, food courts**	**Other services: ware-house, service rooms etc.**
Small	36%	25%	20%	8%	11%
Medium	42%	25%	15%	9%	9%
Large	50%	25%	9%	10%	6%

Building categories	**Shop types**				
	Retail stores: clothing, hobby, home	**Common area**	**Medium stores, big size stores, super-markets**	**Restaurant, cafes, food courts**	**Other services: ware-house, service rooms etc.**
Very large	54%	25%	6%	12%	3%

7.1.2. Building stock

According to the EU Buildings Database, the whole EU-28 and Norway building floor area is almost 24 billion m^2 (European Commission, 2017). The share of the residential building floor area is 75% while the non-residential buildings make up 25% of the total building floor area in EU-28 and Norway (ENTRANZE, 2016), (European Commission, 2017). The retail and wholesale buildings with a share of 28% comprise the largest portion of non-residential floor area (Fig. 57).

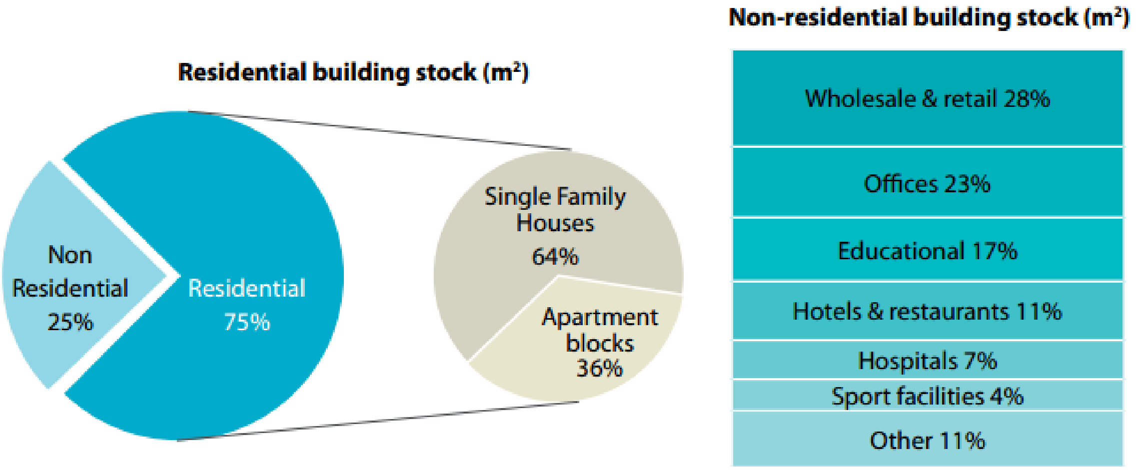

Fig. 57 Breakdown of residential and non-residential building sector in EU-28 and Norway (Buildings Performance Institute Europe (BPIE), 2011)

Table 12 shows total building floor area, residential building floor area, non-residential building floor area, wholesale and retail building floor area and shopping centres building gross floor area in EU-28 and in each single European country.

Table 12 Building floor area by building categories in EU-28 + Norway in 2008 (ENTRANZE, 2016), (European Commission, 2017) , (International Council of Shopping Centers, 2005)

	Building floor area [2], Million m^2	**Residential floor area, Million m^2**	**Non-residential floor area[3], Million m^2**	**Wholesale and retail building floor area, Million m^2**	**Shopping centres, Gross Leasable Area[4], Million m^2**
EU-28	23,696.1	18,030.7	5,665.4	1,668.2	112.1
Austria	455.8	341.4	114.3	21.0	2.9
Belgium	484.1	379.3	104.8	27.2	1.0

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[2] Includes residential and service buidlings with an exaption of Norway, in Norway, statistics provide total building floor area including industrial and agriculture buildings

[3] Service buildings are included: wholesale & retail, offices, hotels & restaurants, health and education

[4] Includes shopping centre buildings with a minimum gross leasible area of 5,000 m²

Bulgaria	261.1	197.2	63.8	11.7	0.1
Cyprus	46.7	38.9	7.8	2.0	0.2
Czech Rep.	398.3	309.6	88.7	15.8	1.6
Denmark	420.1	297.6	122.5	13.9	1.6
Estonia	49.4	37.4	12.0	6.5	0.4
Finland	307.0	199.9	107.1	35.5	1.2
France	3,386.9	2,479.5	907.4	207.0	14.4
Germany	4,334.0	3,229.7	1,104.3	458.0	9.7
Greece	462.6	322.6	140.0	28.4	0.6
Hungary	402.1	303.3	98.8	25.9	1.5
Ireland	227.8	184.6	43.2	11.2	1.5
Italy	2,992.8	2,576.9	415.9	152.0	12.7
Latvia	77.6	61.1	16.6	2.6	0.3
Lithuania	135.2	104.0	31.2	3.5	0.5
Luxembourg	21.2	16.3	4.9	1.3	0.1
Malta	17.5	13.5	4.0	1.0	0.1
Netherlands	925.6	630.8	294.8	88.9	7.2
Poland	1,327.5	942.1	385.4	95.9	3.9
Portugal	512.9	410.1	102.8	26.7	2.7
Romania	515.8	456.4	59.3	18.3	0.6
Slovakia	170.8	132.7	38.2	n.a.	0.4
Slovenia	88.3	60.8	27.5	6.9	0.8
Spain	1,918.0	1,568.0	350.0	78.8	9.5
Sweden	539.0	386.5	152.5	15.3	6.4
UK	2,660.6	1,924.5	736.1	279.5	26.2
Croatia	145.0	112.8	32.2	3.2	1.2
Norway	412.5	313.0	99.5	30.2	3.0

Due to the heterogeneity of the wholesale and retail building stock, there is no data base providing the building floor areas of the building sector within the wholesale and retail sector for the European countries. The data on the shopping centre floor area is taken from the database by the International Council for Shopping centres (ICSC) (International Council of Shopping Centers, 2005).

ISCS statistics provide data for every single shopping centre located in over 100 countries. Each shopping centre is described by the gross leasable area, opening year, type of building. These data were used in my analysis to calculate the total gross leasable area in EU-28 and Norway.

The Shopping centre building Gross Leasable Area (GLA) was 151.1 Million m^2 in EU-28 + Norway in 2015 (International Council of Shopping Centers, 2005). The largest shopping centre gross leasable area is located in the United Kingdom (22.2 Million m^2) followed by Germany (19.6 Million m^2), Spain (16.7 Million m^2) and France (12.8 Million m^2). The total shopping centre building stock in these countries makes up 47% of the total shopping centre gross leasable area in EU28 and Norway.

Fig. 58 shows gross leasable area of the shopping centres by opening year. The oldest shopping centre building stock is in Sweden followed by Denmark and France. In Sweden, more than half of the investigated shopping centre buildings were built before 1990. The share of the buildings gross floor area built before 1990 is 59%, 47% and 39% in Sweden, Denmark and France, respectively. The smallest shopping centre gross leasable area is located in Malta (0.02 Million m2) followed by Cyprus (0.13 Million m2), Luxembourg (0.23 Million m2), Croatia (0.4 Million m2), Slovenia (0.6 Million m2) and Estonia (0.72 Million m2). In the CEE countries, more than 50% of the shopping centres gross floor area was opened between 2002 and 2015. The former EU-15 + Norway remain saturated markets and there is only limited activity in relation to the development of new centres while in most Central and Eastern Europe (CEE) countries, the shopping centre market is still an under-supply. The share of the small, medium, large and very large shopping centres in each vintage shows that small and medium shopping centres were built before 1990 while after 2002, large and very large shopping centres have been constructed.

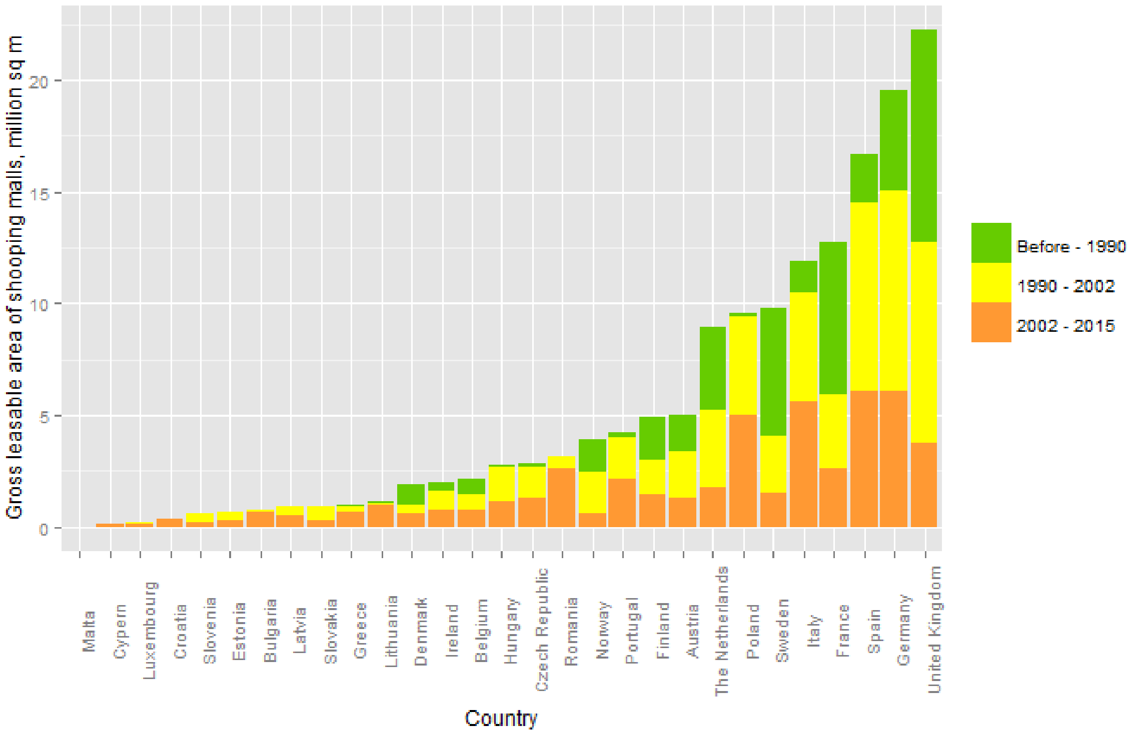

Fig. 58 Gross Leasable Area of Shopping centres [Million m2] by opening year in the EU-28 and Norway in 2015 (International Council of Shopping Centers, 2005)

