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The costs and potentials for heat savings in buildings: Refurbishment costs and heat saving cost curves for 6 countries in Europe

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ABSTRACT

Around 25% of final energy consumption in the European Union is currently used for space heating. The potential for reducing this demand through renovation of existing buildings is very significant and recognised to be an important factor for reaching CO_2 reduction targets. In this analysis we develop two types of cost curves for heat savings in buildings in 6 European countries. This is based on a detailed representation of the existing building stocks and an analysis and comparison of costs and effects of refurbishment actions for several levels of heat savings in each representative building in these countries. We find that the costs for reaching savings of 40–60% are remarkably cheaper than for reaching higher savings and that the highest and cheapest savings are located in buildings that are still not renovated. We also find the following highly influencing factors on the costs of renovation measures: the share of window area in the envelope, the surface-to-volume ratio and the current heat demand. The results of this work can be further used to investigate cost optimal levels of heat savings versus heat supply in order to draw the right decisions on the way to an efficient and low CO_2 energy system.

1. Introduction

In 2012 more than 50% of the total final energy consumption in the European Union was used for heating and cooling purposes, 52% of this demand was needed for space heating [1]. Also in recent years it has been shown that there is a large potential for reducing this demand by decreasing the heat losses through the buildings' surface by insulating exterior walls, building bases, roofs and attics and by changing existing windows for windows with lower transmission losses. Several studies identified saving potentials in European countries in the range between 75% and 80% (e.g. [2,3]). It is also a fact that renovation activities become more and more expensive the higher is the ambition of saving due to higher insulation thicknesses and better quality of the windows (e.g. [4]). This of course brings up the question to which energy demand existing buildings should be refurbished in order to be cost efficient in comparison with heat supply or with saving options in other sectors.

The intention to identify such cost optimal refurbishment levels of existing buildings is nothing new, but has come to the focus in the last 10 to 15 years since the growing recognition of the importance of the building sector for climate change mitigation. The authors of [5] provide a review of studies that analysed the energetic and economic performance of retrofit measures. They show that a variety of different approaches have been used for this purpose in the past and they give a proposal for a systematic framework of analyses that should be undertaken when a building is planned to be retrofitted. They also show that the focus of many studies was on finding cost optimal measures for single buildings or types of buildings, as e.g. [6] analyse the economic and energetic performance of saving measures in a common Greek building type, or a more general approach as e.g. from [7], who intends to find optimal insulation thicknesses when renovating buildings. But there also exists research that tries to find cost optimal renovation measures for more than one building out of an existing building stock. [8] analyse the energetic and economic performance of energy saving measures for 5 reference buildings in Belgium in order to be able to draw conclusions for the Belgic building stock. They analyse various options for insulation, glazing and hot water production and their combinations and presented a prioritization

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based on a net present value calculation. [9] analyse the energy performance and economic viability of measures to increase the energy performance of Finnish brick apartment buildings built in the 1960s. They studied a large number of different combinations of measures using a multi-objective optimisation to identify cost-optimal solutions on a 25-year discounted period. They find renewable energy supply technologies being more cost effective to implement than measures to reduce transmission losses through the building surface. [10] use a methodology following European Directives to find cost-optimal renovation solutions for multi-family buildings built between 1990 and 2007 located in Barcelona. They take active as well as passive measures into account and include technical and economic information comparing global costs over a 30 years period. While these two studies focus on a specific type and construction period of buildings in a selected country, [11] analyse the effects of different measures applied to the Italian residential building stock using the building typology developed in the TABULA project. They use five climatic zones, 4 building categories and one level of refurbishment for each part of the building shell and include changes in the heating system and the domestic hot water system. For the evaluation of the cost effectiveness of the measures and their combinations they use a methodology in line with the EPBD recast (Directive 2010/31/EU) [12].

For presenting and comparing the costs and performance of various measures for saving energy (and emissions) cost curves are a common instrument in energy economics. They show the cumulated potentials for energy supply or conservation options on the x-axis and the related costs of each supply or conservation option on the y-axis. The supply or conservation options are hereby ranked from the cheapest to the most expensive. Two different types of cost curves can be distinguished: cost curves showing for each amount of cumulated potential the average costs of supply or conservation, and marginal cost curves, showing for each amount of cumulated potential the costs of the last option. Cost curves and especially marginal abatement cost (MAC) curves are a widely used methodology to prioritise political intervention according to costs and related potentials (e.g. [13–20]). The method to calculate the economic feasibility of energy efficiency investments was initially developed in the 1970 s after the oil price crises. Meier (1982) (cited in [21]) developed the first cost curve called conservation supply curve for the reduction of electricity consumption. This tool started to be widely used in transport, industry and building sectors to investigate energy efficiency improvements and their economic feasibility. Starting with the analysis between several technologies providing the same energy savings, this tool was then extended showing the quantity of energy conservation for the whole service if everyone opted for more efficient devices compared to a standard [21]. By using cost curves it is possible to show the total amount of energy savings that could be reached via certain saving options for a particular end-use together with the cost per unit of conserved energy for each of the saving options [21]. There are many cost curves showing emissions abatement costs for different sectors and mitigation measures, however only several providing a detailed analysis for the building sector and related energy efficiency measures. [4] provide an analysis for the Swiss building stock. He analyses the costs and savings of different measures on different parts of the buildings for different types of buildings and rank the measures according to their marginal costs. He also includes an economic valuation of co benefits such as improved comfort, indoor air quality etc. However, no comparison of measures in different buildings is performed, thus no prioritisation of buildings is done to identify which buildings should be treated in which way in order to reach certain cumulated saving levels. [16] analyse the CO_2 saving potential in the Thai building sector and their respective marginal abatement costs taking into account 7 different measures. [17] develops MAC curves for the UK domestic building stock. He focuses on the CO_2 emission reduction and the interaction of the domestic stock with other sectors using the MARKAL model combined with decomposition analysis. However, no focus is laid on the identification of measures in various types and construction periods of buildings for prioritization of action. Also in course of the 4th of the Heat Roadmap Europe series of projects cost curves for heating and cooling demand reduction have been developed. Based on two residential and several tertiary building categories, 5 construction periods and 15 different renovation measures cost potential curves have been calculated for 14 different EU countries [22].

We contribute to the discussion on finding cost optimal levels of refurbishment via calculating detailed energy saving cost curves for renovation of the building stocks in different countries of Europe. The novelty of the approach is the high level of detail in the reflection of the existing building stocks (i.e. the high number of representative buildings, and also the representation of the non-residential buildings), the high number of possible renovation levels be performed for each representative building (10 packages of measures on different parts of the building surface for each representative building), the analysis and comparison of refurbishment costs from different sources for different countries, and the application of the approach for several countries in Europe that differ remarkably in climate, status of refurbishment in existing buildings and cost level of refurbishment actions. Furthermore we focus on actions on the building shell in order to allow for a separate comparison of saving vs. supply options in a consecutive step. This allows for an identification of which buildings to renovate to which level in order to reach certain overall saving levels, and for a calculation of cost optimal renovation levels for regions and countries when comparing the resulting costs with the costs for providing heat in the buildings.

Despite the wide use and derivation of abatement cost curves various authors and studies call for caution when using cost curves for policy decisions (e.g. [23–25]). The authors of [23] discuss the factors to be taken into account when using MAC curves by policy makers. They especially stress the following issues: cost curves are only a static representation of costs for a single year, they are not able to consider path dependency, most often do not consider ancillary benefits of saving options, and are unable to consider wider social implications. They recommend to pay attention to the assumptions behind the curves, to always look beyond technology costs and to consider the uncertainty rising from the before mentioned issues.

We agree to these shortcomings of the cost curves for decision making and therefore try to show the methods, assumptions and underlying data as transparent as possible. Furthermore, we see the main benefit of this work in developing and showing cost data for refurbishment actions on a detailed basis being possible to use for entire building stocks of countries and cities, linking these data with a detailed representation of the existing building stocks, and thus the preparation of the data necessary in order to increase insights for policy decision in comparison of these detailed data with as well detailed data on costs of heat supply at various locations.

2. Methodology and input data

The analysis is performed for each investigated country according to the following steps: 1) analysis of the existing building stocks and possible renovation, demolition and construction rates, 2) analysis of costs of various refurbishment actions for different parts of the building envelope, 3) compilation of combinations of renovation actions to packages for pre-defined savings at minimum investment costs, and 4) calculation of cost curves for existing buildings. In the subsequent subchapters we describe the methodology used in each of these steps and the input data used for the generation of the cost curves.

Fig. 1 gives an overview of the calculation process to derive the heat saving cost curves: grey and green boxes show the input data to the calculation process, blue boxes represent the different calculation modules of the Invert/EE-Lab model used in the analysis, and the orange box presents the final results of the calculation.

2.1. Analysis of the existing building stock and derivation of demolition, construction and renovation rates

The analysis of heat savings and associated costs for space heating in the countries under investigation is based on the representation of the existing building stocks of these countries in the Invert/EE-Lab database. The database consists of a number of representative buildings and their properties, and it is organised in a hierarchical structure. The top level, our so-called "building category" level, summarizes buildings based on fundamental building characteristics such as type of usage or size, e.g. single family houses, row houses or public offices. According to the structures of the data sources we distinguish between 14 and 35 building categories per country. The second building structure level, the "building classes" level, clusters buildings that belong to the same building category and that share the following characteristics: geometry, types and properties of the building envelope elements, mechanical ventilation system, climate region and user profiles. Depending mainly on the details of information on historical renovation actions and the number of climate regions distinguished in the country the database contains between 330 and 1370 building classes for the countries of this analysis. The lowest level of the used hierarchical buildings structure represents the "building segments" level, which finally clusters all buildings that belong to the same building class and having the same heat supply and distribution system as well as belonging to the same region with respect to the availability of energy carriers. The database has been compiled in various projects in the last years and is based on data from various national and international sources (see Table 1).

In this study we apply the energy need as the value for quantifying energy demand savings. We understand this as the amount of heat that has to be delivered to a building in order to keep the building indoor temperature at a desired temperature level. Following the definition of building classes in the building stock database as given above, all buildings belonging to the same building class have the same energy need. We calculate the energy needs as the energy use for space heating, cooling or domestic hot water production according to the calculation procedure given in the Austrian Standard ÖNORM B8110 [46], which is the national implementation of the international ISO 13790 [47]. Among the available calculation approaches specified in [47], the quasi-steady-state monthly energy balance approach is used. We are aware that this method might not be as accurate as more complex dynamic simulation approaches. Therefore, in [48] we compared the results of the Invert/EE-Lab model with simulations performed with the EnergyPlus model [49]. The analysis shows that for the given purpose the implemented approach derives results with sufficient accuracy for a wide range of buildings and climate regions from Seville in southern Spain to Helsinki in Finland and that the uncertainties of the results are more prone to the input data than to the calculation approach. In the model we calculate two different variants of the energy needs: a) the "standard energy needs" and b) the "effective energy needs". When the standard user profiles (set temperature, occupation & operation hours, ventilation rates, etc.) are used as specified in the national [50] and European wide [47] standards, then we call this the "standard energy needs". However, extensive literature shows that the results derived by using these standard user profiles drift from measured energy consumption observations. Furthermore, this literature indicates that these deviations cannot only be ascribed to the behaviour of individual users, but that a systematic drift can be observed. The most important factors that describe these systematic deviations are the

