

# **COST CURVES FOR HEAT SAVINGS IN BUILDINGS**

Calculation of costs and potentials for heat savings in existing buildings through the refurbishment of the building surface for various countries in Europe until 2050

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## **Content**

1	Context and aim of the work	4
2	Methodology	4
2.1	Existing building stocks and assumed developments until 2050 .....	5
2.2	Calculation of energy demand .....	6
2.3	Compilation of renovation packages for the analysis .....	7
2.4	Calculation of cost curves.....	7
3	Results	10
3.1	Existing buildings and development of the stocks until 2050 .....	10
3.2	Costs and savings of renovation activities.....	10
3.3	Cost curves for renovation of existing buildings .....	12
4	Conclusions and discussion	16
5	References	16

## 1 Context and aim of the work

In the European Union around 50% of the final energy consumption is used for heating and cooling purposes, about half of it for the supply of space heating (Fleiter et al., 2016). At the same time remarkable saving potentials in the range of 75% and more (cf. eg. (Bettgenhäuser et al., 2014)) can be expected when comparing non renovated with renovated buildings. It has furthermore also become clear in the last decades that it is necessary to reduce energy demand in order to reach a low carbon energy system. However, it is still under discussion how much energy to save in which energy demand sector and with which renewable energy sources and respective technologies to supply the remaining demand.

In the IEA Task 52 subtask A the aim is to identify promising technology mixes and based on that the future importance of solar thermal energy for the national energy system when heading towards low and very low carbon energy systems. Therefore, the energy systems of several countries participating in Task 52 are analysed with modelling frameworks optimising future states of the national energy systems in terms of economic performance, hereby taking into account technical potentials and constraints. In these models an important input are also the costs and potentials for the reduction of the energy demand for space heating. However, until now no detailed analyses of these saving potentials and the related costs have been conducted for the countries under investigation.

The aim of this work as part of subtask A in Task 52 was to develop cost curves for heat savings in buildings for the countries under investigation (Germany, Austria, Italy and Denmark) in order to be able to feed this data into other energy systems models.

This report shows the underlying data on existing buildings, the assumptions regarding future developments of the building stocks, the costs and energetic effects of various renovation measures on different parts of the building shell, the methodology for calculating the cost curves for heat savings in buildings, the resulting cost curves for the countries under investigation including their sensitivity to important input assumptions, and conclusions as well as discussion points that resulted from this work.

## 2 Methodology

To derive the cost curves of heat savings in buildings the following steps were taken: 1) analysis of the structure and current demand for space heating in the existing building stocks and assumption of the development of the current stock until 2050, 2) analysis of costs and energy savings of renovation measures at different parts of the building shell and derivation of various renovation packages for each building in the stocks, 3) calculation of cost curves for heat savings in existing buildings until 2050. These different steps in the analysis process are presented in more detail in the subsequent chapters.

In the other models applied in this IEA Subtask to find promising energy system constellations with low CO<sub>2</sub> emissions, mainly EnergyPLAN, the starting year of calculations is 2010. Due to this, also for the development of the cost curves the selected base year is 2010.

For the analysis the well established simulation model Invert/EE-Lab<sup>1</sup> was used. It has been extended by a module to calculate cost curves for heat savings in buildings. The following Figure 1 shows the

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<sup>1</sup> For a detailed description and a compilation of analyses and projects performed so far we refer to [www.invert.at](http://www.invert.at)

different modules of the tool that are applied for the derivation of cost curves as well as the main data used in the calculation process.