Fig. 59 shows the distribution of the shopping centres by types: small, medium, large and very large shopping centres in the EU-28 and Norway. The small shopping centres dominate in most countries. In Austria, Belgium, Denmark, Finland, Malta, the Netherlands and Sweden, more than 70% of all shopping centres are small shopping malls (GLA of 5,000–19,999 m²). In the Czech Republic, Estonia, Spain, France, Hungarian, Lithuania, Norway, Portugal and Slovakia, the share of the small shopping centres of the total shopping centre buildings is more than 50%. The medium and large shopping centres (20,000 and above m²) dominate in the following countries: Bulgaria, Cyprus, Germany, Croatia, Ireland, Luxemburg, Poland and UK. The share of this type of shopping centres is more than 50%.

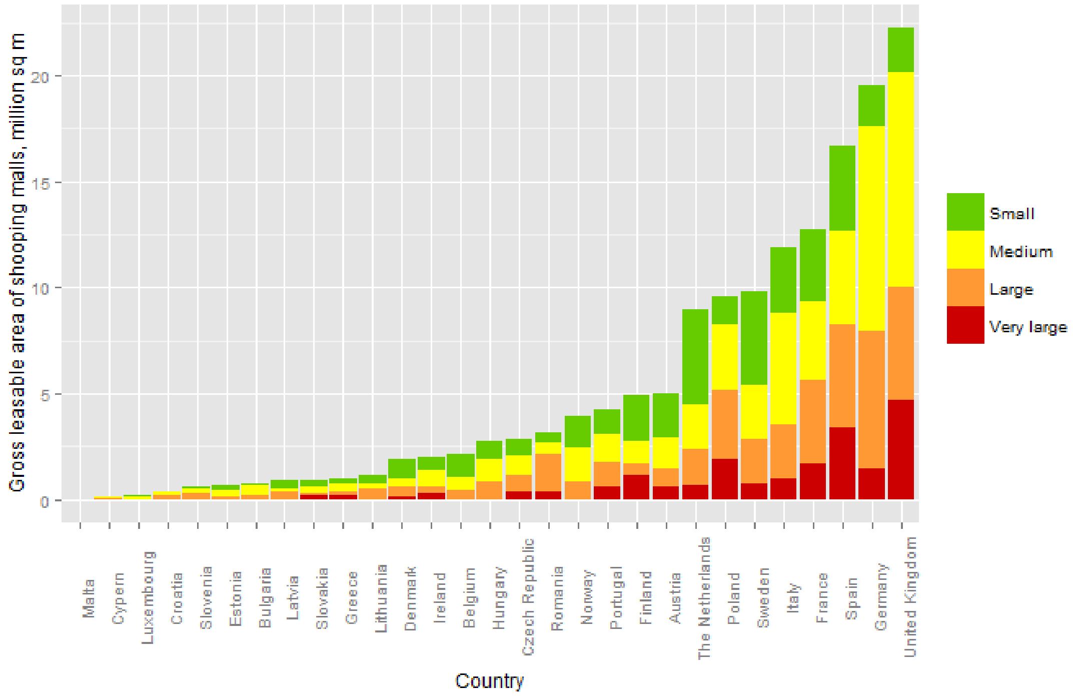

Fig. 59 Gross Leasable Area of Shopping centres [Million m^2] by size in the EU-28 and Norway in 2015 (International Council of Shopping Centers, 2005)

7.1.3. Total energy demand

Energy demand for space heating, cooling, lighting, appliances, refrigeration and ventilation was calculated. Energy demand was calculated for each shop *i* within a shopping centre category and for each energy demand service *s* (space heating, cooling, lighting, appliances, refrigeration and ventilation). Energy demand for energy service in one building category *c* is the sum of energy demand service *s* in shops *i* multiplied with the share of shop floor area *i* on the total building category floor area c:

$$Q_{s,c} = \sum_{i=1}^{n} q_{s,i} * \frac{A_i}{A_c} \qquad \text{7-1}$$

$Q_{s,c}$ ...Energy demand of energy service s in building category c [kWh]
$q_{s,i}$ ...Specific energy demand per floor area of energy service s in shop i [kWh]
A_i ...Shop floor area [m²]
A_c ...Building category floor area [m²]

Total energy demand for space heating, cooling, lighting, appliances, refrigeration and ventilation in one building category *c* is calculated as the sum of energy demand services *s:*

$$Q_{total,c} = \sum_{s=1}^{n} Q_{c,s} \qquad \text{7-2}$$

$\mathrm{Q}_{\mathrm{total,c}}$ …Energy demand for space heating, cooling, lighting, appliances, refrigeration and ventilation in building category c [kWh]

International Council of Shopping Centers (ICSC) provides data on the total floor area by building size and opening year. To estimate the total energy demand of the whole country´s shopping centre building stock, I multiplied the energy demand per shopping categories square meter q_{total} with the total floor area TA of every single shopping centre category *c* in country *j:*

$$Q_{total,j} = \sum_{c=1}^{n} Q_{total,c} * TA_{c,j} \tag{7-3}$$

$\mathrm{Q}_{\mathrm{total,j}}$ …Total energy demand in the total shopping centre building stock in country j [kWh]
$\mathrm{TA}_{\mathrm{c,j}}$ …Total floor area of shopping category c in country j [m²]

Specific energy demand for space heating and cooling was calculated using the monthly energy balance approach quasi-steady-method while energy demand for lighting, appliances, refrigeration and ventilation was estimated using usage duration and specific power.

Energy needs for space heating and cooling of the shopping centre categories in a country is modelled on a monthly basis by using a module of the building stock simulation tool Invert-EE/Lab (Müller, 2015). The specific energy need for space heating and cooling is carried out using the monthly energy balance approach quasi-steady-method, based on EN13790 “Energy performance of buildings - Calculation of energy use for space heating and cooling “ methodology (see 3.2).

Table 13 shows the input assumptions for each zone typology which were collected in the project Commonenergy based on Standard 90.1-2016 Energy Standard for Buildings Except Low-Rise Residential Buildings (American Society of Heating, 2016) and (Rozanska et al., 2017)

Table 13 Input parameters used to calculate energy demand for space heating and cooling (American Society of Heating, 2016), (Rozanska et al., 2017)

Default input data	**Shop types**				
	Retail stores: clothing, hobby, home	**Common area**	**Medium stores, big size stores, super-markets**	**Restaurant, cafes, food courts**	**Other services: ware-house, service rooms etc.**
Average indoor temperature for heating, [°C]	20	20	20	20	20
Average indoor temperature for cooling, [°C]	25	25	25	25	25
Persons per 1 square meter (internal gains persons is185 W/person)	0.2	0.2	0.25	0.25	0
Internal gains lighting; w/m²	36.2	23.7	27	28.2	15
Internal gains appliances, W/m²	10	5	10	10	5
Air exchange rate (mechanical	0	0.5	1.4	3	0

ventilation), (1/h)					

Energy demand for lighting, appliances, refrigeration and ventilation is calculated using usage duration and specific power which varies based on the shop type. The specific power for each energy service and shop type was developed within the Commonenegy project based on Standard 90.1-2016 Energy Standard for Buildings Except Low-Rise Residential Buildings (American Society of Heating, 2016) and demo shopping centres involved in the Commonenergy project (Rozanska et al., 2017).

Table 14 Specific power for different shop types for lighting, appliances, refrigeration and ventilation (American Society of Heating, 2016), (Rozanska et al., 2017)

Specific power, W/m²	**Shop types**				
	Retail stores: clothing, hobby, home)	**Common area**	**Medium stores, big size stores, super-markets**	**Restaurant, cafes, food courts**	**Other services: ware-house, service rooms etc.**
Lighting	36.2	23.7	27	28.2	15
Appliances	10	5	10	10	5
Refrigeration	0	0	25.9	16.4	0
Ventilation	0.7	8.3	3.7	20.8	10.6

Table 15 presents the usage duration which was derived from the demo shopping centres involved in the Commonenergy project. These usage durations are the basis for the further definition of the usage duration for each European country specifically. Data on the opening hours of the shopping centres and national holidays in EU-28 and Norway were collected. These data were used to adapt usage duration for each specific country.