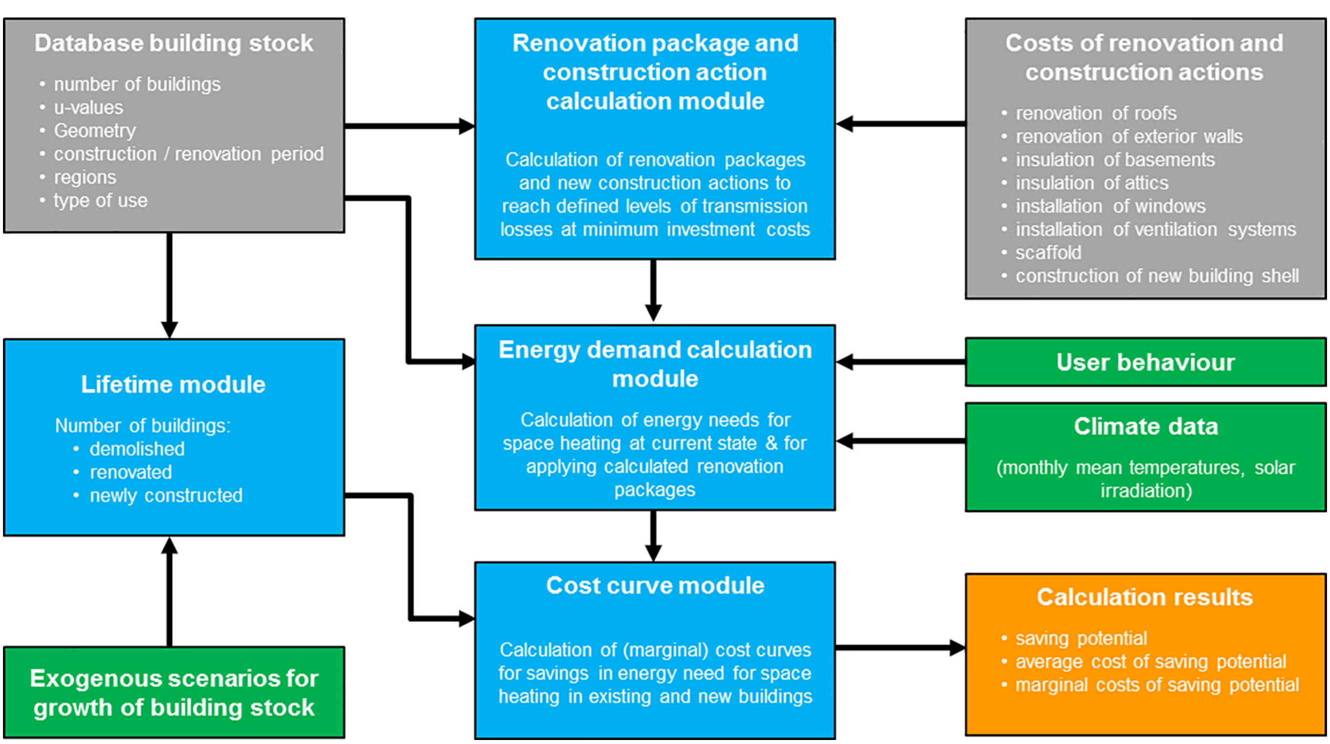


Fig. 1. Structure of the calculation process to derive cost curves with the Invert/EE-Lab model.

Table 1
Main data sources for building stock and related energy consumption data.

Country	Main data sources
Austria	[26,27,28,29,30]
Czech Republic	[31,26,27,28,32,33]
Germany	[26,27,28,34,35,36,37,38,39]
Denmark	[26,27,28,40]
Italy	[26,27,28,41,42]
Romania	[26,28,43,44,45]

floor area per dwelling and the average area-specific heat transfer coefficient: buildings are only partly heated if the total energy demand or the costs associated with the energy consumption per dwelling are high. In our approach, this user behaviour is mainly reflected by different indoor set temperatures for different levels of energy needs, apartment size (m^2) and climate conditions. For a summary of conclusions of available literature and more information on the implementation of this effect in the Invert/EE-Lab model see [30]. If we calculate the energy needs with these adapted indoor set temperatures we call this the "effective energy needs". For the development of the cost curves in this analysis we only use the effective energy needs in order to reflect the rebound effect that occurs after renovation of buildings. The following Fig. 2 shows the weighted average effective energy needs of all buildings in the aggregated building categories in the year 2010. Fig. 2 shows that there exist remarkable differences between the analysed countries. In Romania and Austria the effective energy needs are higher compared to the other countries for most building categories, while Italy and Denmark show the lowest values.

In this paper we analyse the potential savings of the energy need for space heating by refurbishment actions of the building envelope. Such measures do not affect the energy need for hot water preparation; therefore we do not take this energy demand into account in our analysis. All energy need values in this paper exclude the energy need for hot water preparation.

It is a fact that the stock of buildings is changing over time. Not only new buildings are constructed and existing buildings are maintained or renovated, also a part of the existing buildings are demolished. Thus, the building stock in the year 2050 will not consist of the same buildings as today. We model the timing of such developments in the building stock on the basis of Weibull distributions for expectable lifetimes of the different parts of the building shell as well as the buildings itself. Underlying empirically observed lifetimes and depending on the age of the buildings in the stock we calculate with the lifetime module of Invert/EE-Lab that between 10% (Czech Republic) and 25% (Denmark) of the buildings gross floor area existing in 2010 will be demolished in 2050. For the renovation of the different parts of the buildings envelope between 2010 and 2050 we assume a lifetime of 40 years strictly, thus leading to a cumulated renovation rate of 100%. To calculate the construction rate we use the fact that the difference between the total number of buildings to be expected in 2050 and the number of buildings still existing from the stock from 2010 has to be newly constructed. To estimate the number of buildings to be expected in 2050 we use data for the development of the population, the average household size (persons) and the GDP from the PRIMES reference scenario 2013 [51]. We use these renovation, demolition and construction rates to derive the potential for energy savings from 2010 to 2050.

Based on the sources given in Table 1 for the existing building stocks in the analysed countries and the assumptions and method for deriving the development of the building stock as described we use the values as stated in Table 2 for the existing building stocks in 2010 and its development until 2050. Basing the demolition and construction rates on the total gross floor area of buildings in 2010 between 10% (Czech Republic) and 25% (Denmark) of the buildings gross floor area is demolished, and between 9% (Czech Republic & Romania) and 46% (Denmark) of the buildings gross floor area is newly constructed from 2010 to 2050.

For further details on the calculation methodology of energy demand, construction and demolition rates, underlying data of user behaviour and calibration of age and lifetime distributions we refer to the detailed description of the Invert/EE-Lab model in [30].

2.2. Analysis of costs and energy savings from refurbishment activities in the building stock

In order to set the costs of refurbishment actions in buildings we analyse and compare different literature and data sources for the countries under investigation. We hereby distinguish between actions at different parts of the building envelope: insulation of exterior walls, insulation of roofs and attics, insulation of the building base and change of windows. First, we collect cost data of a number of performed refurbishment activities leading to different levels of savings from different data sources distinguishing between actions on the before mentioned 5 parts of the building envelope. Then we compare them on the basis of total investment costs per area of treated building surface, and a) thicknesses of insulation material or b) thermal transmittance of windows.

In the data compilation and the comparison of different data sources we use full costs of refurbishment actions excluding value added tax (VAT). Additional costs of energy saving actions, which we display in the cost curves, are calculated by subtracting the costs of a maintenance action from the full costs of each renovation action.

2.2.1. Costs of refurbishment activities

In order to derive costs for refurbishment actions on different parts of the buildings envelope in different countries in Europe we use data for Germany from [52] and transform them to costs for other countries using the European construction cost index as stated in [53]. The main reason to use this study and not to rely on different national data sources is the level of detail provided: [52] analysed a number of performed refurbishments in German buildings and derive (linear) cost functions for each single part of the building that can be refurbished in order to decrease the energy needs of the buildings. Having cost functions for renovation actions of each single part of the buildings is necessary in order to derive renovation packages for a high number of possible levels of heat savings for each building class. Furthermore [52] also state the costs that occur in case that only maintenance of the different building parts is performed.

In order to verify the validity of the calculated values for each country under investigation we compare them to values from national data sources. In course of the Intelligent Energy Europe (IEE) project ENTRANZE cost data for refurbishment activities were collected for a number of European countries [54]. These cost data were derived on the basis of recent refurbishment projects, standard offers of renovation projects as well as existing cost databases in these countries [55]. From the countries under investigation in this study only for Denmark no data was collected within ENTRANZE. For Denmark we use the following sources for verification: [56–58].

The comparison of investment costs for refurbishment actions of the building envelope between the data used in this analysis and national data sources is shown in the following Fig. 3 for the different parts of the building shell. We find that on the one hand there exist remarkable differences between the values stated in different sources even for single countries, but on the other hand