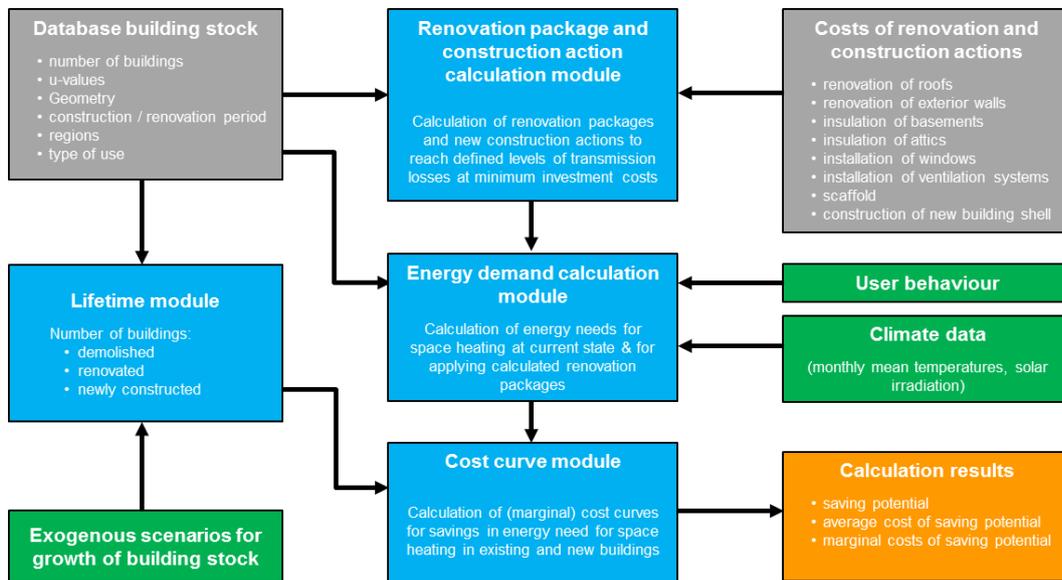


Figure 1: Structure of the calculation process to derive cost curves with the Invert/EE-Lab model

## 2.1 Existing building stocks and assumed developments until 2050

Invert/EE-Lab is a bottom-up techno-economic simulation tool to model developments in buildings such as changes of heating and hot water preparation systems, renovation and construction activities and their effects on the energy demand. It is used to analyse such developments in certain regions, countries and on EU-level. The calculations are based on a detailed representation of the existing building stocks in the Invert/EE-Lab database. The existing stocks are integrated in the database in the following hierarchical structure: the highest and most aggregated level is the “building categories” level. Here building are summarised based on fundamental building characteristics such as type of use or size, e.g. single family buildings or public office buildings. The next level, which is relevant for the calculation of the cost curves as presented in this work, is the level of “building classes”. In building classes, buildings that belong to the same building category and that share the following characteristics are clustered: geometry, types and properties of the building envelope elements, mechanical ventilation system, climate region and user profiles. Mainly depending on the available national information sources this results in 330 to 1370 building classes for the analysed countries.

The building stock database has been set up and updated in the course of various projects. The main data sources for the countries under investigation in Task 52 are presented in Table 1.

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

Country	Main data sources
Austria	(ODYSSEE, 2016), (BPIE, 2016), (TABULA, 2013), (Statistik Austria, 2016), (Müller,

	2015)
Germany	(ODYSSEE, 2016), (BPIE, 2016), (TABULA, 2013), (DESTATIS, 2016), (AGEE-Stat, 2016), (Enerdata, 2016), (Schloman et al., 2011), (UEPC, 2016), (Eurostat, 2016)
Denmark	(ODYSSEE, 2016), (BPIE, 2016), (TABULA, 2013), (Statistics Denmark, 2016)
Italy	(ODYSSEE, 2016), (BPIE, 2016), (TABULA, 2013), (ENEA, 2016), (ISTAT, 2016)

For an estimation of the number of buildings to be expected in 2050 the population, average household size and GDP values presented in the PRIMES reference scenario are used (Capros et al., 2013). Furthermore, the Lifetime module of the Invert/EE-Lab model is applied to calculate the number of buildings that will most probably be demolished in this time frame. This module calculates future demolition based on the timing of historical building construction in connection with Weibull distributions and expectable lifetimes of different types of buildings<sup>2</sup>. The resulting difference between the buildings built before 2010 still existing in 2050 and the number of buildings to be expected in 2050 is assumed to be newly constructed.

## 2.2 Calculation of energy demand

In this analysis the energy need for space heating is applied to quantify energy savings. This is understood 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. The calculation is performed with the energy demand calculation module of Invert/EE-Lab according to the quasi-steady-state monthly energy balance approach defined in ISO 13790 (ISO, 2008). In the model, two variants of the energy needs are calculated: 1) the so-called “standard energy needs” applying user profiles as defined in the Austrian and European wide standards, and 2) the “effective energy needs” taking into account deviations between measured energy consumption values and the values calculated on the basis of the standard user profiles. These deviations resulting mainly from user behaviour are reflected in the model by different indoor set temperatures for different climate conditions, energy needs and apartment sizes<sup>3</sup>. For the analysis the effective energy needs are chosen as energy indicator in order to take into account the rebound effect occurring after renovation of buildings. As mentioned before only the energy need for space heating is considered and reflected in this analysis. This is due to the fact that renovation measures on the building shell only affect the space heating demand, but not the demand for domestic hot water.

<sup>2</sup> For more details on the methodology of calculating demolition and construction rates in Invert/EE-Lab we refer to (Müller, 2015).

<sup>3</sup> For a detailed description of the calculation procedure of energy needs and effective energy needs we refer to (Müller, 2015).

