Cost-curves for heating and cooling demand reduction in residential buildings

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Abstract

The decarbonisation of the energy system is a long-term objective in the European Union, but it is currently unclear how this can be achieved for the heating and cooling (H&C) demand of residential buildings. The European project "Heat Roadmap Europe" aims to develop low-carbon heating and cooling roadmaps, by quantifying changes at the national level for 14 EU member states[1].

One important aspect of such strategies is the refurbishment of the existing building stock and the analysis of associated costs and energy savings. Therefore, cost curves of reducing the H&C demand in residential buildings are calculated, based on the model platform FORECAST. The model includes refurbishment measures per building element (e.g. walls, windows, etc.) for estimation of investment costs for additional savings compared to a baseline development. By ranking the refurbishment measures according to their specific cost and energy saved, one can derive annualized energy saving cost curves. Such curves have been widely used as a decision support tool by showing the additional costs or investments needed for certain additional savings of energy or CO_2 on a national scale.

The analysis shows that supporting deeper thermal renovation of buildings, which anyway undergo renovation under baseline considerations, is the most important missed opportunity to further reduction of H&C demand. This can be achieved by e.g. converting overhaul of buildings into energy efficient retrofit or to include additional building elements in a planned partial retrofit. Further savings can be achieved by increasing the refurbishment rate (i.e. doing renovations in buildings, which are untouched in the baseline). Beyond certain thresholds, however, additional policy efforts would be needed to e.g. convince investors to aim for respective measures. Addressing these options needs more long-term oriented changes in the investment behaviour but it may be needed to achieve the full potential of additional energy savings.

Introduction

The objective of the work described here and in the context of the Heat Roadmap 4 (HRE4) project is to calculate cost curves for reducing the H&C demand in buildings of 14 member states in Europe. Such energy saving cost curves combine information on overall energy savings and related costs. With the cost curves calculated and analysed in this study, additional energy savings of existing residential buildings can be quantified compared to a baseline scenario. These energy savings are based on multiple individual measures such as thermal renovation of buildings or increase of refurbishment rate.

Due to their transparent way of illustrating costs and potentials of energy savings, cost curves have been widely used in the past, also often also to illustrate CO_2 mitigation potentials (Sorrell, 2015). In this work, we compare cost curves for different countries, highlighting the need for specific policies, incorporating information on building stock, age distribution and

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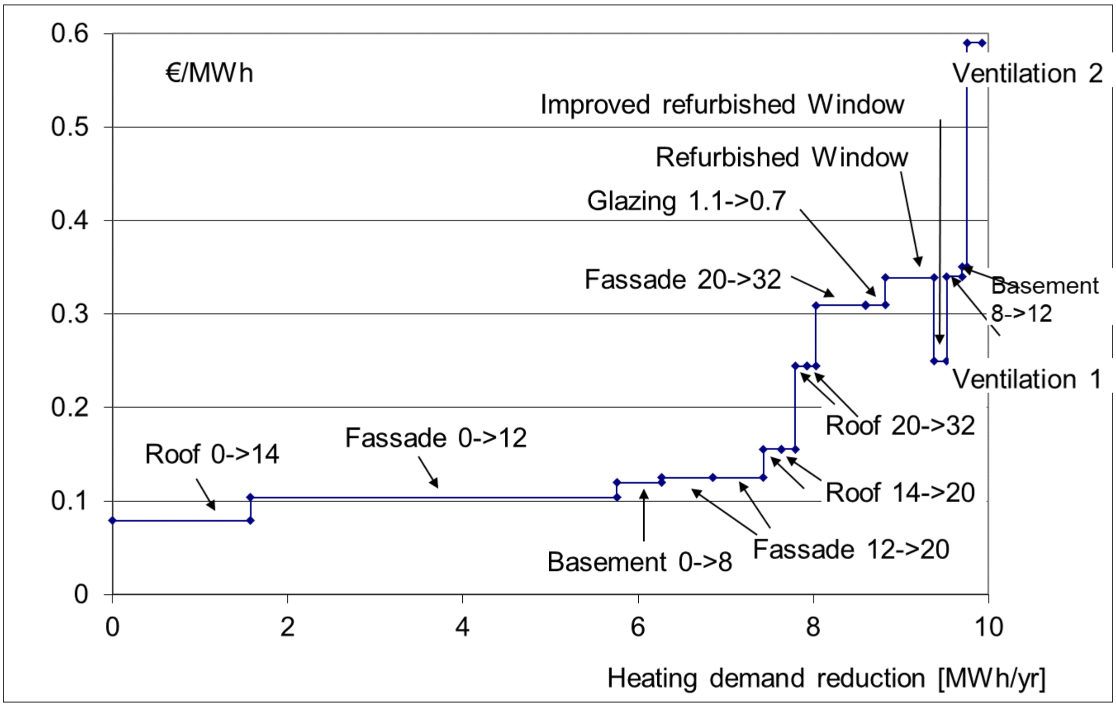

Figure 1. Typical cost-potential curve implemented in FORECAST adapted from (Jakob, 2008).

refurbishment strategies. With this broad overview, we allow for a systematic overview of the current level of cost curves to reduce energy demand from building stock in Europe.