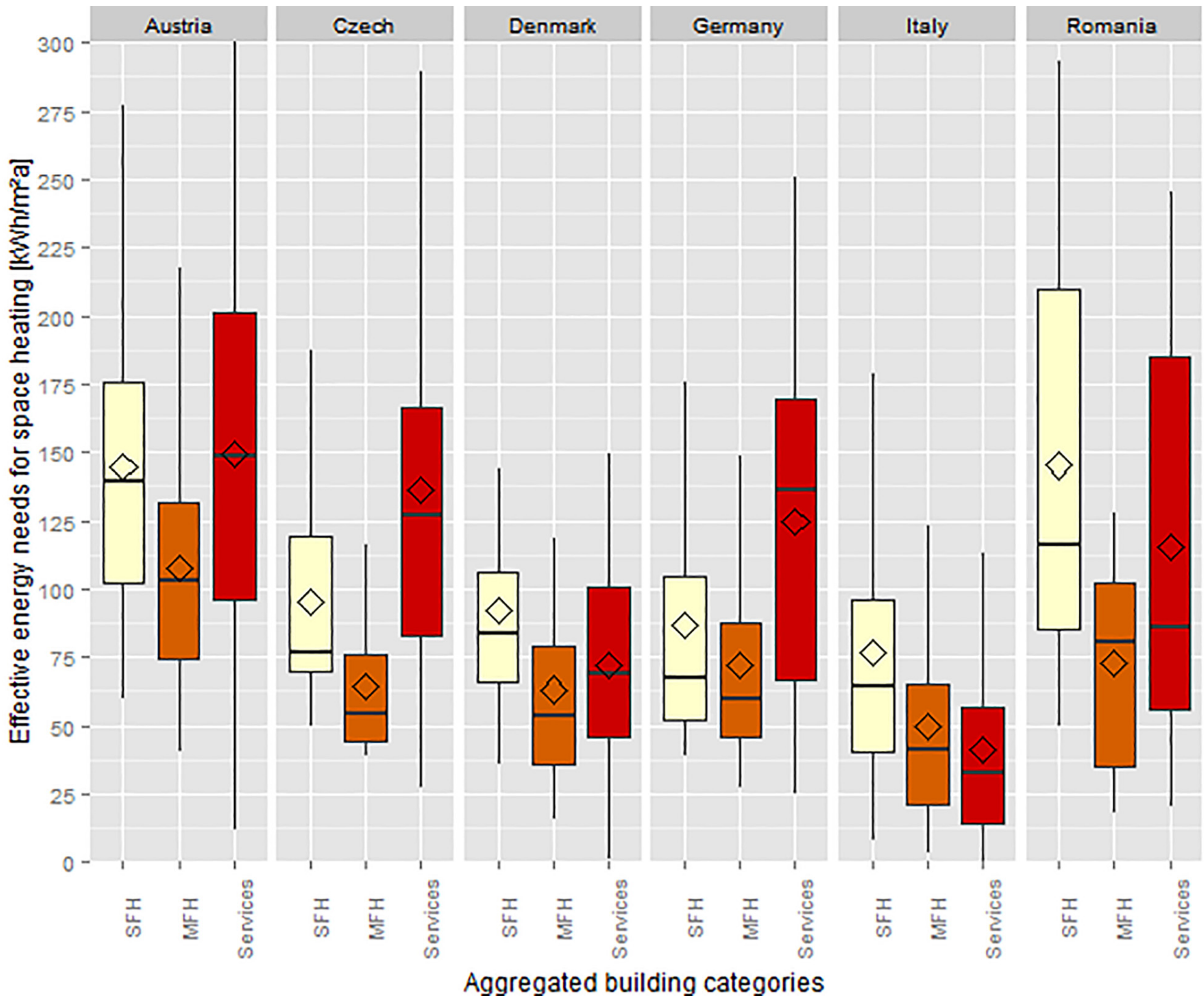


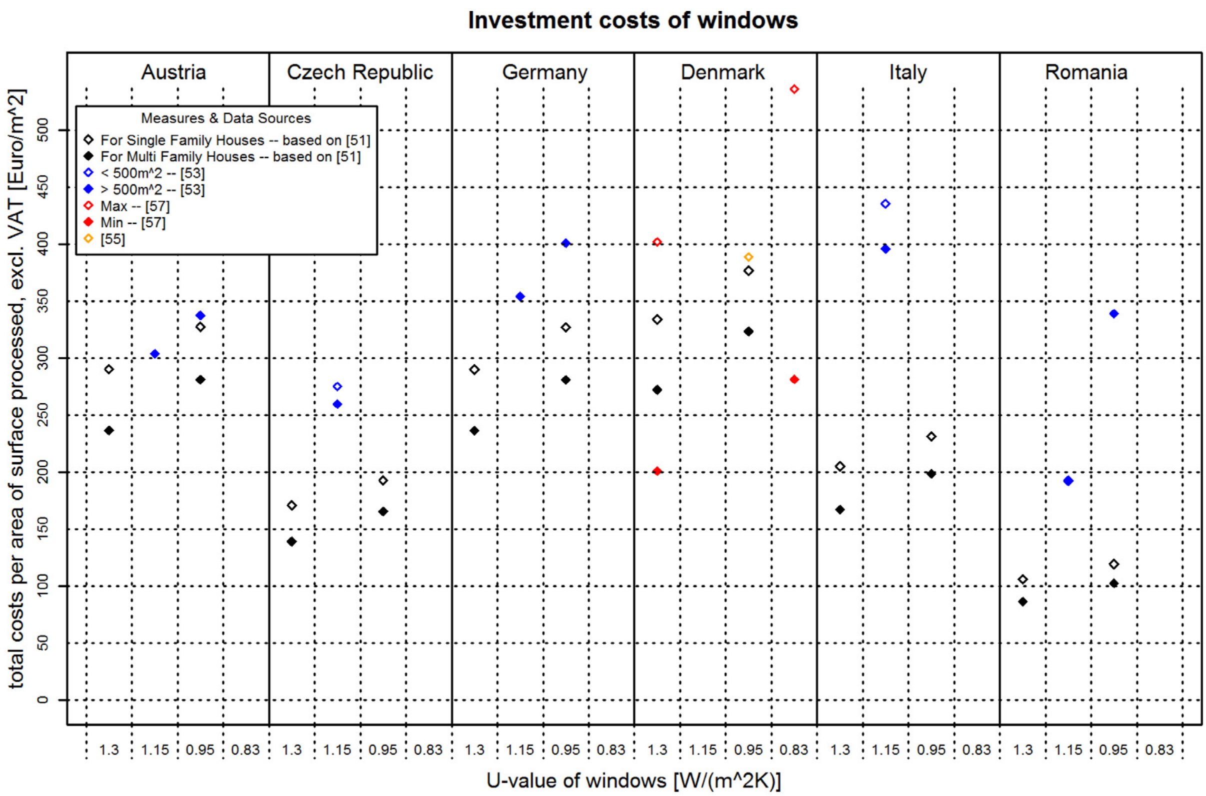
Fig. 2. Distribution of effective energy needs for space heating per gross floor area of the buildings in the different building categories in the analysed countries (Source: Invert/EE-Lab database, values for 2010; SFH … single family houses, MFH … multi-family houses).

Table 2
Development of the gross floor area of the building stock from 2010 to 2050 as used in the analysis (values given in Mio. m^2, sources for 2010 are stated in Table 1, 2050 values are calculated with Invert/EE-Lab as described in Section 2.1).

	Austria			Czech Republic			Germany		
	2010	2050		2010	2050		2010	2050	
		From stock 2010	New		From stock 2010	New		From stock 2010	new
Single Family Houses	268.9	232.9	83.5	241.8	215.1	22.7	2405.0	1965.1	131.3
Multi Family Houses	158.8	135.7	51.8	160.8	145.7	12.2	1632.2	1329.3	113.6
non-residential buildings	167.9	123.9	75.1	91.4	82.8	10.8	1380.3	874.1	315.2
	Denmark			Italy			Romania		
	2010	2050		2010	2050		2010	2050	
		From stock 2010	New		From stock 2010	New		From stock 2010	New
Single Family Houses	216.5	153.4	114.2	1025.5	888.9	240.3	392.9	317.2	48.6
Multi Family Houses	88.3	49.7	55.1	2390.5	2075.5	349.4	204.4	182.7	8.0
non-residential buildings	129.1	120.3	29.8	435.7	287.0	201.1	77.7	69.6	1.2

that the values calculated as described in chapter 2.2.1 based on [52] for the different countries are similar to national data sources for many cases. The existence of partly remarkable differences between the sources is understandable as all sources are limited in the number of refurbishment actions taken into account for calculating average cost values. Also the exact implementation of the refurbishment actions differs a lot between countries and buildings leading to corresponding differences in the resulting costs. Even for buildings of the same type and age in the same country different refurbishment investments may apply depending on the needs of the building owners.

Looking at the figures we see the following three biggest differences in the comparison between national data sources and our calculations based on [52]: 1) windows in Italy and Romania are



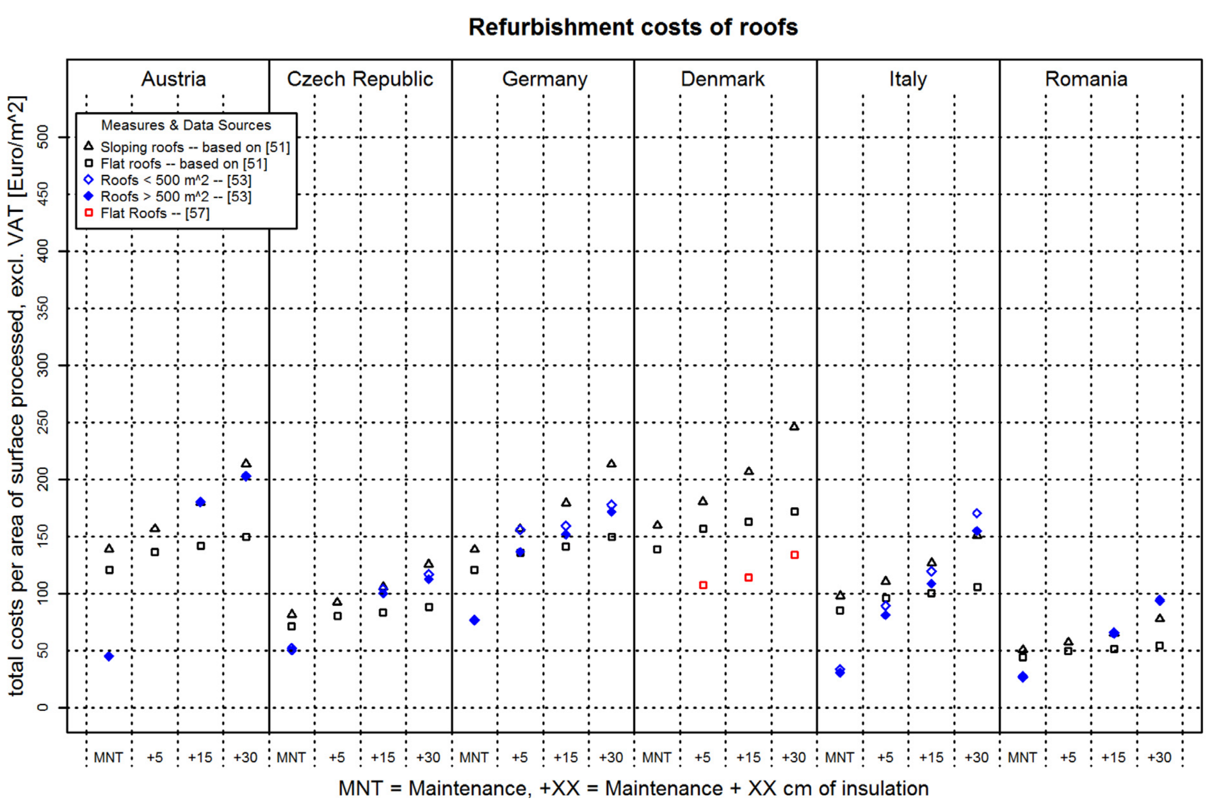
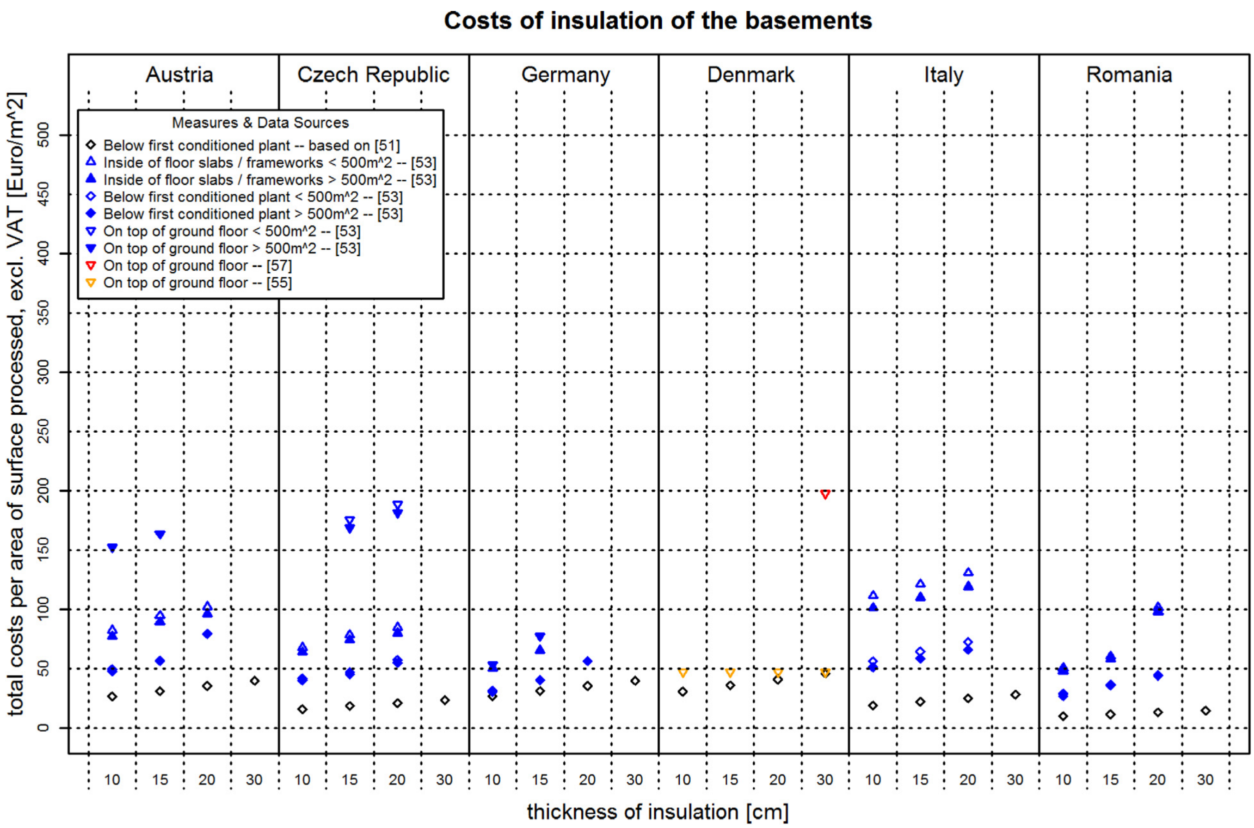


Fig. 3. Total investment costs for renovation (and maintenance) activities on different parts of the buildings from different data sources for the countries under investigation.