Table 15 Usage duration used to calculate annual energy demand for lighting, appliances, refrigeration and ventilation

Duration	**Shop types**				
	Retail stores: clothing, hobby, home)	**Common area**	**Medium stores, big size stores, super-markets**	**Restaurant, cafes, food courts**	**Other services: ware-house, service rooms etc.**
Lighting	3357	3310	3357	3310	2097
Appliances	3518	2915	3494	2915	2330
Refrigeration	8760	8760	8760	8760	8760
Ventilation	3881	4269	3881	4269	3881

7.1.4. Building stock development

The renovation rate of the shopping centre buildings and technology change rates are calculated using Weibull-distribution. For each defined building vintage, before 1990, 1991-2002 and after 2002 and renovation rate is calculated. The yearly rate is calculated for building envelope renovation, lighting, refrigeration and appliances. Table 16 shows two parameters, shape factor and characteristic life time, used for the calculation. These parameters were defined for lighting, refrigeration and appliances as well as for thermal renovation specifically.

Table 16 Characteristics of the Weibull-Distribution for building renovation (International Council of Shopping Centers, 2005), (Müller, 2015))

Renovation option	**Renovation measure**	**Shape factor β [-]**	**Characteristic life time T [years]**
Lighting	Installation of LEDs	2.7	10
Refrigeration and appliances	More efficient system installation	2.7	12
Thermal Renovation	Whole building envelope, built before 1990	2.7	22.4
	Whole building envelope, built between 1990 & 2002	4.0	
	Whole building envelope, built after 2002	5.0	

Fig. 60 shows cumulated renovation rate of the building stock which undertakes different renovation options from 2012 to 2030. It can be seen that lighting has the highest penetration rate among other options followed by refrigeration and appliances. The cumulated renovation rate for lighting reaches almost 100% in 2030 compared to 2012. Thermal renovation of the building envelope follows rather moderate renovation rate achieving 43%, 34% and 29%, of the cumulated renovation rate in 2030 compared to 2012 for buildings built before 1990, 1990-2002 and after 2002 respectively.

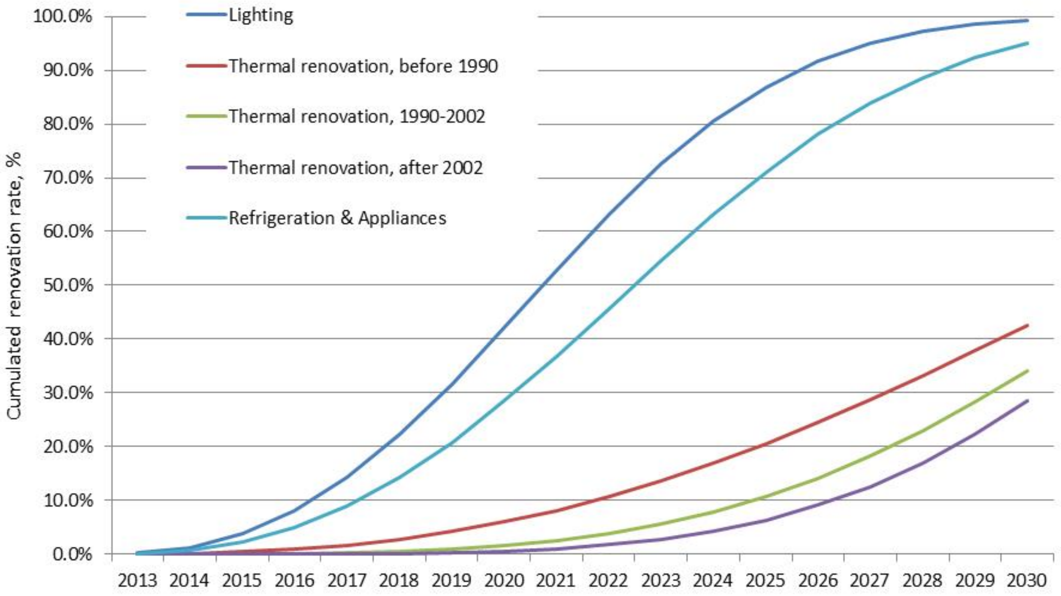

Fig. 60 Penetration of the building stock which undertakes different renovation options from 2012 to 2030

To estimate the future shopping centre development in EU-28 and Norway, two parameters were taking into account, the trend of the gross domestic product (GDP) and historical sales growth data of shopping centres from 2000 to 2012. The GDP forecast was taken from the statistics provided by the Organisation for Economic Co-operation and Development (OECD, 2016). Historical sales growth data of shopping centres per country comes from the ICSC statistics (International Council of Shopping Centers, 2005).

In this analysis, it was identified that the development of new shopping centres is limited in most European countries. However, there is still an under-supply in the so called non-mature markets in Central and Eastern Europe (CEE).

7.1.5. Energy efficiency solutions

Future energy demand development is driven by the technologies which are replaced in the existing shopping centres and by new technologies in new shopping centres. In this calculation, the technologies for lighting, appliances, refrigeration, ventilation and space heating are defined.

Within the Commonenergy project, the energy efficiency solution sets were defined for specific shopping centres and their impact on the energy need reduction, improvement of the indoor environmental air quality was tested (Cambronero et al., 2017). The investigation was made for the specific shopping centres involved in this project using a dynamic simulation. Among different solutions, the most feasible solutions were selected based on the following selection criteria: energy savings (75% of energy consumption reduction (compared to baselines), availability of installation and cost of investments (7 years payback period). Table 17 shows some examples of the selected solutions sets for some of the demo cases located in different climate zones in Europe.

Table 17 Solution-sets of energy efficiency measures selected for shopping centres located in different climate zones in Europe (Cambronero et al., 2017)

Shopping centre location	Solution-set
Valladolid –Spain	Geothermal heat pump; Modular climate adaptive multifunctional façade; Effective artificial lighting equipment + control strategies
Trondheim – Norway	Efficient lighting system and controls; Efficient appliances; Natural ventilation; Insulation; Photovoltaic plant
Modena – Italy	Efficient lighting system and controls; Replacement of refrigeration cabinets; Building envelope thermal improvement; Reflective coating; Improving HVAC efficiency; Coupling HVAC and refrigeration
London - UK	Efficient lighting system and controls; Appliances replacement; PV system
Vienna - Austria	Efficient lighting system and controls; Efficient appliances; Cooling set point control; Natural Ventilation; Photovoltaic plant; Revolving doors
Silute - Lithuania	Effective artificial lighting equipment + control strategies; Building envelope thermal improvement; Heat recovery and heating set point Management; RES integration (PV panels + Wind turbine)

As can be seen in Table 17, the selected energy efficiency measures differ from one shopping centre to another. This is due to many parameters which have an impact on the selection of most feasible solutions sets, such as building technical characteristics, climate, shop types inside the building and associated electricity loads. However, it can be seen that effective lighting system and control is the most often installed energy efficiency measure.

The experience from the Commonenergy project shows, that in order to achieve an optimal energy savings and associated cost savings, a holistic approach has to be carried out for each building specifically. This is, however, possible by having many data and by making a dynamic simulation for every single shopping centre.

This study aims to analyse the energy saving potential in the total building stock and therefore an application of a holistic approach for each shopping centre is not possible. In this study, I used a simplified approach by defining two renovation packages. These renovation packages are applied to all buildings which undertake renovation within the calculation period from 2012 to 2030. The first package includes moderate renovation measures while the second one undertakes ambitious energy efficiency measures. Both packages include measures for lighting, appliances, refrigeration, ventilation and space heating and cooling.

The calculation was carried out by defining the specific power for each energy efficiency measure. The specific power for lighting, appliances, refrigeration and ventilation were defined based on the expert interview from the Commonenergy project. Table 18 shows the specific power after system replacement for both renovation packages. Energy efficiency measures for building envelopes were defined by setting the U-values for building elements. These two packages of implemented energy efficiency solutions can be defined as follows:

- Package I:
    - **Lighting**. This package involves switch to LED lamps by which lighting loads are reduced by 47%, 80%, 50%, 50% and 70% compared to the reference case in retail stores, common areas, medium stores, restaurants and other shops respectively.
    - **Appliances**. Energy consumption for appliances are reduced by replacing them with more efficient appliances. Appliances replaced in shopping centres can be as follows, distribution transformers, IT equipment, water treatment, cash machines, kitchen equipment, security systems and others. It is assumed that electricity load is reduced by 50% in all shops compared to the reference case.
    - **Refrigeration.** Refrigeration consumption can be reduced by replacing old, low efficient cabinets with closed new ones, in order to uniform temperature distribution between cabinet's corridors and the rest of the supermarket. It is assumed that the electricity load is reduced by 50% in medium stores and restaurants compared to the reference case.
    - **Natural ventilation.** Better control strategies for opening openable windows, sliding doors and skylights are implemented. These measures reduce the electricity load of mechanical ventilation by 50% in all shops.
    - **Energy demand for space heating and cooling.** Energy demand for space heating is reduced by improving building envelope through the insulation of external walls and roof. Energy demand for cooling is mainly reduced by switching lighting to LED lamps. Energy demand for space heating is reduced by 25% and cooling by 20%.
- Package II: In addition to the replacement of the system in Package I, active control systems for lighting, appliances, refrigeration, ventilation, heating and cooling systems are installed. According to Siemens report (Siemens, 2016), 5% of additional savings can be earned for lighting, appliances and refrigeration, as well as 13.5% for heating and 27% for ventilation and cooling. These savings are equal to a shift from C (standard case) to B (advanced energy efficiency) class building automation control systems in the wholesale and retail sector, according to Siemens report on "energy efficiency in building automation and control (Siemens, 2016).