### 2.3 Compilation of renovation packages for the analysis

In order to derive detailed cost curves for renovation activities in the building stock it is necessary to analyse various levels of renovation, i.e. levels of quantitative savings, for each representative building. To develop such renovation packages and compile the necessary cost and energy saving data the following approach is used: 1) for actions at each part of the building envelope (insulation of exterior walls, insulation of roofs and attics, insulation of the building base and change of windows) costs are analysed separately and derived as a function of insulation thickness and quality of windows respectively, 2) renovation packages for each representative building are derived as combinations of these single actions meeting different saving targets at minimum investment costs.

To derive the costs for renovation actions at different parts of the building's envelope the data from (BMVBS, 2012) for Germany were used. Cost functions have been set up to calculate the costs of renovation actions at different intensity. For the other countries the German costs were transformed via the European construction cost index. The resulting cost functions were then compared with costs derived in the course of the Intelligent Energy Europe (IEE) project ENTRANZE, where an extended data compilation has been performed (ENTRANZE, 2014). For Denmark, which was not a target country in the ENTRANZE project, the resulting cost functions have been compared with (Kragh and Wittchen, 2010), (Wittchen et al., 2016) and (Tommerup et al., 2010). In the data compilation and comparison full costs of refurbishment actions excluding value added tax (VAT) are used.

The derived cost functions were then utilised to calculate the costs of renovation packages to reach predefined saving targets for each representative building in the stock. These saving targets are defined relative to the level of energy need that has to be achieved in course of a thermal renovation according to the national building standards. The following packages have been defined: Package 1 reflects a maintenance action to extend the lifetime of the building without a decrease of the energy need, package 2 represents a renovation action according to the requirements of the national building codes<sup>4</sup>, and 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 combination of measures for each renovation package at minimum investment costs an integer linear optimisation is used. The additional costs of energy saving actions, which are displayed in the cost curves, are then calculated by subtracting the costs of the maintenance action from the full costs of each renovation action.

### 2.4 Calculation of cost curves

In this analysis refurbishment actions of the building shell are taken into account, while changes in heating systems that can also lead to a decrease in fuel demand for space heating are excluded. Therefore, the resulting cost curves are based on savings of energy needs for space heating. This also allows using the resulting cost curves in other models or approaches to compare the savings from building refurbishment with savings from change in heat supply systems. As described in chapter **Error! Reference source not found.** the effective energy needs as an indicator for energy savings are applied.

As an indicator for the costs of refurbishment actions investment costs per gross floor area of the buildings are used on the one hand, and on the other hand these costs are transformed into

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<sup>4</sup> We use the interpretation of the national building codes in terms of u-values according to (Kontonasiou et al., 2016) and (Atanasiu et al., 2014).

annualised investment costs of energy need savings in order to be able to compare these values to average heat supply costs of different technologies.

Two different types of cost curves are developed in this analysis:

1. Marginal Energy Saving Cost Curves (MES-Curves): These curves show for each amount of cumulated savings (x-axis) the costs of the most expensive implemented option (y-axis) to reach these savings.
2. Energy Saving Cost Curves (ESC-Curves): These curves show for each amount of cumulated savings (x-axis) the average costs of all implemented options (y-axis) to reach these savings.

Figure 2 shows the difference between both types of cost curves graphically.