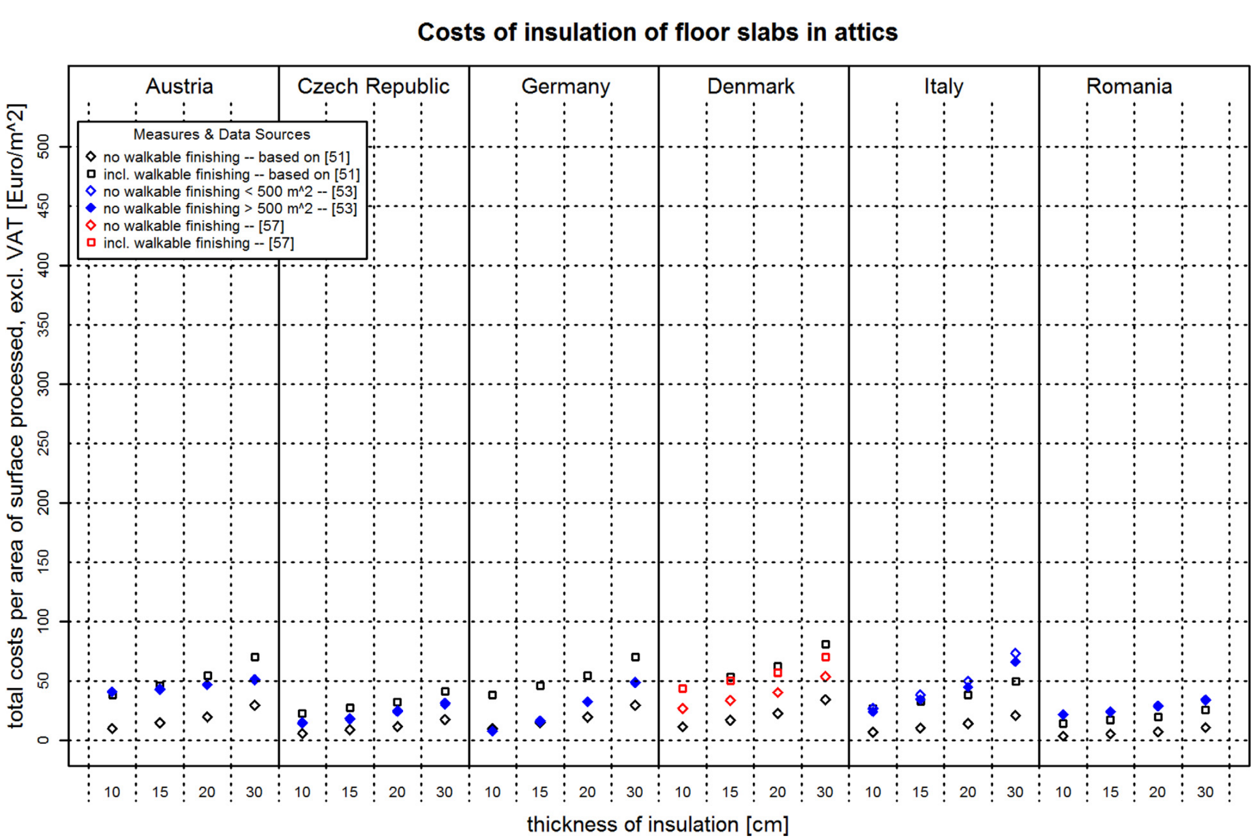


Fig. 3 (*continued*)

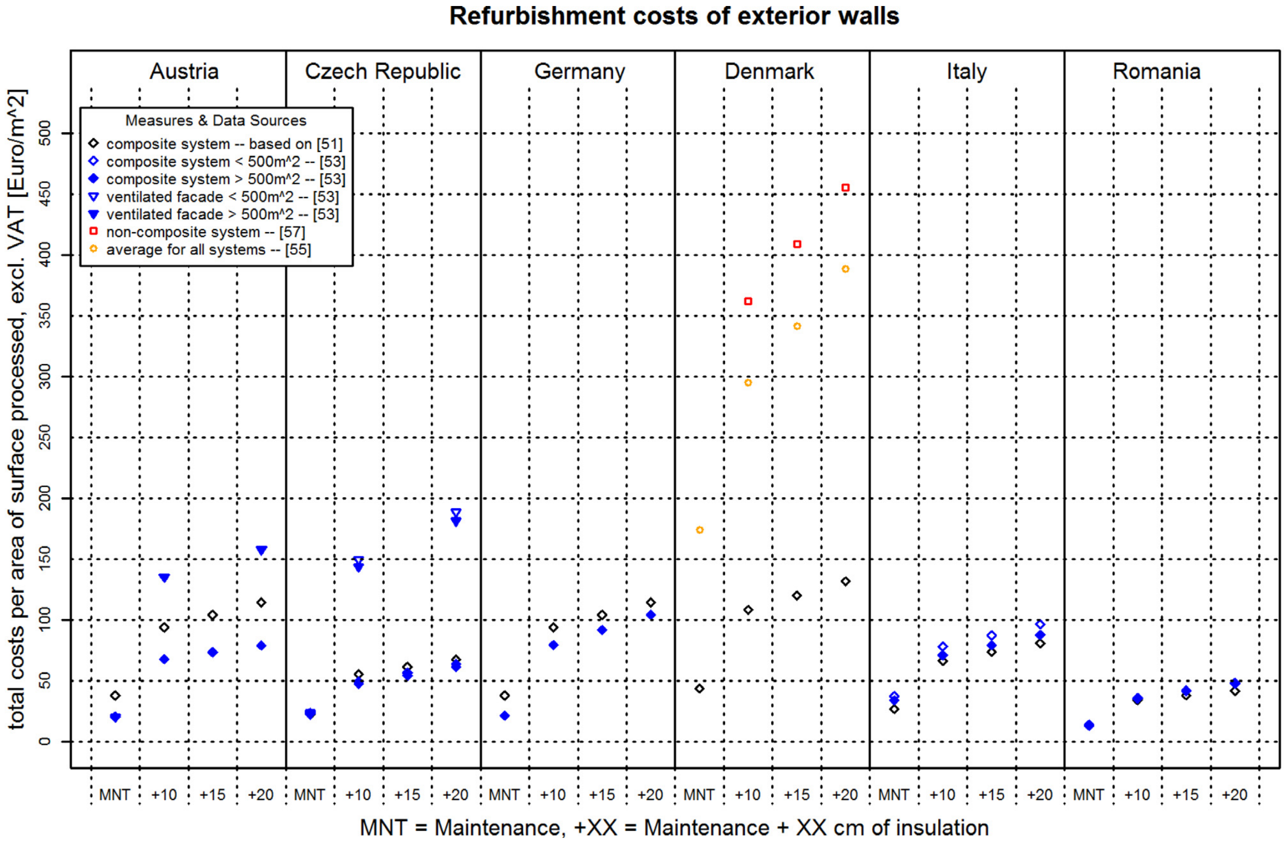


Fig. 3 (*continued*)

between twice and triple as expensive according to national sources as based on our calculation. We do not find an evidence for windows being so expensive in these countries, and for us it is not understandable that windows in Italy are more expensive than in Germany or Denmark, and that in Romania they cost as much as in Austria or Germany. 2) While the total costs for refurbishment actions on roofs are similar between the different data sources and our calculation, remarkable differences can be seen for the maintenance cost of roofs. We assume that this is due to differences in the activities understood as being part of a maintenance action. However, it is not possible to further trace that difference as no details about the composition of maintenance costs from the national sources is provided. 3) The national data sources for Denmark show investment costs for refurbishment of exterior walls three times as expensive as according to our calculation. We believe that this is mainly due to the fact that the national sources refer to a non-composite system and the average of all possible systems, while in [52] the data refer to a composite system.

Costs of measures to reduce the cooling need of the buildings are not taken into account in the calculation. However, the lower is the thermal conductivity of the outer surface of the buildings the higher is the resulting cooling need in the buildings, unless shading measures are undertaken (see e.g. [59]).

2.2.2. Development of renovation packages to reach different levels of energy needs

In order to get detailed curves for possible heat savings in existing buildings we calculate 10 different packages of measures for each building class according to the following idea: Package 1 represents a maintenance action to extend the lifetime of each building component but without a decrease of the energy needs. Package 2 represents a refurbishment activity inspired by the requirements for renovation actions stated in the national building codes. We use the interpretation of the national building codes in terms of thermal transmittances according to [60] and [61] (see Table 3). Packages 3 – 10 represent different levels of refurbishment leading to transmission heat losses relative to the value reached by implementing the national standards of 190%, 175%, 160%, 145%, 130%, 115%, 85% and 70%.

To derive the combinations of measures on different parts of the buildings envelope reaching certain levels of transmission heat losses at minimal investment costs we use an integer linear optimisation

Table 3
Thermal transmittance [W/m^{2}K] used in the analysis to reflect renovation actions according to definitions in the national building codes (set on the basis of [60,61]).

	Austria		Czech Republic		Germany		Denmark		Italy		Romania	
	res	non-res	res	non-res	res	non-res	res	non-res	res	non-res	res	non-res
Ceiling/roof	0.38	0.42	0.19	0.19	0.24	0.24	0.10	0.15	0.31	0.31	0.20	0.20
Exterior walls	0.53	0.67	0.24	0.24	0.24	0.24	0.15	0.20	0.35	0.35	0.56	0.56
Basement	0.71	1.11	0.36	0.36	0.50	0.50	0.10	0.12	0.35	0.35	0.22	0.22
Windows	1.42	1.54	1.20	1.20	1.30	1.30	1.40	1.65	2.29	2.29	1.30	1.30

* res – residential buildings; non-res – non-residential buildings.

$$Min(\sum_j a_b^{EW} \cdot c_j^{EW} \cdot X_{b,j}^{EW} + \sum_j a_b^{RA} \cdot c_j^{RA} \cdot X_{b,j}^{RA} + \sum_j a_b^{BA} \cdot c_j^{BA} \cdot X_{b,j}^{BA} + \sum_j a_b^{WI} \cdot c_j^{WI} \cdot X_{b,j}^{WI} + a_b^{SC} \cdot c^{SC} \cdot X_b^{SC})$$

EW: Exterior Walls; RA: Roofs/Attics; BA: Basements; WI: Windows; SC: Scaffolds

with a being the surface areas of each of the respective building envelope components in building class b, c the investment costs per surface area for each possible level of refurbishment j (thickness of insulation for exterior walls, roofs/attics and basements or quality of windows), and X being binary variables to specify if a certain refurbishment level is possible or a scaffold is needed for that refurbishment activity. For each building class of the existing stock we calculate these renovation packages taking into account the current state of the buildings. The renovation packages resulting in transmission heat losses higher than the value before renovation are discarded in the further analysis.

Fig. 4 shows the range of effective energy need for space heating as well as the total investment costs that occur in the different building classes in the analysed countries when implementing one of the 10 defined packages. As the maintenance action has no effect on the energy needs these values therefore reflect the current state of energy need.

2.3. Calculation of cost curves for heat savings in buildings through renovation actions

In this analysis we develop two different types of cost curves:

1. Marginal Energy Saving Cost Curves (MESC-Curves): These curves show for each amount of energy demand savings (x-axis) the costs of the last renovation action to be taken to reach these savings (y-axis).
2. Energy Saving Cost Curves (ESC-Curves): These curves show for each amount of energy demand savings (x-axis) the average costs of all renovation actions to be implemented to reach these savings (y-axis).