Table 18 Specific power for different shop types for lighting, appliances, refrigeration and ventilation (package I and package II)

Specific power, W/m²	**Shop types**				
	SHP (Retail stores: clothing, hobby, home)	**CMA (Common area)**	**MDS (Medium stores, big size stores, super-markets)**	**RST (Restaurant, cafes, food courts)**	**WRH (Other services: ware-house, service rooms etc.)**
Lighting	18.1/17.1	4.5/4.3	13.5/12.8	14.1/13.4	4.5/4.3

Specific power, W/m²	Shop types				
	SHP (Retail stores: clothing, hobby, home)	CMA (Common area)	MDS (Medium stores, big size stores, super-markets)	RST (Restaurant, cafes, food courts)	WRH (Other services: ware-house, service rooms etc.)
Appliances	5/4.8	2.5/2.4	5.0/4.8	5.0/4.8	2.5/2.4
Refrigeration	0	0	13.0/12.3	8.2/7.8	0
Ventilation	0.4/0.3	4.2/3.0	1.8/1.3	10.4/7.6	5.3/3.9

7.1.6. Scenario framework

I built four different scenarios which reflect different parameters and try to identify their impact on the final energy demand development: (1) The first scenario is a status quo scenario including package I (see previous section) which covers energy efficiency measures for lighting, appliances, refrigeration, ventilation and space heating. (2) The second scenario includes policies addressing more ambitious measures and control systems for lighting, appliances, refrigeration, ventilation and space heating. In this scenario, package II of energy efficiency measures are implemented. (3) The third scenario includes policies addressing higher energy efficiency, as in the second scenario, and additionally there is a renovation rate obligation for space heating. (4) The fourth scenario includes an external framework condition taking new shopping centre developments which are linked to the internet sales into account.

Scenario I is a status quo scenario. In general, system component replacement and renovation are more frequent in the wholesale and retail sector than in any other sector because a modern design is essential for the excitement of shopping (Bointner et al., 2014). The market uptake and diffusion of energy efficient technologies are in place in this status quo scenario. Yearly renovation rate of thermal renovation reducing space heating is 1.8% and the replacement rates of other energy services are as follows: 5.5% for lighting, 5.3% for refrigeration and appliances. Package I (as described in the previous section) is implemented including energy efficiency measures for lighting, appliances, refrigeration, ventilation and space heating and cooling. New construction is based on shopping centre market sales in the respective country. In general, the lower the market saturation, the more shopping centres will be built and extended.

Scenario II includes policies addressing more ambitious measures and control systems for lighting, appliances, refrigeration, ventilation and space heating. The same replacement rates as in the status quo scenario are applied but energy efficiency measures are more ambitious. Package II (see description in the previous section) which includes energy efficiency measures for lighting, appliances, refrigeration, ventilation and space heating is implemented. There are policies triggering investments in higher energy measures and there is the mandatory use of active control systems for lighting, appliances, refrigeration, ventilation systems, heating and cooling.

Scenario III includes policies on renovation depth and rate. This scenario includes the energy efficiency measures and control systems as in the second scenario, and, additionally, there is an obligated renovation rate. On top of technologic and economic solutions, as introduced in the previous scenarios, legal obligations to foster energy efficiency could lead to further energy demand reductions. For instance, literature showed that thermal renovation is not always cost-effective in shopping centres (Haase et al., 2015) (Bointner et al., 2014). Thus, shopping centres are not willing to invest. These retrofitting solutions, however, may provide a big potential to reduce energy demand and greenhouse gas emissions. In this scenario, the renovation rate obligation is implemented. The yearly thermal renovation rate is 3.5 %.

Scenario IV considers the growing market of online shopping. More and more people search and buy goods and services online; it is comfortable, and not dependent on opening hours or location. The online market is growing every year. As a consequence conventional shopping centres have to re-think their sales strategies. On the other hand, internet sales are not a full substitute to traditional markets, but partially complimentary. For instance, customers order/reserve a good on the internet and check the quality, fit, etc. in the shop before making their purchase decision. It can be assumed that unsaturated shopping centre markets are less affected by internet sales than saturated shopping centre markets. This leads to lower footfall, reduced shopping centres sales and, in turn, to lower construction rates and/or an increased change of use, e.g. a shopping centre is rededicated to an office building. This assumption is modelled with an annual reduction of 1.5% on the initial sales growth.

7.2.Results

7.2.1. Energy demand breakdown

Fig. 61 shows calculated specific annual demand for appliances, lighting, refrigeration, space heating, space cooling and ventilation used in European shopping centres. Energy demand for lighting makes up the highest share on the total annual energy demand followed by space cooling. The share of the lighting, space cooling, refrigeration, appliances, space heating and ventilation on the total final energy demand in an average shopping center is as follows: 30%, 22%, 17%, 17% 8% and 5% respectively. Even in the Northern European countries, the share of the specific heating energy demand on the specific total energy demand is 4.2% in Norway and 6.5% in Latvia for example.

The high share of the cooling energy demand in the shopping centres is mainly caused by internal heat gains from lighting, people and equipment. This is true for all European countries. The specific energy demand for the abovementioned services was calculated for different shopping centre categories, small, medium, large and very large. The total annual specific demand in shopping centres varies from 300 kWh/m² to 410 kWh/m² in small shopping centres and from 250 kWh/m² to 360 kWh/m² in large shopping centres. Small shopping centres have the highest energy demand due to the high share of the supermarket floor area on the total shopping centre floor area which leads to higher energy demand for refrigeration and appliances compared to other shop types.

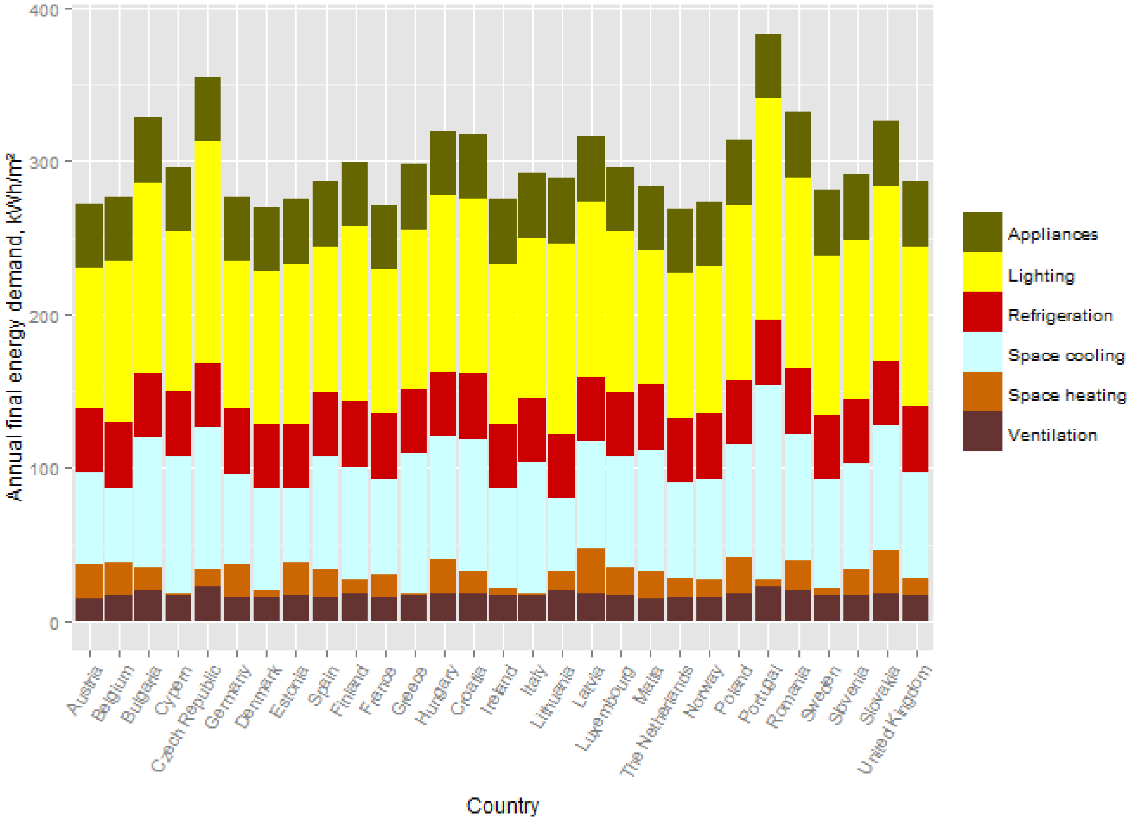

Fig. 61 Calculated specific final annual demand for appliances, lighting, refrigeration, space heating, space cooling and ventilation per m² gross floor area in an average shopping centre in EU28 and Norway

7.2.2. Building stock development

Fig. 62 shows the share of the total gross leasable area of the new shopping centre building development from 2012 to 2030 and existing shopping centre building stock which was built until 2012 in EU-28 and Norway. The calculation was made using the shopping centre data coming from the ICSC statistics which provide data of every single shopping centre located in European countries. The share of the new buildings in 2030 varies from country to country. The share of the new buildings in the total building floor area in 2030 is above 50% in Bulgaria, Lithuania, Latvia, Luxembourg, Malta, Poland, Romania and Slovakia. In these countries, the market growth in the last 12 years was very high and the GLA per 1000 Capita is still low. Consequently, there is an exploitable untapped potential for new building development. In Norway, Sweden and the United Kingdom, the new shopping centre construction rate from 2012 to 2030 is very low and the share of the new buildings makes up less than 15% on the total shopping centre floor area. The countries which were identified as the markets with low share of the shopping centres per capita will have a continued growth of the new shopping centre building. The share of the new building floor area on the total floor area is approximately 30% in 2030 in the following countries: Cyprus, Denmark, Estonia, Finland, France, Greece, Croatia, Ireland, The Netherlands and Spain. This development of the total gross leasable area of the new shopping centre was used in the first scenario (status quo scenario), second and third scenarios.