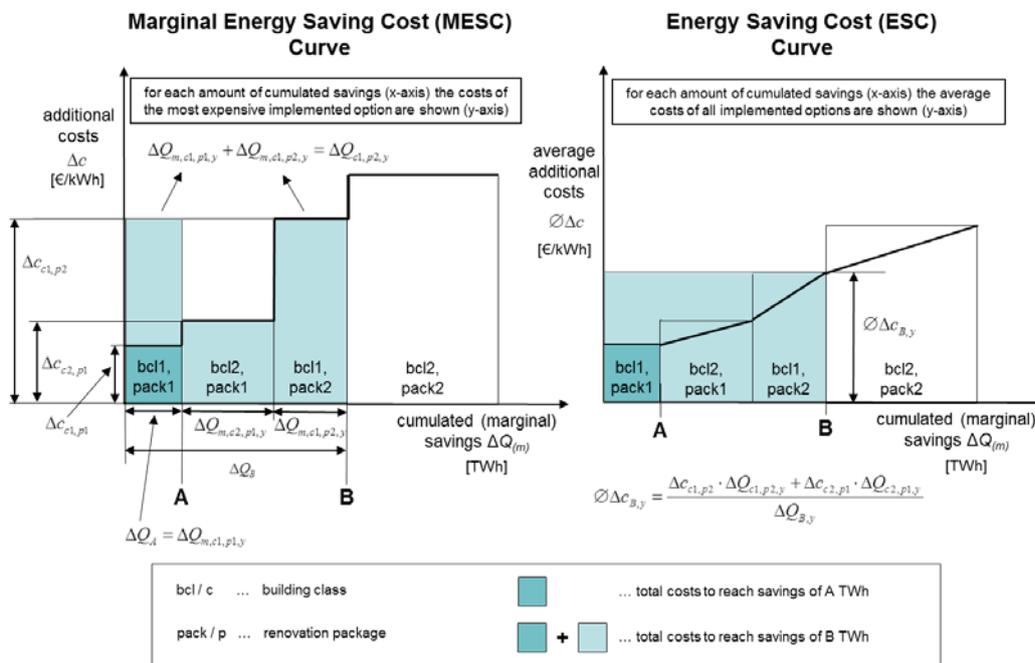


Figure 2: Exemplary Marginal Energy Saving Cost (MES-C) curve and Energy Saving Cost (ESC) Curve for two building classes and two renovation packages per class

In order to calculate the MES-Curves in terms of additional investment costs per gross floor area the following steps are taken:

1. Calculate the energy needs  $q_{i,j}$  in kWh/yr of each reference building in the building class j after renovation with renovation package i
2. Calculate energy savings per square meter of gross floor area  $\Delta q_{i,j}$  as the difference of the energy need for each renovation package i and the energy need of the reference action (no thermal improvement of the building envelope)

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

3. Calculate additional investment costs per square meter of gross floor area  $\Delta c_{i,j}$  (€/m<sup>2</sup>) for renovation package i in building class j compared to investment in the reference action by dividing the overall additional costs for all buildings in building class j  $\Delta C_{i,j}$  through the total gross floor area  $A_j$  of all buildings in class j

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

4. Rank renovation package and building class combinations according to specific additional costs  $\Delta c_{i,j}$
5. From this, derive marginal specific savings of energy needs  $\Delta q_{i,j}$  (kWh/yr) per building for each renovation package i in each building class j compared to the previous ranked level of saving, i.e.:

- a. If  $\Delta c_{1,j} < \Delta c_{2,j}$

- i. For renovation package 1: savings over baseline package

$$\Delta q_{1,j} = q_{base,j} - q_{1,j}$$

- ii. For renovation package 2: savings over renovation package 1

$$\Delta q_{2,j} = q_{1,j} - q_{2,j}$$

- b. If  $\Delta c_{1,j} > \Delta c_{2,j}$ : only the second renovation package is taken into account (the cheaper one, since the marginal savings of package 1 compared to 2 would be negative and could not be displayed in the cost curve):

$$\Delta q_{2,j} = q_{base,j} - q_{2,j}$$

6. Calculate marginal aggregate energy savings  $\Delta Q_{i,j}$  for each building class j and each renovation package i, according to the formula:

$$\Delta Q_{i,j} = \Delta q_{i,j} \cdot A_j \cdot f_s$$

with

$\Delta Q_{i,j}$  aggregated energy savings for renovation package i and building class j (kWh)

$A_j$  total gross floor area of buildings in building class j in base year of calculation

$f_s$  scaling factor for calculating the potential savings until 2050; for buildings from 2010 still existing in 2050 this is (1 – demolition rate), for new buildings between 2010 and 2050 this is the construction rate; both rates referring to gross floor area of buildings demolished or built

7. Plot the data on an Energy Saving Cost Curve by representing every relevant renovation package and building class combination as a bar where  $\Delta c_{i,j}$  represents the height and  $\Delta Q_{i,j}$  the width of the bars, ranking the bars by the costs of energy savings and starting with those bars with lowest costs on the left hand side, where  $\Delta Q_{i,j}$  represents the total energy savings in the building class j of renovation measure i.

For calculating the MESC Curves in terms of additional annualised investment costs per unit of heat saved the same procedure is applied, but the indicator for costs is changed according to the following formula

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

with  $a$  being the annuity factor. For all calculations in this work a lifetime of 40 years and an interest rate of 4% is assumed to calculate the annuity factor.

The ESC-Curves are then calculated on the basis of the MESC data in the following way: Instead of the marginal additional costs for each renovation action  $i$  in each building class  $j$  the average additional costs of all renovation actions (ranked from cheapest to most expensive) in all building classes to reach a certain level of savings  $Q$  is used. This is calculated according to the following formula:

$$\Delta c(Q) = \frac{\sum(c_{i,j} \cdot Q_{i,j})}{\sum Q_{i,j}}$$

### 3 Results

#### 3.1 Existing buildings and development of the stocks until 2050

Based on the data sources stated in Table 1 and the methodology explained in chapter 2.1 the development of the gross floor area of the building stocks as shown in Table 2 is derived. Depending on the country and the age of its existing buildings between 15% (Italy) and 25% (Denmark) of the existing stock is assumed to be demolished until 2050. The oldest buildings in the analysed countries are the multi-family houses in Denmark, the newest are the non-residential buildings in Denmark.