In the following section we first describe the procedure to generate a MESC-Curve, and then explain the additional steps to generate an ESC-Curve. The steps 1 to 4 of this procedure are shown in Fig. 5 for an example of two building classes and three renovation packages. Fig. 6 then shows exemplary MESC and ESC-Curves graphically.

1. For all combinations of building classes[1] and renovation packages[2] calculate the following two values:
   a. The savings of energy need[3] $\Delta q_{i,j}$ in kWh per year and square meter of gross floor area in buildings of the building class i as the difference between the energy need after implementation of renovation package j $q_{i,j}$ and the energy need after implementation of the reference action[4] $q_{i,ref}$:

$$\Delta q_{i,j} = q_{i,j} - q_{i,ref}$$

   b. The additional costs $\Delta c_{i,j}$ of implementing renovation package j in buildings of the building class i as the difference between an investment in renovation package j $c_{i,j}$ and the investment in the reference action $c_{i,ref}$. Hereby we distinguish between two different indicators for the additional costs:
      i. Additional investment costs in € per square meter of gross floor area:

$$\Delta c_{i,j} = c_{i,j} - c_{i,ref}$$

      ii. Additional annualised investment costs in € per kWh saving applying the annuity factor a[5]:

$$\Delta c_{i,j} = \frac{(c_{i,j} - c_{i,ref}) \cdot a}{\Delta q_{i,j}}$$

2. Rank the combinations of building classes and renovation packages according to additional costs $\Delta c_{i,j}$ from lowest to highest
3. Sort out combinations of building classes and renovation packages that provide fewer savings than the previous ranked renovation package in the same building class, i.e. packages being more expensive and at the same time resulting in fewer savings for the same building classes than others. For the resulting sequence of combinations of building classes and renovation packages after this step we will further on use the index k (see steps 6 to 9)
4. Calculate marginal savings of energy need $\Delta q_{m,i,j}$ in kWh per year and square meter of gross floor area in buildings of the building class i as the difference between the savings of energy need implementing renovation package j and the savings of energy need implementing the previous ranked renovation package:
   a. For the cheapest (and thus the first ranked) renovation package in each building class i:

$$\Delta q_{m,i,1} = \Delta q_{i,1}$$

   b. For all other renovation packages $j \neq 1$ in each building class i:

$$\Delta q_{m,i,j\neq 1} = \Delta q_{i,j} - \Delta q_{i,j-1}$$

5. Calculate marginal savings of energy need $\Delta Q_{m,i,j,y}$ in a given year y in TWh for all buildings in building class i when implementing renovation package j according to

$$\Delta Q_{m,i,j,y} = \Delta q_{m,i,j} \cdot A_i \cdot r_{ren,i,y} \cdot (1 - r_{dem,i,y}) \cdot 10^{-9}$$

where A_i is the total gross floor area of buildings in building class i in the base year of calculation, $r_{ren,i,y}$ is the cumulated renovation rate of buildings in building class i between the base year and year

[1] For a definition of building classes and the number of classes per country we refer to chapter 2.1.

[2] For this study we defined 10 renovation packages for each building class with one of them being the reference action. It is important for the understanding of the calculation procedure to recall that the renovation packages are independent from each other, i.e. either one or another package can be implemented (see chapter 2.2.2).

[3] In this analysis we take into account renovation actions of the building shell but exclude changes in heating systems that can also lead to a decrease in fuel demand for space heating. As written in chapter 2.1 we use the effective energy needs as indicator for energy savings.

[4] In this analysis the reference action is a maintenance action without thermal improvement of the building envelope.

[5] For all calculations in this analysis, except for the sensitivity calculations, we use a lifetime of 40 years and an interest rate of 4% to derive the annuity factor.

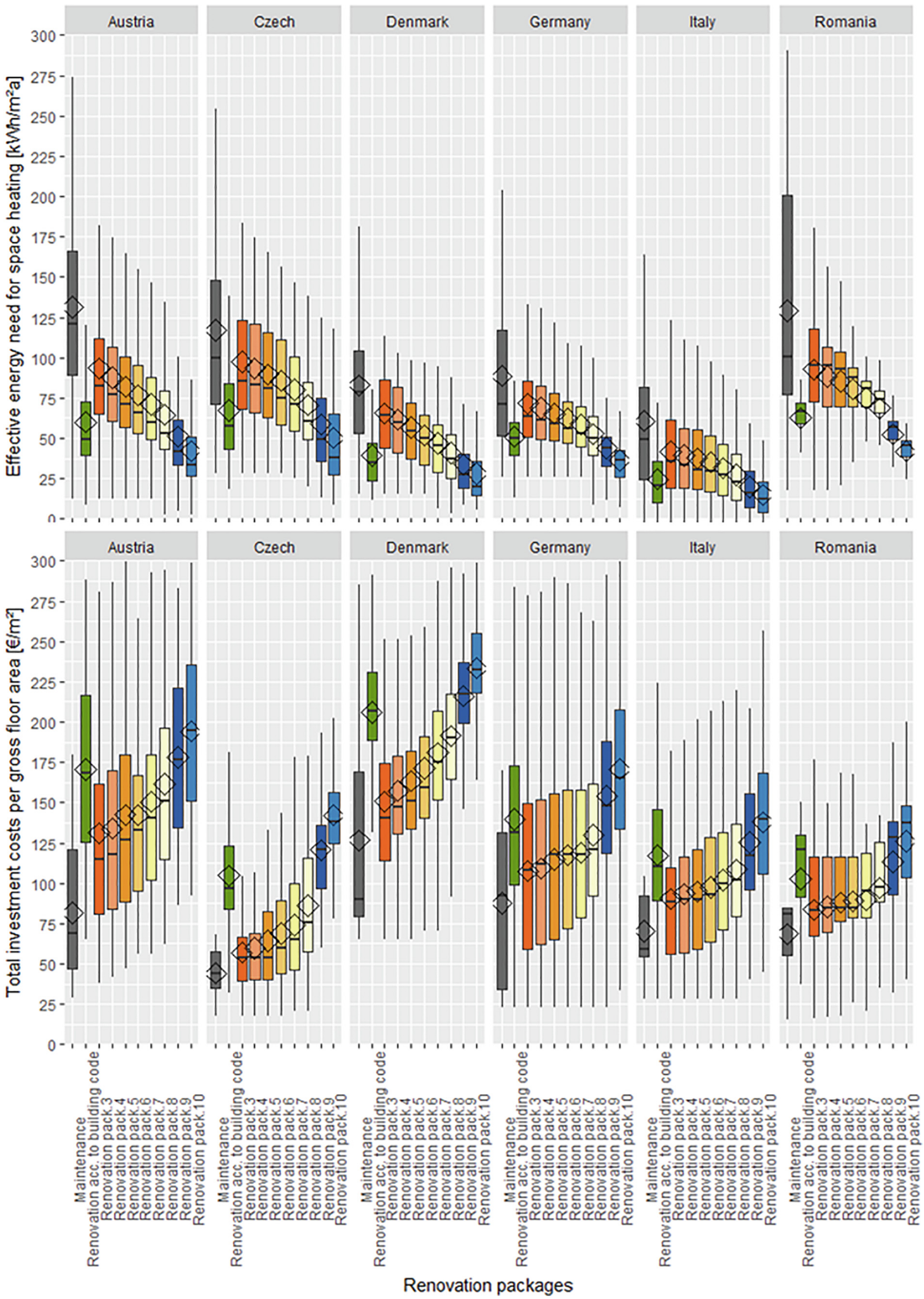


Fig. 4. Box plots of effective energy need and total investment costs for all building classes in the different countries when implementing the maintenance and renovation packages as defined for this analysis.

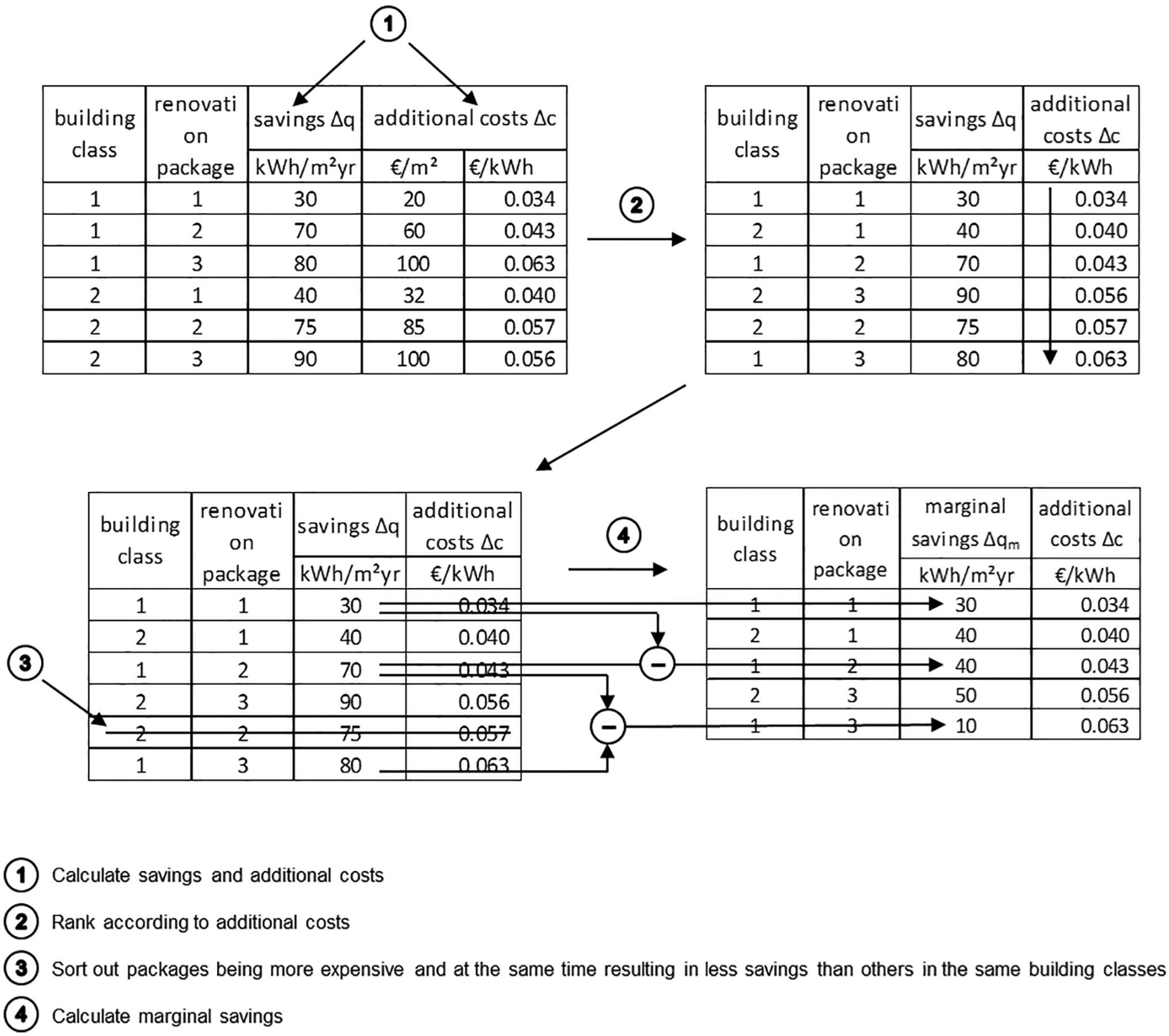


Fig. 5. Exemplary calculation of cost curve data (steps 1 to 4) for two building classes and three renovation packages per building class.

y, and $r_{dem,i,y}$ is cumulated demolition rate of buildings in building class i between the base year and year y.