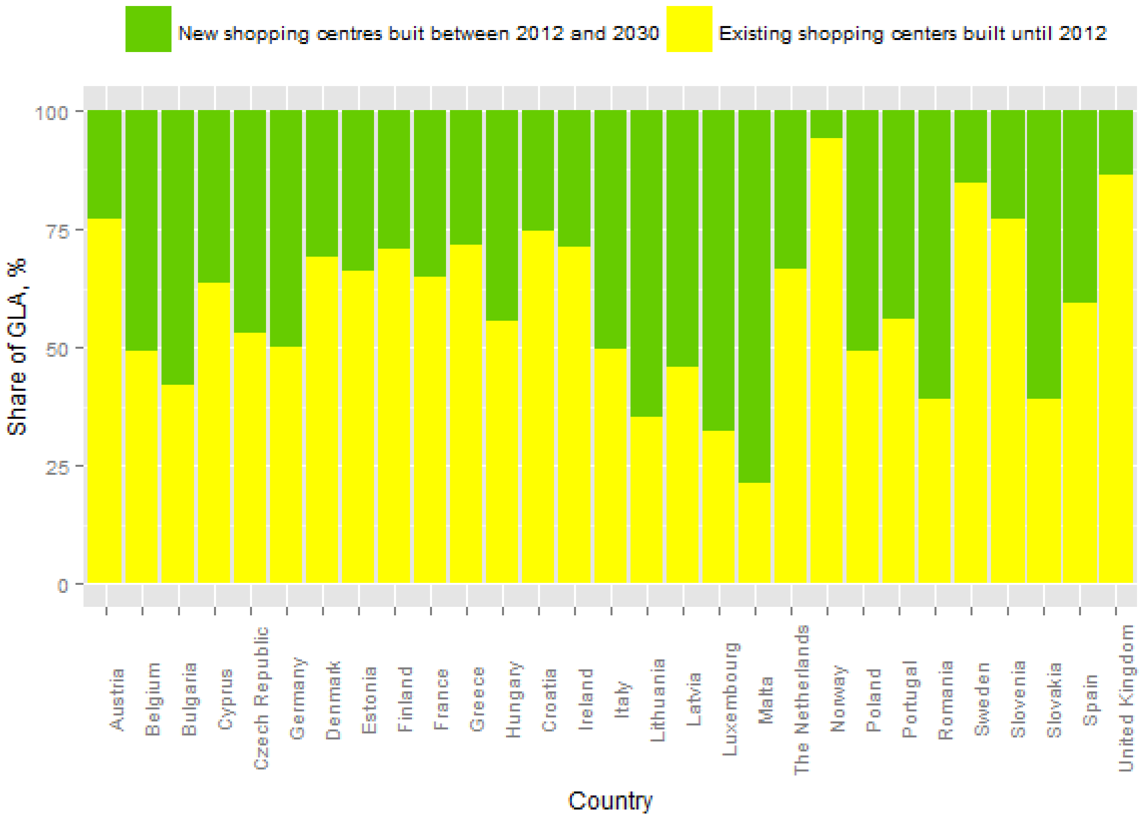

Fig. 62 Share of the total gross leasable area in 2030 of new buildings built between 2012 and 2030 and existing building stock built until 2012

7.2.3. Energy demand development

We calculated the final energy demand by the energy services in EU28 plus Norway. Fig. 63 shows aggregated final energy demand for space heating, cooling, appliances, ventilation, refrigeration and lighting in EU-28 and Norway. Final energy demand was 43 TWh in the shopping centre building stock in 2012. Total energy demand for each European country is shown in Fig. 69 which is in Appendix D. Energy demand scenarios in the shopping centres.

With the 33% share the energy demand for lighting dominates in the total final energy demand followed by space cooling (25%), appliances (16%), refrigeration (15%), ventilation (6%) and space heating (5%) in EU28 plus Norway. By using the energy efficiency measures, 36% of the total energy savings can be achieved until 2030 in the status quo scenario using moderate energy efficiency measures. The highest energy saving potential can be achieved by replacing the lighting technologies. 59% of the energy demand for lighting can be saved from 2012 to 2030. In the second scenario which includes policies addressing higher measures for lighting, appliances, refrigeration, ventilation and space heating and control systems, 45% of the total energy savings can be achieved by 2030. In this scenario, lighting again has the highest saving potential.

Fig. 63 Final total energy demand by energy services in the shopping centers of EU28 plus Norway in 2012, and in 2030 in the four scenarios

Fig. 64 shows the change in the final energy demand in the existing shopping centre building stock from 2012 to 2030 in all four scenarios.

There is an obvious trend in the results showing an energy demand reduction in all scenarios in saturated markets and energy demand increase in non-mature markets from 2012 to 2030. One of the main reasons is the development of the shopping centre building stock.

In the first scenario, which is the status quo scenarios, the change of the final energy demand from 2012 to 2030 is -15%, -38%, -27% and 6.5% in Austria, Norway, Sweden and France respectively. The second scenario which includes policies addressing more ambitious measures for lighting, appliances, refrigeration, ventilation and space heating and control systems shows a higher energy demand reduction from 2012 to 2030. The final energy demand from 2012 to 2030 will decrease by 24%, 45%, 35% and 5% in Austria, Norway, Sweden and France respectively. In the third scenario, 25%, 46%, 36% and 6% of the energy savings are achieved in the abovementioned countries.

Due to the strong increase of the new buildings in the non-mature markets until 2030, the total energy demand will increase, too. In the first scenario, which is the status quo scenarios, the final energy demand from 2012 to 2030 will increase by 114%, 125%, 67% and 120% in Bulgaria, Lithuania, Poland and Romania respectively. In the second scenario, the final energy demand from 2012 to 2030 will increase by 94%, 111%, 51% and 99% in Bulgaria, Lithuania, Poland and Romania respectively. The Internet sale scenario which reduces the future shopping centre growth shows a significant difference of the change in energy demand compared to the status quo scenario in abovementioned markets. In the internet sale scenario, the final energy demand from 2012 to 2030 will increase by 58%, 24%, 23% and 56% in Bulgaria, Lithuania, Poland and Romania respectively.

Fig. 64 Change in total energy demand for space heating, cooling, appliances, ventilation, refrigeration and lighting in Shopping Centres from 2012 to 2030 in the European countries in different scenarios

7.3. Summary and discussion

In this chapter study, the energy demand scenarios in the European shopping centre building stock from 2012 to 2030 were calculated taking different economic and technical conditions into account. These scenarios were calculated using a bottom-up approach by breaking down the energy demand into six energy services: energy demand for space heating, space cooling, lighting, refrigeration, appliances and ventilation.

Calculated final energy demand for space heating, cooling, appliances, ventilation, refrigeration and lighting was 43 TWh in the shopping centre building stock in 2012. The future energy demand is dependent on the quality of renovation, the replacement rate of building technologies, new shopping centre construction and the market saturation in the respective country. Literally this means all emerging markets have a growing energy demand in the status quo scenario. For instance, in the formerly socialist CEE countries the shopping centre era began after 1990 and the shopping centre stock is young compared to many western European countries. However, if energy efficiency measures are being implemented and the retail market will change by expanding web shops, the energy demand in these markets will go down (as it was shown in the fourth scenario). The following main conclusions can be highlighted:

Lighting technologies have the highest replacement rate in the shopping centres. Moreover, the energy demand for lighting makes up the highest share of the total final energy demand. From 2012 to 2030, the energy demand for lighting can be reduced in the total shopping centre building stock in EU28 and Norway by 59% in the status quo scenario and by 62% in the second scenario. Improvements and new innovative technologies (LED, control systems) have a high potential to reduce energy demand in the shopping centres.

In the transition economies and especially in the countries Bulgaria, Lithuania, Latvia, Poland, Romania and Slovakia in a business as usual –scenario, it can be expected that a considerable amount of new shopping centres might be built. The share of the new buildings built between 2012 and 2030 on the total building floor area in 2030 is above 50% in these countries. Consequently, the total energy demand of the shopping centre building stock is growing until 2030 in these markets. Thus there is a need for new and innovative energy efficiency technologies or new green business models. According to (Haase et al., 2015), certifications enhancing green branding play an important role in the decision of investing in energy efficiency measures for shopping centres. Building codes might have a similar motivational function as certification schemes.