**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<sup>2</sup>, sources for 2010 are stated in Table 1)**

	Austria			Germany		
	2010	2050		2010	2050	
		from stock 2010	new		from stock 2010	new
Single Family Houses	268.9	232.9	83.5	2,405.0	1,965.1	131.3
Multi Family Houses	158.8	135.7	51.8	1,632.2	1,329.3	113.6
non-residential buildings	167.9	123.9	75.1	1,380.3	874.1	315.2

	Denmark			Italy		
	2010	2050		2010	2050	
		from stock 2010	new		from stock 2010	new
Single Family Houses	216.5	153.4	114.2	1,025.5	888.9	240.3
Multi Family Houses	88.3	49.7	55.1	2,390.5	2,075.5	349.4
non-residential buildings	129.1	120.3	29.8	435.7	287.0	201.1

#### 3.2 Costs and savings of renovation activities

According to the approach described in chapter 2.3 in each country for each representative building 10 packages of measures are calculated: a maintenance action, a renovation according to the

national standards and 8 other renovation packages. From the latter ones two packages lead to energy needs below the values reached when applying the standard renovation, and 6 leading to higher energy needs. The following Figure 3 shows boxplots of the effective energy needs and total investment costs of all representative buildings in the countries for the 10 different renovation packages. In the figure it is visible that with lower energy needs reached with a renovation package also the investment costs increase. This increase is not linear, but becomes stronger with decreasing energy needs. The reason is that 5 cm of insulation material attached on a wall that still has no insulation leads to a higher decrease of the transmission losses than if the same 5 cm of insulation material would be attached on a wall that already has insulation material attached.