6. Generate the following bar diagram to get a MESC-Curve: all remaining combinations of building classes and renovation packages constitute one bar where the additional costs $\Delta c_{i,j}$ represent the height and the marginal savings of energy need $\Delta Q_{m,i,j,y}$ the width of the bars. Sort the bars according to the additional costs $\Delta c_{i,j}$ (as performed in step 2) starting with those bars with lowest costs on the left hand side. Fig. 6 shows a MESC-Curve for the example of two building classes and two remaining renovation packages per building class.

In order to generate an ESC-Curve the steps 1 to 5 in the previous description are the same. Subsequently the following additional steps are carried out[6]:

7. For all building class and renovation package combinations $k = 1 \ldots n$ calculate the following values:
   c. The savings of energy need $\Delta Q_{i,j,y}$ in a given year y in TWh for all buildings in building class i when implementing renovation package j using the same equation and parameters as described in step 5, but changing the marginal savings of energy need per year and gross floor area $\Delta q_{m,i,j}$ for the savings of energy need per year and gross floor area $\Delta q_{i,j}$ as calculated in step 1.a.
   d. The cumulated savings of energy need $\Delta Q_{cum,k,y}$ resulting from the additional implementation of the combination $k = a$ as the sum of marginal savings $\Delta Q_{m,k,y}$ of combination a and all combinations being cheaper than combination a:

$$\Delta Q_{cum,k=a,y} = \sum_{k=1}^{a} \Delta Q_{m,k,y}$$

8. For each level of cumulated savings of energy need $\Delta Q_{cum,k,y}$ with $k = 1 \ldots n$ identify the following facts:

[6] Here it is important to recall that the combinations of building classes and renovation packages are ranked from cheapest to most expensive combinations in terms of additional costs $\Delta c_{i,j}$ (since after step 3 of the calculation procedure) and the resulting order of building class and renovation package combinations are referred to by the index k.

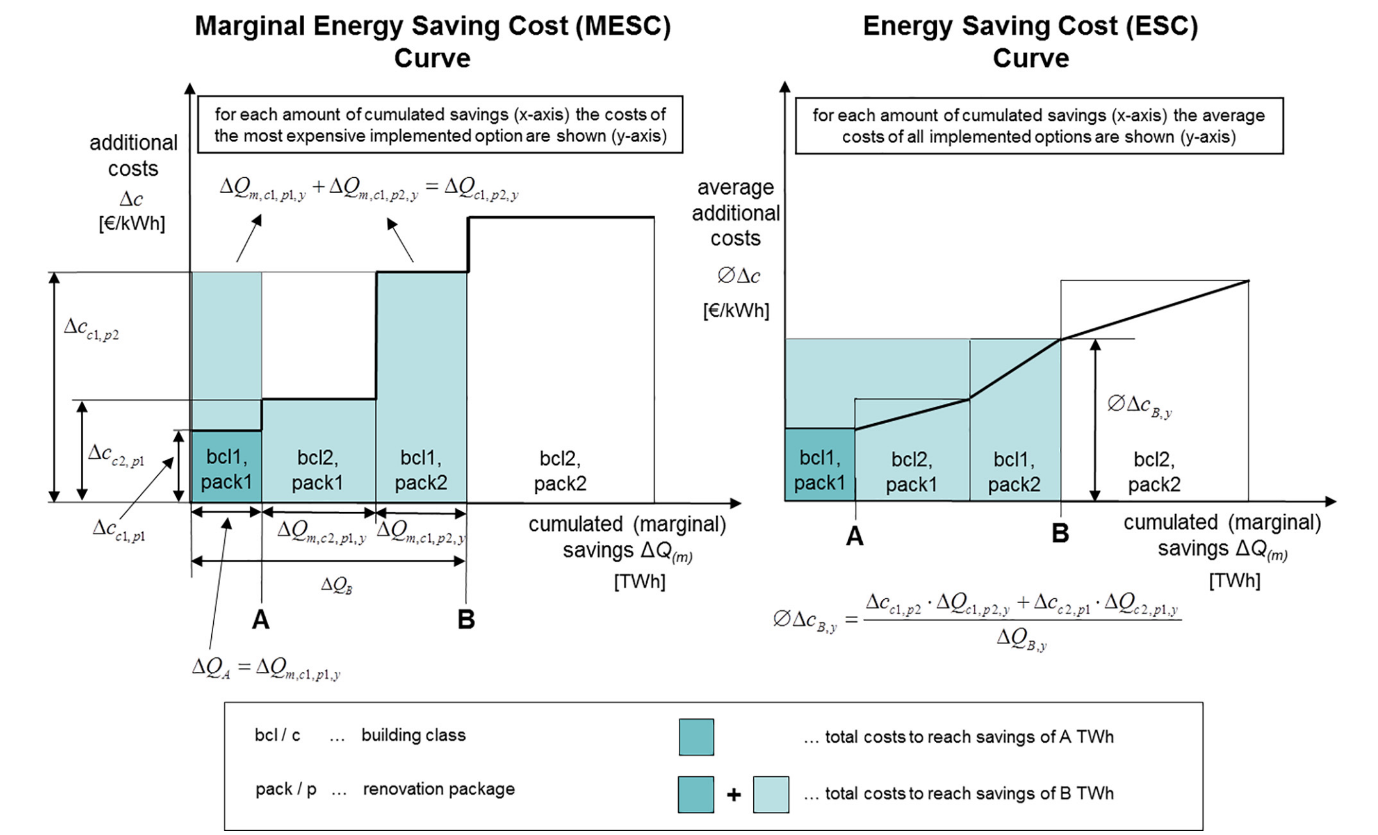


Fig. 6. Exemplary Marginal Energy Saving Cost (MESC) curve and Energy Saving Cost (ESC) Curve for two building classes and two renovation packages per class.

e. Identify those building classes $R \subseteq M$ from all existing building classes M that have to be renovated to reach the given level of cumulated savings.
f. For each building class $i \in R$ identify the renovation package $j = p$ that has to be implemented in buildings in this building class to reach the given level of cumulated savings.

9. For each level of cumulated savings of energy need $\Delta Q_{cum,k,y}$ with $k = 1 \ldots n$ calculate average additional costs $\varnothing\Delta c_k$ as the average of the additional costs Δc_k of all renovation actions that have to be implemented in order to reach the given level of cumulated savings, weighted by the savings of the implemented packages:

$$\varnothing\Delta c_k = \frac{\sum_{i \notin R} (\Delta c_{i,j=p} \cdot \Delta Q_{i,j=p,y})}{\Delta Q_{cum,k,y}}$$

10. Generate the following diagram to get an ESC-Curve: for all building class and renovation package combinations $k = 1 \ldots n$ plot cumulated savings of energy need $\Delta Q_{cum,k,y}$ on the x-axis and the average additional costs $\varnothing\Delta c_k$ on the y-axis. Fig. 6 shows an ESC-Curve for the example of four building class and renovation package combinations.

Additionally to the MESC and ESC Curves we also calculate a Payback Period Curve for each country. The calculation procedure is the same as described for the MESC curves. However, instead of the additional costs of the measures the static payback period is used. For each renovation package j in each building class i the static payback $pb_{i,j}$ is calculated according to

$$pb_{i,j} = \frac{\Delta c_{i,j} \cdot \eta_{ng}}{\Delta q_{i,j} \cdot p_{ng}}$$

where $\Delta c_{i,j}$ are the additional costs of implementing measure j in building class i in € per square meter of gross floor area, $\Delta q_{i,j}$ are the savings of energy need in kWh per year and square meter of gross floor area, η_{ng} is the efficiency of an average gas boiler and p_{ng} is the current price of natural gas in the respective country.

3. Results

In the following we show three different cost curves for heat savings in buildings from the stocks in 2010 most probably still existing in 2050: 1) MESC Curves in terms of additional investment costs per gross floor area of the buildings. These curves can be used to estimate how high investments in renovation actions would be to reach certain levels of savings. 2) MESC Curves in terms of investment costs per unit of energy saved. These curves and more concretely the underlying data can be used to calculate the optimal level of savings versus supply for single buildings. 3) ESC Curves in terms of investment costs per unit of energy saved. These curves can be used to calculate the optimal level of savings versus supply for entire regions and countries. Fig. 7 shows these cost curves for the analysed countries. Furthermore, we show static payback curves for the different countries in Fig. 8.

For the interpretation of the curves the following facts have to be taken into account: 1) the additional costs are calculated with a maintenance action as reference. 2) The relative savings of effective energy need for space heating in 2050, as shown in the x-axis of all cost curves, is calculated based on the total expected demand in 2050 without savings. This total expected demand is the sum of a) the demand of the buildings from the stock in 2010 most probably still existing in 2050 without any renovation action, and b) the demand of the new buildings constructed according to the actual building codes.

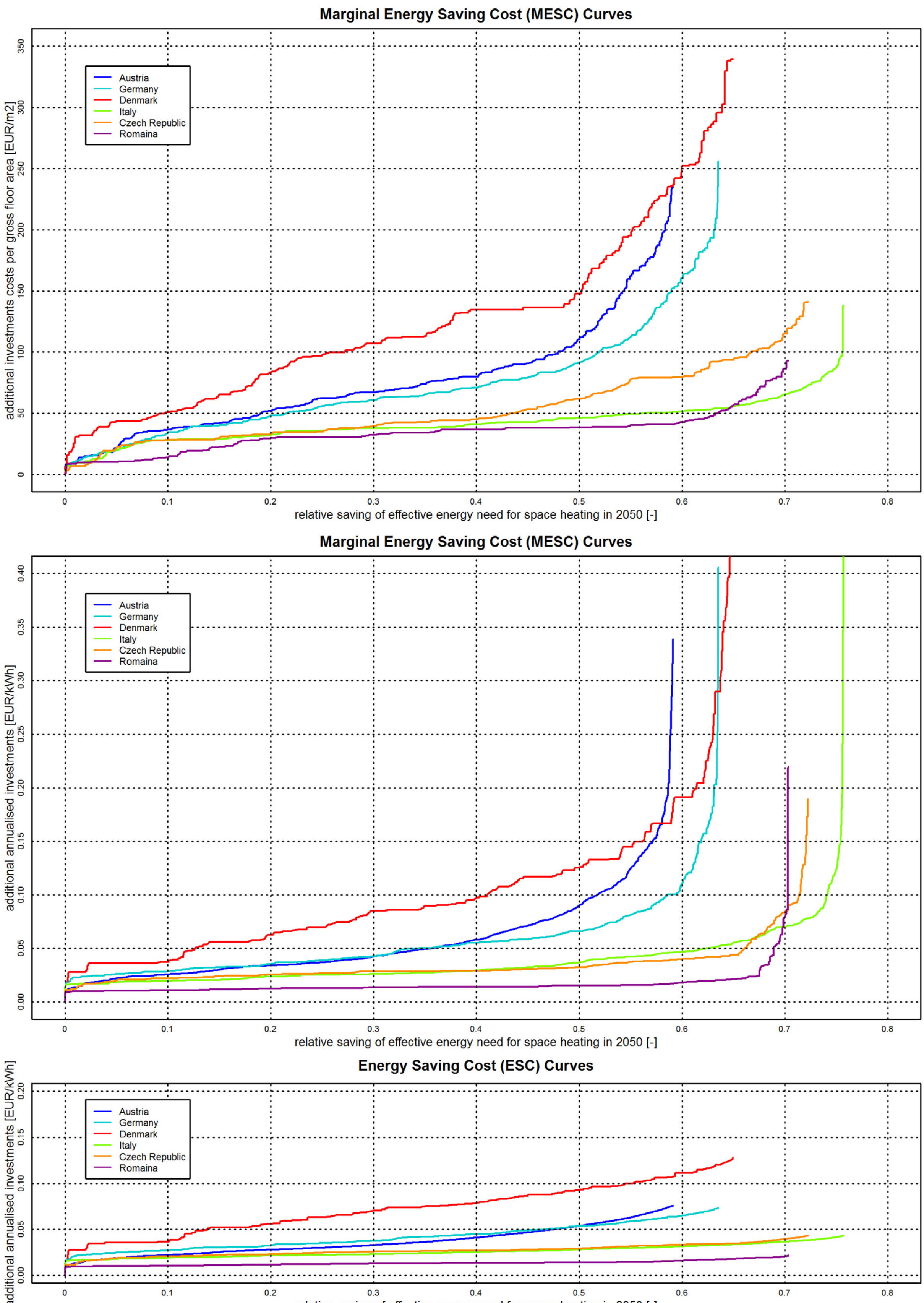


Fig. 7. (Marginal) Energy Saving Cost (M)ESC – Curves for renovation actions in six countries in Europe.