Customer satisfaction is the essential motivation to renovate the shopping centres. This is the main reason explaining why shopping centres are the only sector with high building renovation rates (average 4.4%/yearly). However, this renovation rate is often consisted of renovation measures which are not related to energy savings. The main stakeholders, the owners, managers and the biggest shops are very much concentrated on two main issues, aesthetic renovation and costs. There is a high potential to realize energy-saving solutions alongside planned aesthetic renovations and to avoid lock-in effects. The main obstacles hindering investments in the energy-saving solutions are as follows, the lack of information about the benefits of the investments in energy-saving solutions and the lack of communication between building owner and shops inside a shopping centre.

Policies addressing any issues of shopping centres must pay attention to the socio-economic and technical complexity of this sector. For instance, the physical structure of shopping centres and the social multi-stakeholders decisional processes involving owners, tenants, customers and administration are a case sui generis. Thus, policies addressing shopping centres should build on already existing and efficient, voluntary certification schemes such as BREEAM certification or green leases. Moreover, an in-depth, ex ante evaluation of the impact of any shopping centre policy on the numerous stakeholders should be conducted.

8. Conclusions

What is the cost-effectiveness of different energy efficiency solutions in the building stock and how does their implementation contribute to the energy savings in buildings?

The technical and economic energy saving potential in the building sector varies considerably from one country to another. This is due to the following key parameters for the energy savings; current energy performance of buildings, realisable renovation rates and depth, policy packages and energy prices. These parameters have an impact on the economic efficiency of investments in different renovation packages. In some countries, medium and deep renovations are cost-effective due to the cold climate (for example in Norway) or high energy fuel prices (for example oil price in Italy). However, in some investigated countries, renovation is not cost-effective for particular buildings due to the low energy prices (for example coal, gas and biomass prices in Romania). Policy instruments should be directed towards stringent energy taxation. As long as this is not the case, direct subsidies or soft loans will be needed in countries like Romania but should be considered only as second-best policy instrument. On the other hand, these policy instruments would lead to a free-rider effect in Norway. Thus, it is possible to conclude that if the energy taxation settings and overall energy price levels are sufficiently high, standards and regulatory measures – accompanied by offset for low-income people – are preferable compared to high subsidies.

This analysis showed that the implementation of deep renovation measures lead to a high energy saving potential 2030. However, it is still not clear whether the implementation of certain retrofitting measures is sufficient to achieve recently adopted climate mitigation targets.

Do ambitious energy saving scenarios and assumed policy package in buildings reflect the recently adopted climate and energy targets?

The target of keeping the increase in global average temperature below 2°C set in Paris Agreement, requires the CO_2-reductions beyond 80-90% in the building sector. The ambitious scenarios that I developed which include more stringent policy instruments compared to the current policy instruments show CO_2-reductions of around 80% only in the most ambitious cases. This shows that an achievement of COP21 agreements require even higher policy ambitions, going beyond the assumptions of ambitious policy scenarios developed in this thesis.

Building renovation rate and renovation depth together with uptake of renewable heating systems are required measures for the building decarbonisation. However, long-term energy savings is strongly linked to the electricity generation and its decarbonisation. The scenario results showed that in some countries fossil fuels like oil and gas in Italy and particularly coal in Poland are gradually substituted by electricity. However the electricity generation mix is currently dominated by fossil fuels and correspondingly high CO_2-emissions. This leads to an untapped potential of CO_2-emisson savings. Thus, these results call for an ambitious shift towards low-carbon electricity generation as well.

The results of this analysis showed that the current policies – and even discussed “ambitious” policies – are not sufficient to reach the adopted Paris COP 21 targets. Rather, it will require enhanced policies. Therefore, it is also essential to better understand where the most cost-effective solutions are situated and how those potentials and building sectors which are not yet profitable could be properly addressed by policies:

What building sectors and energy efficiency solutions have to be addressed by policy instruments to achieve the climate and energy targets?

This question was answered by using a cost curve approach which selected specific energy efficiency solutions and buildings which have to be addressed by policy makers in order to achieve high energy savings in the most cost-effective way. This showed that instead of setting policy instruments for all buildings equally, more segmented policies should be provided. Lithuanian case study showed that the highest and most economically feasible potential is by renovating old apartment buildings built before 1990. A++ energy performance class which fulfil the national nZEB requirements need to be implemented.

The cost-effectiveness of investments has been considered as the main driver to invest in energy efficiency solutions and thus reduce the overall energy demand in the building sector in this thesis. However, in many cases, the cost-effectiveness of energy efficiency solutions is not always the main driver to invest. In the last part of my thesis, the energy saving potential in the shopping centre building stock was assessed. This sector is more complex sector compared to the residential sector due to variations in usage pattern, energy intensity and construction techniques (Bointner et al., 2014).

What are the perspectives to increase the energy performance in the shopping centre building stock?

Modelling of the future energy demand was extended by taking different energy services into account such as space heating and cooling, lighting, appliances, refrigeration and ventilation. The European shopping centre building stock provides a huge energy saving potential due to the fact that it is the only sector with a yearly renovation rate of 4.4%. However, achievement of the energy saving potentials requires a comprehensive analysis in this complex building stock. One of the challenges is the close connection between energy load and demand. This is, however, also a potential in achieving high energy savings. Strong collaboration between stakeholders is a crucial issue by choosing the most proper retrofitting solutions. All these issues require corresponding policy framework to enhance energy efficiency.

By considering these derived conclusions, the limitations of this work should be considered. The following issues are also an outlook for further analysis:

- The literature review showed that climate will play an important role for the future energy demand in the building sector. In this analysis, the future energy demand was calculated under one future climate scenario taking the outdoor temperature forecast into account (based on Fleiter et al., 2017). However, a sensitivity analysis should be carried out using different climate scenarios.
- Results showed that the decarbonisation of the building sector is strongly linked to the decarbonisation of the electricity and district heating sectors. Sector coupled modelling approach should be carried out.

- The following aspects should be taken into consideration which might reduce calculated energy saving potential:
    - Imperfect and lack of information which prevents consumers investing in energy efficiency measures.
    - Absence of markets. There is no energy efficiency market, as it is difficult to sell energy efficiency as a product, however, energy efficiency services and energy performance contractors can fill this gap.
    - Split incentives (classic example of the landlord/tenant relationship). This aspect was discussed for the shopping centres building. It is, however, relevant for all building types.
    - Transaction and hidden cost.

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10. List of Figures

11. List of Tables

Appendix A. Cost figures

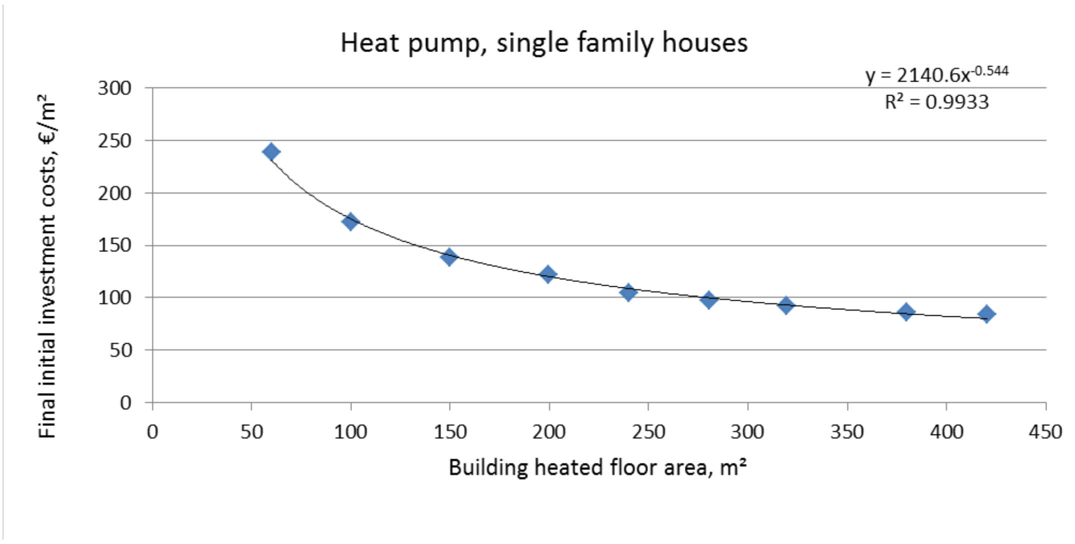

Fig. 65 Investment costs of heat pumps in relation to building heated floor area (own calculations based on data from (European Commission, 2013b))