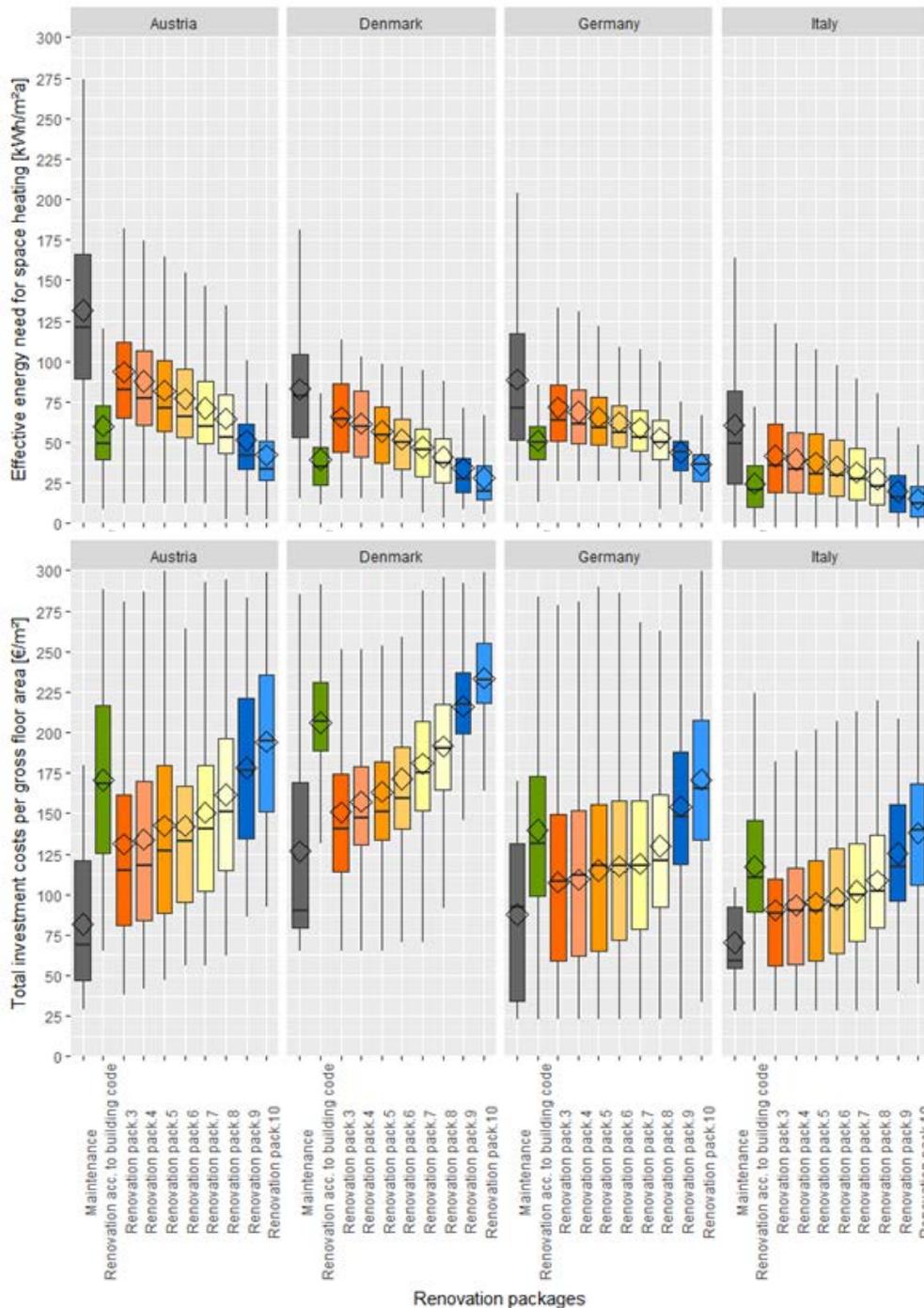


Figure 3: Box plots of effective energy needs and total investment costs for all building classes in the different countries when implementing the maintenance and renovation packages as defined for this analysis

### 3.3 Cost curves for renovation of existing buildings

The following Figure 4 shows three different cost curves for heat savings in currently existing buildings most probably still existing in 2050: 1) MESCCurves in terms of additional investment costs per gross floor area of the buildings. These curves can be applied to estimate how high investments in renovation actions would be to reach certain levels of savings. 2) MESCCurves 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.

For the interpretation of the cost curves it is important to take into account the following facts: 1) the additional costs are calculated with a maintenance action as reference. 2) The relative savings of effective energy needs for space heating in 2050, as shown on 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.

Generally a similar shape of the cost curves can be observed in the figure: in the first part of the cost curves (around 2/3 to 3/4) the cost increase is remarkably lower than in the second part of the curves. This is mainly due to the fact that using the same amount of insulation on a non insulated surface leads to higher savings than using the same insulation on a surface that is already insulated (see also chapter 3.2 and Figure 3). 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. Furthermore, the overall saving potential differs between the analysed countries. There are two reasons for these differences: first, the different demolition rates in the countries (see chapter 3.1) lead to different amounts of buildings from the stocks in 2010 that can potentially be renovated. Second, the potential for heat saving as calculated in this analysis depends on a) the energy need before the renovation, and b) the energy need reached when applying the national standards of renovation. Both characteristics vary remarkably between the countries under investigation.

Figure 4 shows that heat savings do not cost the same in the four countries under investigation. While in Italy cheap savings can be expected mainly due to low investment costs for renovation measures, in Denmark savings are relatively expensive. This is because not only the investment costs are high, but also the savings are relatively low due to the mild climate. As expected, Austria and Germany show very similar cost curves, as the investment costs are very similar. The main difference in the cost curves is the overall saving potential, which results from differences in the ratio between the current state energy need of the buildings and the energy need after renovation according to national building codes.

In order to display the sensitivity of the calculated cost curves to main influencing assumptions, further scenarios for the Austrian case have been calculated: 1) In contrast to the default assumption that all buildings from the stock in 2010 and still existing in 2050 can potentially be renovated, a scenario with 60% cumulated renovation rate for these buildings is calculated. 2) Instead of using the effective energy needs as indicator for the savings, a scenario is calculated using the energy needs based on the standard calculation (cf. chapter 2.2). 3) The default values of 4% interest rate and 40 years lifetime for calculating the annuity factor are replaced in a scenario with 7% interest rate and 20 years depreciation time. The results of these sensitivity scenarios are displayed in Figure 5.