Methodology

The proprietary model platform FORECAST[2] is used to calculate the development of heating and cooling demand of 14 European countries (Fleiter *et al.*, 2017). FORECAST is a bottom-up simulation model, which considers the dynamics of technologies and socio-economic drivers as well as behavioural decision parameters in the demand sectors. Its main objective is to support the scenario design and analysis for the long-term development of energy demand and greenhouse gas emissions for the industry, residential and tertiary sectors on country level.

GENERAL APPROACH FOR COST CURVES

To introduce the cost curve approach applied in the context of the HRE4 project, we briefly explain how cost curves are developed in FORECAST (Harmsen and Fleiter, 2017). With this model approach, two general types of cost curves can be differentiated:

- A cost potential curve: Such curve only covers energy system costs of technical measures and disregards considerations of investment decisions.
- A marginal abatement cost curve (MACC): Such curve can be calculated as CO_2-price sensitivity by running a number of model-runs with varying CO_2 prices. The resulting cost curve then considers all investment inertia and routines included in the model. It, thus, goes beyond only technical energy system cost. Depending on the assumptions of market barriers and discount rates, the resulting energy savings potential can be much lower than in cost potential curves.

A stylized cost-potential curve of the first type for building related measures and related saving potentials is given in Figure 1. On the horizontal axis the (potential) cumulative savings in the target year are given in MWh/year, whereas on the vertical axis the specific costs for each of the savings technologies is shown in €/MWh. Each step in the curve represents a savings option. The area of each step (in MWh/year × €/MWh) represents the costs or benefits for that particular option in the target year only (e.g. first measure on the left, Figure 1: "Roof 0->14" refers to the insulation of the roof with 14 cm insulation material starting from a non-insulate roof. For the measure "Glazing 1.1->0.7" the U-value is the related indicator, defining the qualitative improvement of windows). Generally, the FORECAST model includes measures for building envelope improvements as well as end-use supply options such as boilers and heat pumps, however, such supply options are not considered in this analysis.

Cost curves have been developed for most countries and sectors in the past. Despite their wide application, there are also methodological shortcomings and particularities that need to be mentioned. *Cost potential curves* have a tendency for simplification when it comes to systemic complexities, while *marginal abatement cost curves* are less well suited for illustration and are rather a tool for analysis and model coupling. Further, *cost potential curves* often show negative costs (i.e. earnings), while this is typically not the case in marginal abatement cost curves (Taylor, 2012). For a more comprehensive discussion of advantages and disadvantages of cost curves, we refer to (Fleiter *et al.*, 2009).

With such cost-potential curves one can calculate the energy savings potential relative to a baseline scenario, using the

2. For more information see: www.forecast-model.eu

FORECAST model. By allowing the model to invest in additional energy efficiency measures, the additional costs can be calculated (this also applies for potential cost savings in case of negative costs per MWh saved).

Generally, the specific costs (y-axis in the cost-potential curve) are calculated with the following formulas:

specific costs=(αΔI+Δ(C-B))/ΔE,

with the parameters

ΔI = the additional investment of the energy savings technology compared to the reference technology in real prices (e.g. €2015),

Δ(C-B) = the annual net additional benefits (or costs) of the energy savings technology compared to the reference technology (including O&M costs, fuel costs, etc.) in real prices

ΔE = the annual energy savings of the savings technology compared to the reference technology

and α = annuity or capital factor, with

$$\alpha = \frac{r}{(1-r)\hat{}(-L)}$$

r = discount rate

L = technology lifetime.

DEMAND COST CURVES FOR RESIDENTIAL SECTOR BUILDINGS

In this study, we calculate a demand cost curve as illustrated in Figure 2, so that the cumulative investments are shown on the y-axis. Such curve shows the H&C demand in a specific target year, which can be reduced by investing in additional saving measures. The larger the savings the higher the investment costs of the next unit of savings (reducing marginal utility). In this way, a demand cost curve is developed, both for the years 2030 and 2050.

The curve in Figure 2 should be read from the right to the left. Starting point is the delivered heat in a specific target year (e.g. 2030 or 2050) in the baseline scenario (x-axis with energy demand for heating and cooling). The cumulative investment costs (y-axis) in 2030 or 2050 (the dotted line) include all heating and cooling related investments in the baseline scenario starting from 2015 until 2030 and 2050, resp.), being both investments in demand savings and activity growth (e.g. more m² for new building stock, etc.). The solid curve represents all saving measures that can be implemented additional to the baseline scenario, reducing H&C demand based on increasing cumulative investment costs for additional saving measures. For each saving measure its saving potential (in TWh) and its investments costs (in €) additional to the baseline scenario are included.