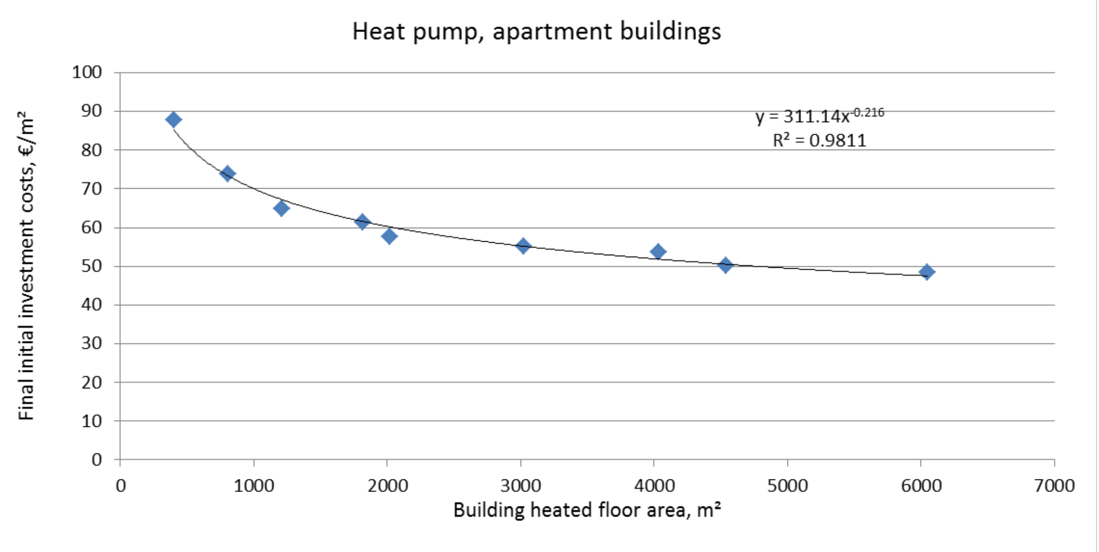

Fig. 66 Investment costs of heat pumps in relation to building heated floor area (own calculations based on data from (European Commission, 2013b))

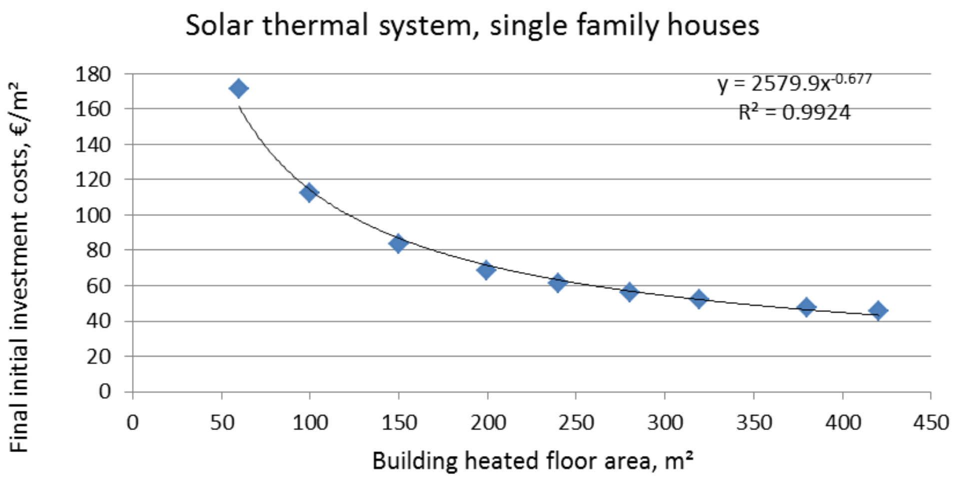

Fig. 67 Investment costs of solar thermal panels in relation to building heated floor area (own calculations based on data from (European Commission, 2013b))

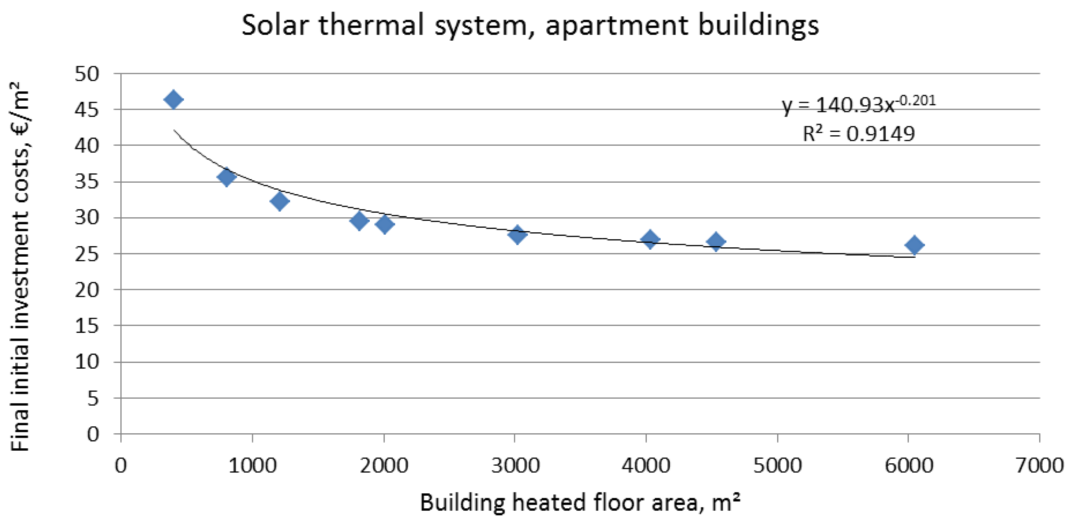

Fig. 68 Investment costs of solar thermal panels in relation to building heated floor area (own calculations based on data from (European Commission, 2013b))

Appendix B. Building types

Table 19 Building types and selected renovation options

Index	**Cost of conserved energy (**Fig. 53 Energy saving cost curve showing the building investors ‘perspective using cost of conserved energy**)**	**Cost-effectiveness (**Fig. 54 Energy saving cost curve showing the building investors ‘perspective using levelized cost per heated floor area**)**
1	MFH(1800 - 1940,Biomass)-C, HP	MFH(1800 - 1940,District heat)-A
2	MFH(1941 - 1960,Biomass)-C, HP	MFH(1941 - 1960,District heat)-A
3	MFH(1961 - 1990,Biomass)-C	MFH(1961 - 1990,District heat)-A
4	MFH(1800 - 1940,District heat)-C	SFH(1800 - 1940,District heat)-C
5	MFH(1800 - 1940,Gas)-C	MFH(1800 - 1940,Gas)-C
6	MFH(1941 - 1960,District heat)-C, HP	SFH(1961 - 1990,District heat)-C
7	MFH(1941 - 1960,Gas)-C, HP	MFH(1991 - 2009,District heat)-A
8	MFH(1961 - 1990,District heat)-C, HP	SFH(1941 - 1960,District heat)-C
9	MFH(1961 - 1990,Gas)-C, HP	MFH(1941 - 1960,Gas)-C
10	SFH(1800 - 1940,Biomass)-C	MFH(1961 - 1990,Gas)-C
11	MFH(1991 - 2009,Biomass)-A	MFH(2010 - 2012,District heat)-A
12	SFH(1961 - 1990,Biomass)-C	MFH(1800 - 1940,Biomass)-C
13	SFH(1941 - 1960,Biomass)-C	MFH(1961 - 1990,Biomass)-C
14	MFH(1991 - 2009,District heat)-A	MFH(1991 - 2009,Gas)-A
15	MFH(2010 - 2012,Biomass)-A	MFH(1941 - 1960,Biomass)-C
16	SFH(1800 - 1940,District heat)-C	MFH(2010 - 2012,Gas)-A
17	MFH(1991 - 2009,Gas)-A	SFH(1991 - 2009,District heat)-A
18	SFH(1800 - 1940,Gas)-C	MFH(2010 - 2012,Biomass)-A
19	SFH(1961 - 1990,District heat)-C	MFH(1991 - 2009,Biomass)-A
20	SFH(1961 - 1990,Gas)-C	SFH(2010 - 2012,District heat)-A
21	SFH(1941 - 1960,District heat)-C	SFH(2010 - 2012,Gas)-A
22	SFH(1941 - 1960,Gas)-C	SFH(2010 - 2012,Biomass)-Maintenance
23	MFH(2010 - 2012,District heat)-A, HP	SFH(1941 - 1960,Gas)-C
24	SFH(1991 - 2009,Biomass)-A	SFH(1991 - 2009,Gas)-A
25	MFH(2010 - 2012,Gas)-A, HP	SFH(1961 - 1990,Gas)-C
26	SFH(1991 - 2009,District heat)-A	SFH(1991 - 2009,Biomass)-Maintenance
27	SFH(1991 - 2009,Gas)-A	SFH(1941 - 1960,Biomass)-C
28	SFH(2010 - 2012,Biomass)-A	SFH(1800 - 1940,Gas)-C
29	SFH(2010 - 2012,District heat)-A	SFH(1961 - 1990,Biomass)-C
30	SFH(2010 - 2012,Gas)-A	SFH(1800 - 1940,Biomass)-C