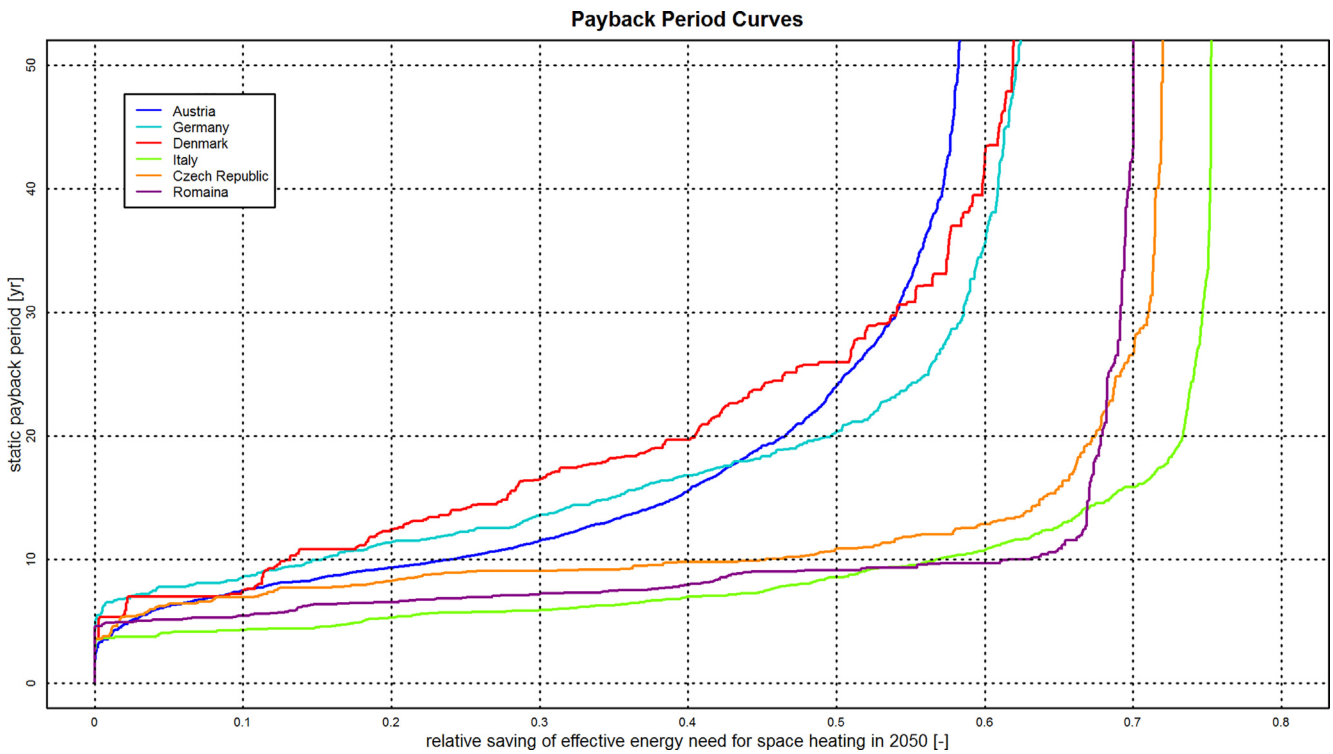


Fig. 8. Static Payback Period Curves for renovation actions in six countries in Europe.

In general we see a similar shape of the cost curves for the different countries: in the first part of the marginal cost (MESC) curves a relatively lower increase of costs occurs until savings of 50–60%; then in the second part of the MESC curves a sharper increase of the costs occurs. The sharp increase of the MESC Curves in terms of € per kWh saved is due to the fact that not only the costs for measures increase, but also the savings reached with these measures are remarkably lower compared to other possible savings. The different full potentials for renovation of the existing buildings shown in the curves for the different analysed countries depend on two facts: the higher the demolition rates in the countries are, the lower the potential; and, the higher the required thermal transmittance in the building codes are and the lower the thermal transmittance in the stocks in 2010 are, the lower is this potential. This is the main reason for the difference between the Austrian and the German cost curve, as the underlying costs for single measures are very similar (see Fig. 3).

We see Denmark showing the most expensive and Romania the cheapest savings in all cost curves, which is understandable looking at the underlying cost data. Although the Czech Republic has lower investment costs in single measures than Italy (see Fig. 3), the MESC Curve in terms of € per gross floor area is higher for the Czech Republic than for Italy. This is mainly due to the fact that in the Czech Republic a higher share of windows is installed in the outer surface than it is in Italy: the change of windows is around three times more expensive than an insulation of the exterior walls to reach similar savings in transmission losses. However, in terms of € per kWh saved the Czech cost curve is cheaper than the Italian one again, which is due to the fact that the absolute savings per building are higher in the Czech Republic mainly because of the colder climate in this country. The very cheap savings in Romania are driven by two facts: total investment costs for single measures are cheaper than in all other investigated countries, but also the current energy needs in this country are remarkably higher than the level of energy needs reflected in the building codes. Denmark on the other hand not only shows expensive investment costs for single measures compared to the other investigated countries, but also the absolute savings per building are lower than in many other countries. This is due to already lower demands and lower possible savings in absolute terms because of a milder climate than in other investigated countries.

Looking at the ESC Curves we find that for reaching savings of 50% of the effective energy needs of the buildings from 2010 still existing in 2050 in the investigated countries very different average costs occur (from lowest to highest): 0.014 €/kWh in Romania, 0.028 €/kWh in Italy, 0.029 €/kWh in the Czech Republic, 0.053 €/kWh in Germany, 0.054 €/kWh in Austria and 0.093 €/kWh in Denmark. For all investigated countries this is cheaper than the average price for district heating (without taxes) [62] and for many countries cheaper than the actual prices for natural gas (also without taxes) [39]. A similar picture can be seen in the Payback Period Curves shown in Fig. 8. Especially for the countries Romania, Czech Republic and Italy remarkably low static payback periods in the range of 3 to 15 years can be found for savings up to 60% and more. Also for countries like Austria, Germany and Denmark the static payback period for renovation activities stays well below the lifetime of the measures for savings up to 50% of the total energy need in the buildings. This indicates that relatively high levels of savings seem to be cost effective in comparison with the costs of energy supply at current price levels.

The cost curves shown in Fig. 7 are calculated assuming a cumulated renovation rate of 100% between 2010 and 2050, using 4% interest rate and 40 years lifetime for calculating the annuity factor and applying the savings in terms of effective energy needs for space heating, thus taking into account the rebound effect after renovation. In Fig. 8 three sensitivity calculations of the before mentioned assumptions for the Austrian default curve are shown: one curve showing a reduced cumulated renovation rate of 60% between 2010 and 2050, one curve calculated with the energy needs based on the standard calculation (see Section2.1) and one

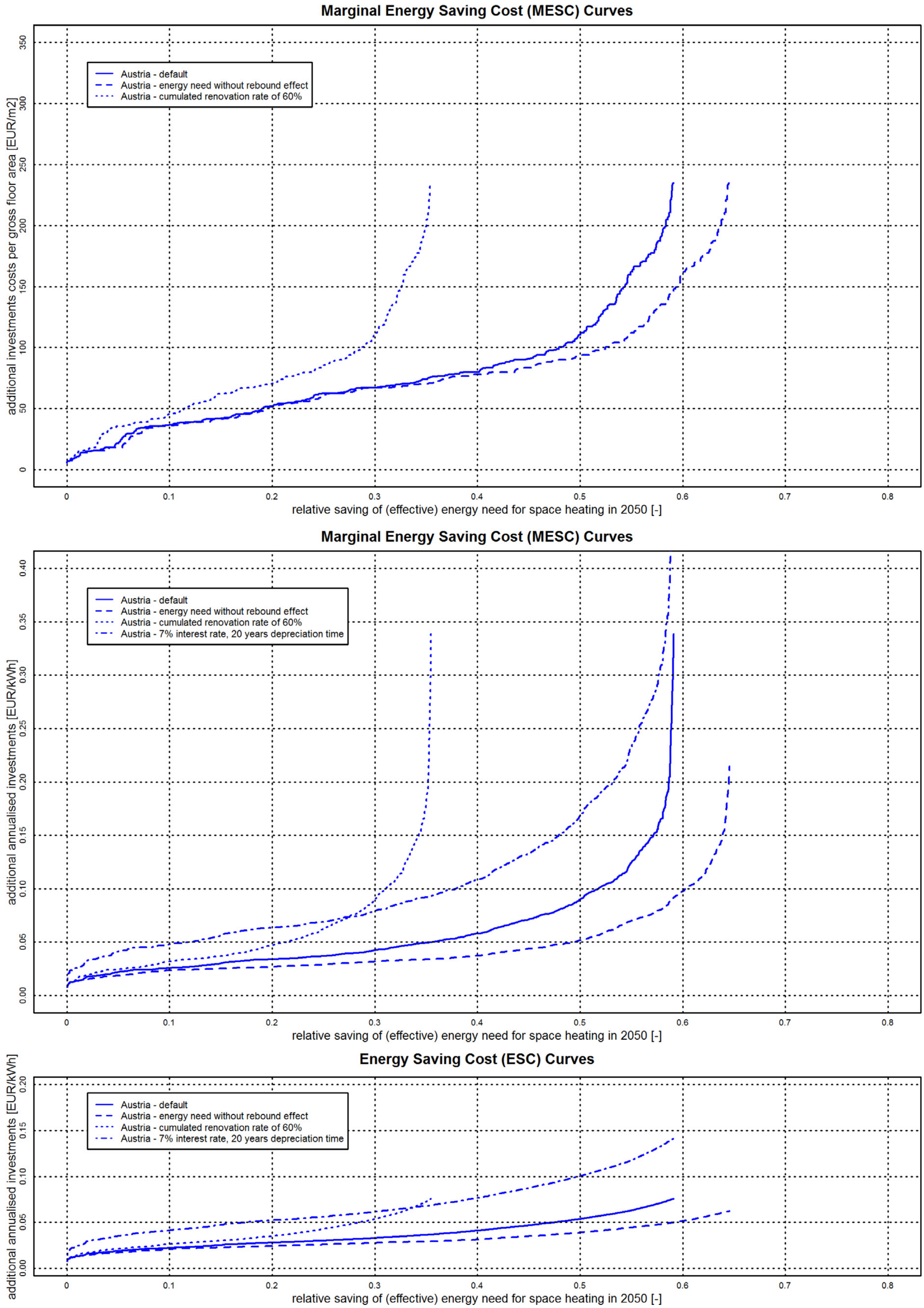


Fig. 9. Sensitivity calculations of the (Marginal) Energy Saving Cost (M)ESC – Curves for renovation actions for the Austrian case.