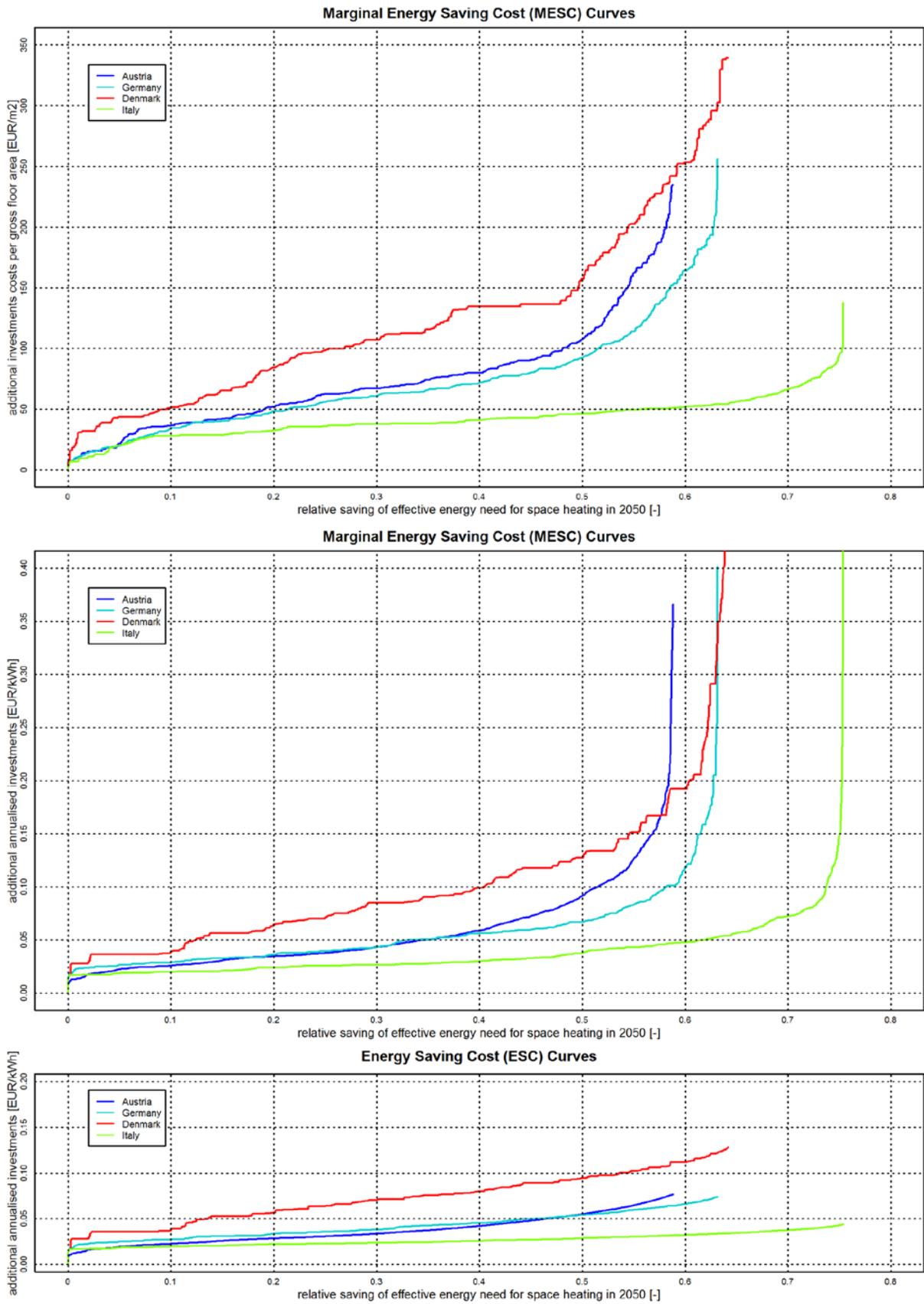


Figure 4: (Marginal) Energy Saving Cost (M)ESC - Curves for renovation actions in four countries in Europe