Appendix C. Parameters to calculate U-values

Table 20 Parameters used to calculate the U-values of the renovation solutions

Code	Element	Thickness, mm	Layer	U-value, W/m2K
1	Roof	0	EPS 035; λ = 0,035 W/mK; μ = 20 / 100; ρ = 30 kg/m^3; c = 1500 J/kg/K; Insulating wall panel made of expanded polystyrene (rigid foam)	Maintenance
2	Roof	0		Maintenance
3	Roof	50		0,61
4	Roof	50		0,61
5	Roof	150		0,223
6	Roof	150		0,223
7	Roof	300		0,114
8	Roof	300		0,114
9	Roof	50		0,61
10	Roof	50		0,61
11	Roof	50		0,61
12	Roof	50		0,61
13	Roof	300		0,114
14	Roof	300		0,114
15	Roof	100		0,33
16	Roof	100		0,33
17	Roof	200		0,169
18	Roof	200		0,169
19	Wall	0	λ = 0,04 W/mK; μ = 20 / 100; ρ = 20 kg/m^3; c = 1500 J/kg/K; Insulating wall panel made of expanded polystyrene (Styrofoam)	Maintenance
20	Wall	0		Maintenance
21	Wall	50		0,66
22	Wall	50		0,66
23	Wall	100		0,36
24	Wall	100		0,36
25	Wall	200		0,19
26	Wall	200		0,19
27	Wall	50		0,66
28	Wall	50		0,66
29	Wall	100		0,36
30	Wall	100		0,36
31	Wall	200		0,19
32	Wall	200		0,19
33	Wall	50		0,66
34	Wall	50		0,66
35	Wall	100		0,36
36	Wall	100		0,36
37	Wall	200		0,19
38	Wall	200		0,19
39	Wall	50		0,66
40	Wall	50		0,66

Appendix C. Parameters to calculate U-values

Code	Element	Thickness, mm	Layer	U-value, W/m2K
41	Wall	100	EPS 035; λ = 0,035 W/mK; μ = 20 / 100; ρ = 30 kg/m³; c = 1500 J/kg/K; Insulating wall panel made of expanded polystyrene (rigid foam)	0,36
42	Wall	100		0,36
43	Wall	150		0,249
44	Wall	150		0,249
45	Wall	50		0,66
46	Wall	50		0,66
47	Wall	100		0,36
48	Wall	100		0,36
49	Wall	150		0,249
50	Wall	150		0,249
51	Floor	50		0,57
52	Floor	50		0,57
53	Floor	100		0,31
54	Floor	100		0,31
55	Floor	150		0,216
56	Floor	150		0,216
57	Floor	50		0,57
58	Floor	50		0,57
59	Floor	100		0,31
60	Floor	100		0,31
61	Floor	150		0,216
62	Floor	150		0,216
63	Floor	50		0,57
64	Floor	50		0,57
65	Floor	10		0,31
66	Floor	10		0,31
67	Floor	150		0,216
68	Floor	150		0,216

Table 21 Parameters used to calculate the U-values for windows

Code	Element	U-value, W/m2K	Ag	Ug	Af	Uf	lg	ψg
74	Window	maintenance	1.2743	-	0.54612		1	0.08
75	Window	maintenance	1.2743	-	0.54612		1	0.08
76	Window	2,59	1.2743	2.7	0.54612	2.2	1	0.08
77	Window	2,59	1.2743	2.7	0.54612	2.2	1	0.08
78	Window	1,89	1.2743	1.7	0.54612	2.2	1	0.08
79	Window	1,89	1.2743	1.7	0.54612	2.2	1	0.08
80	Window	1,40	1.2743	1	0.54612	2.2	1	0.08
81	Window	1,40	1.2743	1	0.54612	2.2	1	0.08
82	Window	2,59	1.2743	2.7	0.54612	2.2	1	0.08
83	Window	2,59	1.2743	2.7	0.54612	2.2	1	0.08
84	Window	1,65	1.2743	1.7	0.54612	1.4	1	0.08
85	Window	1,65	1.2743	1.7	0.54612	1.4	1	0.08

Appendix C. Parameters to calculate U-values

Code	**Element**	**U-value, W/m2K**	**Ag**	**Ug**	**Af**	**Uf**	**Ig**	**ψg**
86	Window	1,04	1.2743	1	0.54612	1	1	0.08
87	Window	1,04	1.2743	1	0.54612	1	1	0.08
88	Window	0,78	1.2743	0.65	0.54612	0.95	1	0.08
89	Window	0,78	1.2743	0.65	0.54612	0.95	1	0.08
90	Window	5,00	1.2743		0.54612		1	0.08
91	Window	5,00	1.2743		0.54612		1	0.08
92	Window	2,70	1.2743		0.54612		1	0.08
93	Window	2,70	1.2743		0.54612		1	0.08
94	Window	1,30	1.2743		0.54612		1	0.08
95	Window	1,30	1.2743		0.54612		1	0.08
96	Window	Maint. Solar shading	1.2743		0.54612		1	0.08
97	Window	Maint. Solar shading	1.2743		0.54612	2.2	1	0.08
98	Window	Shading	1.2743		0.54612	2.2	1	0.08
99	Window	Shading	1.2743		0.54612	2.2	1	0.08
100	Window	Shading	1.2743		0.54612	2.2	1	0.08
101	Window	Shading	1.2743		0.54612	2.2	1	0.08
102	Window	Shading	1.2743		0.54612	2.2	1	0.08
103	Window	Shading	1.2743		0.54612	2.2	1	0.08
104	Window	1,89	1.2743	1.7	0.54612	2.2	1	0.08
105	Window	1,89	1.2743	1.7	0.54612	2.2	1	0.08
106	Window	Shading	1.2743		0.54612	2.2	1	0.08
107	Window	Shading	1.2743		0.54612	2.2	1	0.08
108	Window	1,89	1.2743	1.7	0.54612	2.2	1	0.08
109	Window	1,89	1.2743	1.7	0.54612	2.2	1	0.08
110	Window	Ventilation	1.2743		0.54612	2.2	1	0.08
111	Window	Ventilation	1.2743		0.54612	2.2	1	0.08

Appendix D. Energy demand scenarios in the shopping centres

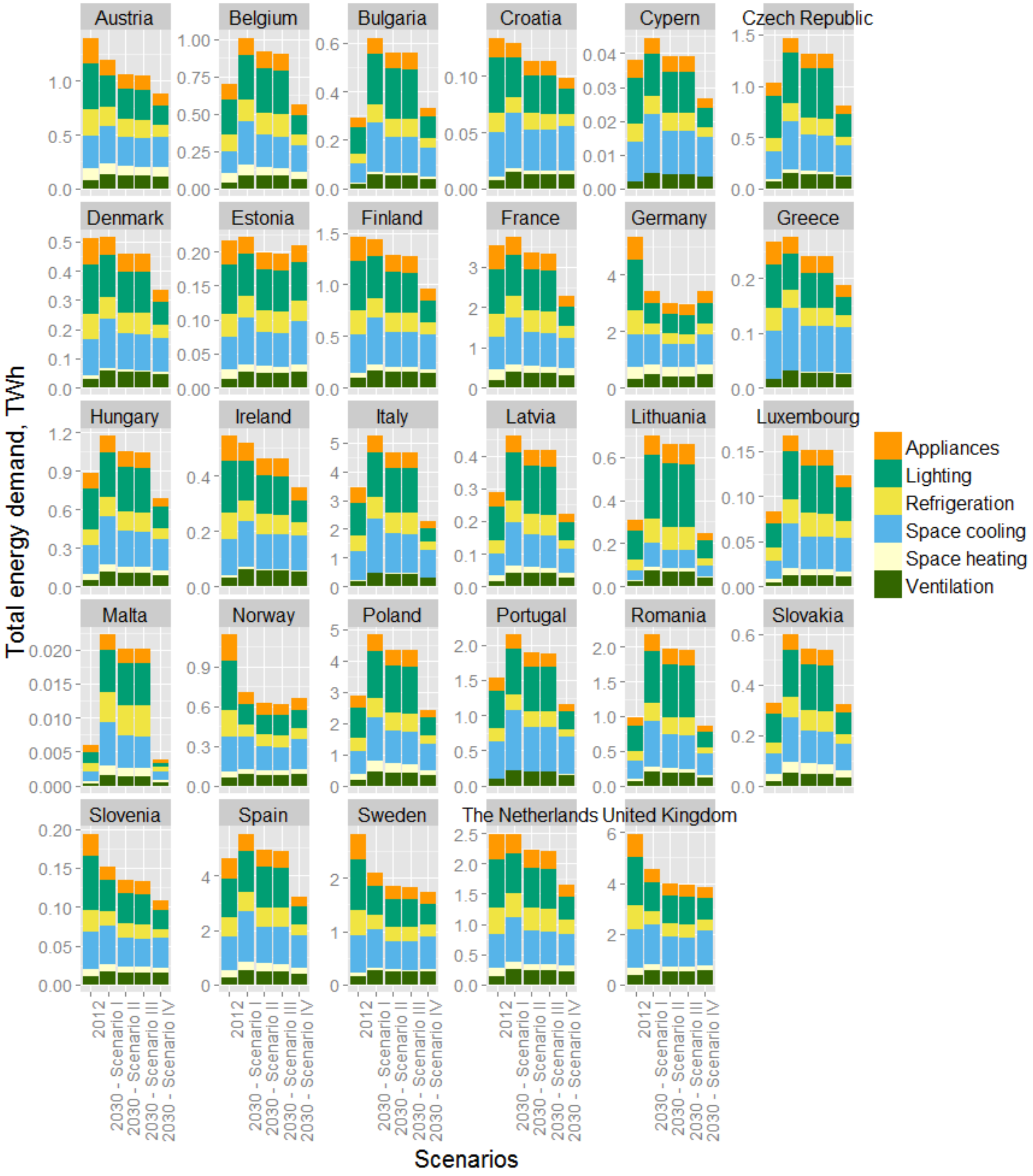

Fig. 69 Total energy demand by services in the European shopping center building stock in 2012 and 2030 in four scenarios (Chapter 7.1.6)