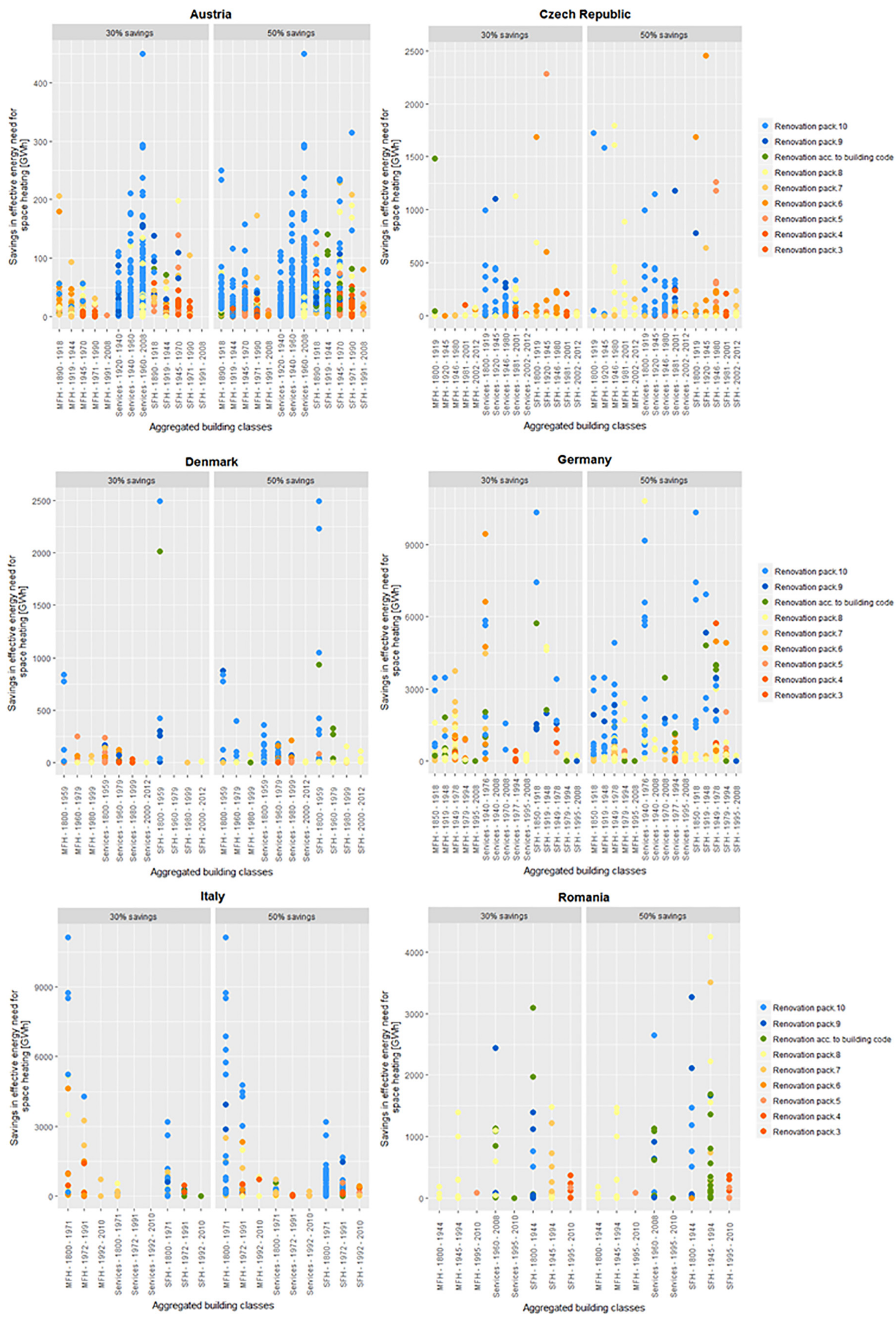


Fig. 10. GWh of savings and implemented renovation package for each building class in the analysed countries to reach overall savings of 30% (left side of each figure) and 50% (right side of each figure) respectively.

curve using 7% interest rate and 20 years depreciation time for calculating costs per saving. The Figure shows the remarkable influence of these assumptions on the resulting cost curves.

In order to better understand which building classes are more important in terms of costs and potentials for saving energy in space heating and which renovation measures should be performed in these buildings we carried out a further analysis of the cost curve data: for two predefined saving targets relative to the total effective energy need for space heating in 2050 (30% and 50% respectively) the combination of the cheapest renovation activities to reach these saving levels is detected. The results of this analysis are shown in Fig. 9. Each point in the graphs represents one building class[7] belonging to the aggregated building class indicated in the x-axis and resulting in the savings as indicated in the y-axis. The colour of the points shows the level of renovation that is applied: renovation according to the national building codes is shown by a green dot, red to yellow dots represent renovations not meeting the requirements of the building codes, and blue dots represent renovations exceeding these requirements. Fig. 9 shows that renovations with important overall potential are not always reaching the requirements of the building codes (e.g. in Romania, Czech Republic and Germany). It is subsequently also clear that if all renovations that are performed in real life would be performed according to the requirements in the building codes savings of well above 50% would be reached. The most important building classes in terms of costs and saving potentials in all countries are buildings that are not renovated still or renovated long time ago. While in the Czech Republic, in Germany, Romania and Denmark the single family houses show higher cost effective savings than other sectors, in Italy the multifamily houses show to be the most important target for renovations. In Austria the savings are broadly distributed between the sectors, however with buildings from the service sector showing the highest cost-effective saving potentials (Fig. 10).

4. Conclusions and discussion

In this work we analysed the costs and potentials for heat savings in buildings in different countries in Europe. This is based on a detailed representation of the current state of the building stocks in these countries as well as a detailed research and comparison of costs and savings of various levels of refurbishment activities. We find that although the level of costs for savings in terms of € per kWh saved is different in the investigated countries, the shape of the cost curves is similar: the increase of the costs with increased level of savings is relatively low for saving 40–60% of the overall expected demand in 2050 without renovation activities, while for reaching higher relative savings this increase is remarkably higher. The main reason is the more than exponential increase of renovation costs (in € per kWh saved) with decreasing energy needs in the buildings. This effect is driven by both, the energy needs of the buildings before renovation, i.e. the lower is the energy need for heating of a building, the lower are the energy savings when applying the same renovation measure at the same costs, and also the energy need of the buildings after renovation, i.e. more ambitious saving targets lead to a disproportionate increase of the renovation costs (in € per kWh). Furthermore we find the following highly influencing factors on the additional costs of heat savings in buildings: 1) Buildings with high shares of window area in the envelope have higher renovation costs, because the costs for reducing similar amounts of losses are around three times higher for windows than for opaque surfaces. 2) High surface-to-volume ratios also lead to higher renovation costs because more external surface area increases investment costs. 3) Renovation measures targeting the building envelope lead to decreased energy needs for space heating, but do not affect the energy needs for hot water preparation. Therefore, such renovation measures are cheaper in places with higher space heating needs: the same measure results in lower savings in warmer places or in places where buildings already contain higher levels of insulation. 4) The definition of the reference action for calculating the additional costs for heat savings: the additional costs for heat savings are remarkably higher for the case that a maintenance action is the reference action compared to the case where a standard renovation is the reference action. However, also for the case that a maintenance action is assumed we find remarkable variations in the total costs of maintenance actions for the different building components from different data sources.

The analysis of the cost curve data for two predefined saving targets of 30% and 50% relative savings reveals that in all analysed countries the most important buildings in terms of high saving potentials and low costs are buildings that are still not renovated or renovated already a long time ago. In the majority of the analysed countries these most important buildings are single family houses, in Italy these are multifamily houses and in Germany, Austria and Romania also the service buildings show important saving potentials. Furthermore the analysis shows that in order to meet a 50% reduction target at minimal costs a remarkable number of building classes would have to be renovated without meeting the requirements of the national building codes.

We also find that remarkable amounts of savings show to be cheaper than average prices for district heating in 2013 in all investigated countries. However, in order to draw profound conclusions on a cost efficient level of renovation of existing buildings also the heat supply costs have to be analysed in detail for each country and location. This was considered as a next step and not the core part of this analysis.

The additional costs and savings represented in the developed cost curves are calculated to our best knowledge. However, there are a number of influencing factors that have to be discussed. First and foremost is the level of costs for savings depending on the data of total costs for renovation actions used for the analysis. In this context we see an uncertainty of the cost levels arising from the facts that a) the used cost data are derived on the basis of a limited number of renovation projects due to the absence of a comprehensive data repository for renovation measures in the countries, and b) there exists a wide range of different types of renovation measures on different building components, leading to different costs and savings. We only took into account one possible type of action for each part of the buildings' envelope according to our main data source, which in part of the buildings might be difficult to realise due to technical requirements. Especially in Denmark non-composite systems seem to be mainly used for the refurbishment of exterior walls, while we take into account only composite systems in the analysis. This would lead to even higher saving costs for the Danish case.

In the default calculations of this analysis we assumed that all buildings from 2010 most probably still existing in 2050 can be renovated in this time horizon, thus representing a lifetime of 40 years for the different building components and a yearly renovation rate of 2.5% respectively. Currently we observe yearly renovation rates below 2.5%, which means that the full potential shown in Fig. 7 can only be reached with political assistance. The remarkable influence of the renovation rates on the cost curves is shown in Fig. 8.

In this analysis we did not include ventilation systems with heat recovery in the renovation packages. This is mainly due to the fact that such systems do not decrease the transmission heat losses of the buildings and therefore cannot be integrated in the minimisation of investment costs for renovation packages with

[7] See definition of building class in chapter 2.1.

the chosen methodology (see Section 2.2.2). However, in order to get a first idea of the cost effectiveness of the integration of ventilation systems with heat recovery we compared the derived packages for several countries with the same packages including a ventilation system. We see that for packages with lower levels of savings an additional heat recovery system doesn't seem to be cost effective, as the additional costs for such a system do not remarkably increase the achievable savings. Instead, very ambitious packages leading to high levels of savings with an additional heat recovery system could lead to decreased additional costs per saving compared to the same package without heat recovery system. An important open question is, if a heat recovery system is already cost effective to integrate in a renovation package that is still cheaper than the cheapest supply option.

The focus of this analysis was on the costs and the effect of measures on the building envelope to decrease the energy need for space heating, the effect of such measures on the energy needs for space cooling was not taken into account. However, it has to be pointed out that integrated renovation packages also have to take into account the energy need for space cooling, not only due to the increasing cooling needs in buildings because of climate change, but also due to the increase of the cooling needs with decreasing transmission heat losses. Thus, if renovation packages only target a decreased energy need for space heating, the risk of overheating in summer will increase remarkably. Furthermore it should be noted that this analysis does not take into account any non-economic benefits of renovation actions in the buildings.

The results of this work can and should be further used to investigate cost optimal levels of heat savings versus heat supply in order to draw the right decisions on the way to an efficient and low CO_2 energy system. This can be done on the one hand for entire countries and regions using the ESC Curves showing average additional costs for reaching certain levels of savings and comparing them to average costs of heat supply from different technologies. On the other hand this can be done in more detailed analyses by comparing the data of the MESC Curves with heat supply costs for different technologies for each building class. In any case it is very important to analyse cost efficient saving targets in order to initiate the right renovation options in the right buildings and to avoid the lock-in of measures that would in the end not allow for a certain saving target to be met.

CRediT authorship contribution statement

M. Hummel: Conceptualization, Methodology, Writing - original draft, Visualization, Funding acquisition, Project administration, Investigation, Data curation. **R. Büchele:** Investigation, Validation. **A. Müller:** Methodology, Software. **E. Aichinger:** Software. **J. Steinbach:** Methodology, Software. **L. Kranzl:** Funding acquisition, Conceptualization, Writing - review & editing, Methodology. **A. Toleikyte:** Visualization, Data curation. **S. Forthuber:** Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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