In this paper, we present the demand cost curves for building related saving measures, focussing on refurbishment of old buildings and the construction of new buildings. The main characteristics of the developed demand cost curves are the following:

- they are based on detailed technology-specific, bottom-up modelling which takes the structural dynamics within the building stock into account;
- they allow for capital age and inertia from the slow replacement and refurbishment of buildings;
- they take the characteristics of buildings into account, thereby considering technical constraints of energy-saving measures and
- they consider the individually-different starting points of EU countries and their individual framework conditions (e.g. climate, energy prices, etc.).

The model FORECAST-Residential calculates H&C demand at country scale based on:

- building types (e.g. multifamily houses or single-family houses);
- building parameters (e.g. heated/cooled floor size);

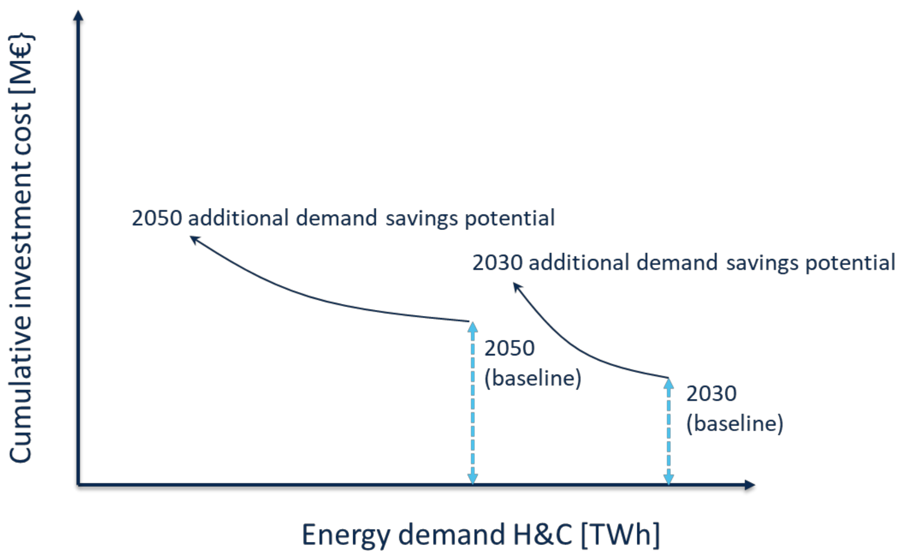

Figure 2. Demand cost curve adapted from (Harmsen and Fleiter, 2017).

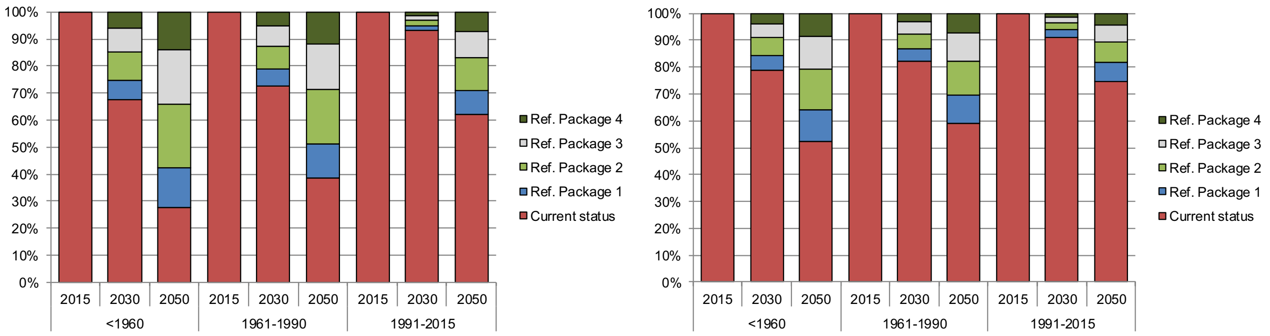

Figure 3. Exemplary share of refurbishment packages for SFH in Germany (left) and Italy (right) in the baseline scenario. Depicted are the three timesteps 2015, 2030 and 2050.

- building elements (e.g. walls, windows, etc.) and their associated properties (e.g. lifetime, U-value, etc.) and
- technology specific values such as fuel types and related efficiencies.