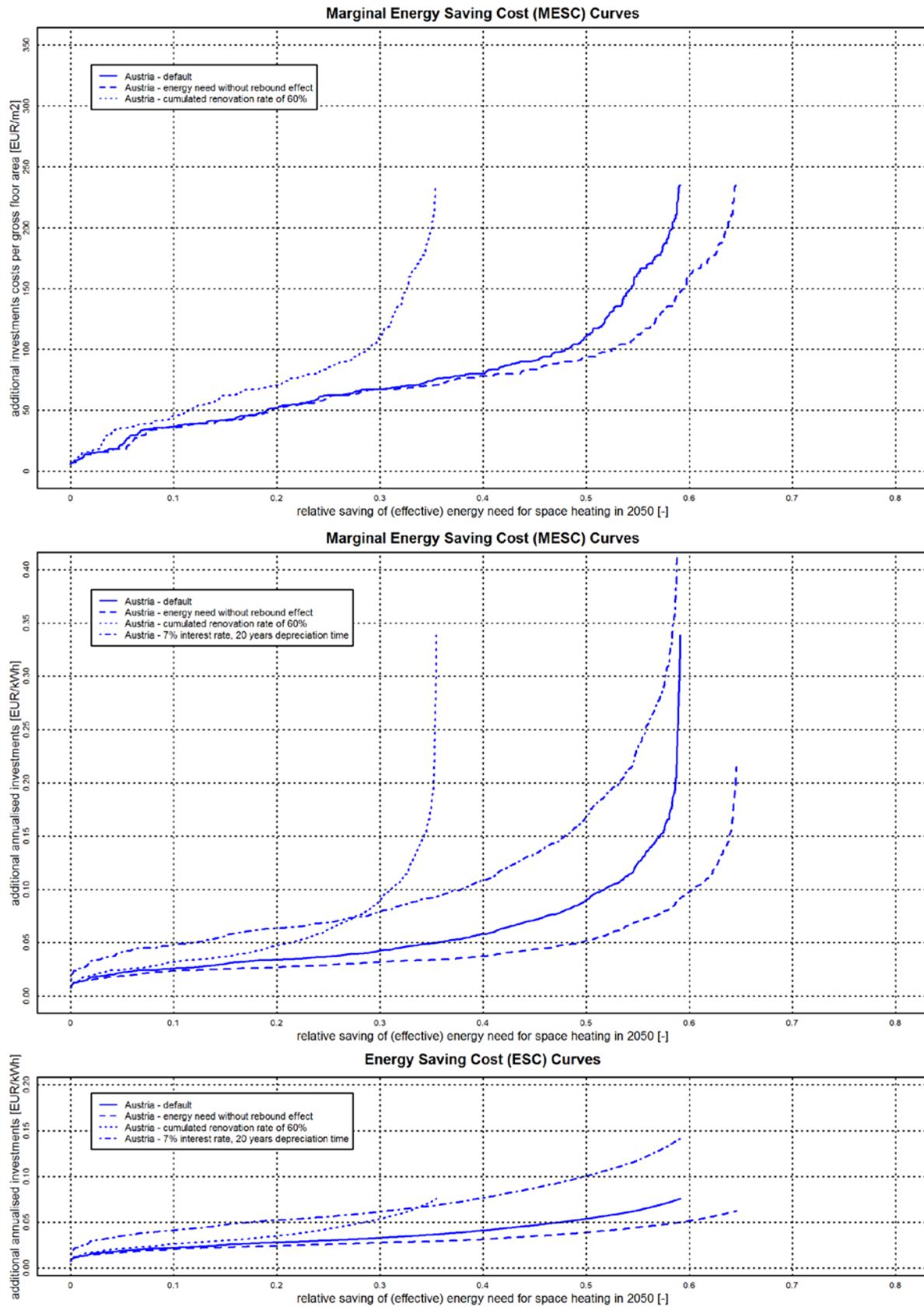


Figure 5: Sensitivity calculations of the (Marginal) Energy Saving Cost (M)ESC - Curves for renovation actions for the Austrian case

## 4 Conclusions and discussion

The development of cost curves for heat savings in buildings by the application of measures on the building envelope in the course of this work showed remarkable saving potentials in existing buildings for all analysed countries. While the overall potentials for heat savings as well as the costs for these savings differ between the countries, the shape of the cost curves is similar. In the first part of the cost curves, reflecting the cheaper saving options, the increase of costs with increased level of savings is relatively low. In the second part of the cost curves, reflecting cumulated savings of more than 60 – 80% of the overall saving potential, the costs increase remarkably. This is due to the lower effect of the same insulation applied to an already insulated surface compared to a non insulated surface.

The analysis showed the following highly influencing factors on the additional costs of heat savings in buildings:

1. High shares of window area in the building envelope lead to remarkably higher investment costs for reaching similar savings. This is due to the fact that the investment costs for windows per square meter of surface area are around three times higher than for the insulation of opaque surfaces.
2. More external surface area increases the investment costs and therefore higher surface-to-volume ratios lead to higher renovation costs.
3. Renovation measures on the building surface are more cost effective in places with higher space heating needs. This is because applying the same measure leads to lower savings in warmer places or in places where buildings already contain higher levels of insulation.
4. The additional costs for heat savings are remarkably higher if a maintenance action is assumed as reference action compared to assuming e.g. a standard renovation as the reference action.

The calculated cost curves proofed to be a valuable basis for the analysis of cost-effective savings vs. supply at the national as well as regional level and for the prioritization of policy intervention in different parts of the building stocks. However, the results of the analysis and the derived cost curves rely on the available data, depend on various influencing assumptions and focus on a specific type of measure, i.e. measures to reduce transmission losses through the building envelope, for saving energy in existing buildings. The most important influencing factors have been discussed before and also been integrated in the sensitivity analysis. Furthermore, it has to be noted that the costs for renovation actions can differ remarkably from the cost data used in this analysis, if the specific measure taken into account is not applicable or more expensive to apply in a certain building due to technical reasons or user needs. Also the integration of ventilation systems with heat recovery in the renovation packages as well as the effect of the applied renovation measures on the cooling needs in summer has not been analysed in this work.

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