The development of number of households are taken from the EU Reference Scenario 2016 (Capros *et al.*, 2016) and serve as a starting point to model and characterize the development of the building stock. The age distribution of the building stock is output of the model as a result from the demolition and construction rates and the number of households assumed. The standards concerning the minimum efficiency requirements for large refurbishments and new constructions, essentially defined by the EU building performance directive (EPBD, (EC, 2010)) and by country legislation, are an input to the model and referred to as building envelope data, see also (Fleiter *et al.*, 2017).

In the baseline scenario, the building codes for new buildings after 2020 are derived from the EPBD, which sets the standard as Nearly Zero-Energy Buildings (NZEB). Therefore, by definition, new buildings only marginally contribute to the overall heating demand in the future. Given these high standards, which are implemented in the baseline scenario, additional savings beyond the NZEB in the cost curve calculation are neglected.

To model the refurbishment of buildings in FORECAST Residential, a set of possible actions, affecting one or more building elements with different levels of energy efficiency, are grouped in "refurbishment packages". Each refurbishment package includes a set of refurbishment measures for the considered building elements (e.g. wall insulation, window replacement, etc.) and represents potential actions to reduce energy demand from buildings (see also Table 1 for more details on the different refurbishment packages). In the baseline scenario, four different refurbishment packages can be applied by the model. Starting from the current state (2015 U-values) and the lifetime of the building element, the model decides on necessary refurbishment measures and implements one of the four packages available. As a result, for the considered building construction periods and building types, the model calculates the amount of buildings that will apply the different refurbishment packages, and the related efficiency gains (Figure 3).

In the baseline scenario, the shares for packages 1 to 4 represent the buildings, which have renovations implemented with energy performance improvement by 2030 or 2050, while the share for "Current status" (or "P0") represents the buildings that by 2030 or 2050 are in the same thermal condition as in base year 2015. When a renovation is carried out, the lifetime of the elements involved is extended.

SAVINGS POTENTIAL

To derive the additional savings potential from the baseline scenario results, these savings are targeted as fixed steps of pre-defined 5 %[3] reduction steps each of the baseline energy demand, up to 25 % additional savings, if achievable.

To calculate these extra savings, eleven additional refurbishment packages are defined to enlarge the possibilities of cost-effective combinations of energy-efficiency renovations that could be applied by 2030 or 2050 (see Table 1[4]). These additional packages are considered on top or instead of the already applied renovation packages in the baseline scenario. Two aspects need to be highlighted here:

- For buildings erected past 2020, no additional refurbishment packages or more stringent building codes are introduced. This is because the implemented EPBD standards (NZEB) in the baseline scenario are already highly efficient. However, depending on the effective future implementation of the NZEB standards for new buildings in the various countries, the potential for additional measures could be potentially underestimated;
- The share of buildings that have the same thermal condition as in the base year are split into two possible cases: "P0a" represents the cases where no renovation of any type is carried out while "P0b" represents cases where a maintenance renovation of the façade's painting is carried out (see (Harmsen *et al.*, 2017) for a more detailed description of the refurbishment packages). For the calculation of the energy savings in the baseline scenario, this separation was not relevant, but for the calculation of the additional costs for the savings potential, the costs of painting gains relevance.

3. 5 % values are chosen to generate step function to narrow down potential cross-section point between cost-potential curve and investment curve for additional renewable energy generation within the overall context of the HRE4 project.

4. The standards of package 4 (high) in Table 1 are taken as a reference for the increase of the energy performance (U value) to three even more stringent levels ("higher", "highest" or to the equivalent of a "passive house").

Table 1. Renovation packages and their respective ID code.

	ID Code	Refurbishment Package
Baseline Packages	P0a	No renovation
	P0b	Overhaul: repair and brush renovation, no energy efficiency improvement
	P1	Only windows (low)
	P2	Window and wall (low)
	P3	Window and wall and roof (middle)
	P4	Window and wall and roof and floor (high)
Additional packages for the extra savings goals	P5	Building on package 4, window and wall and roof and floor (higher)
	P6	Building on package 4, window and wall and roof and floor (highest)
	P7	Building on package 4, window and wall and roof and floor ("passive house")
	P8	Window (high) and roof (higher)
	P9	Only walls (low)
	P10	Window (higher)
	P11	Window and wall (higher)
	P12	Window (middle) and roof (middle) and floor (high)
	P13	Windows and roof and floor (higher)
	P14	Roof (middle) and floor (high)
	P15	Roof and floor (highest)

PATHWAYS FOR ADDITIONAL SAVINGS

With the enlarged set of packages (Table 1), two main pathways for achieving higher savings are explored in the current model environment set-up, see also (Staniaszek *et al.*, 2013). Other potentials might be plausible but are not considered in this study. The selected pathways describe potential behavioural aspects for the situation that the measures chosen in the baseline are enhanced or deepened in the extended analysis.

1. By different policy measures, building owners, which are already taking energy improving renovations in the baseline scenario (package P1 to P4), are encouraged to use their momentum to refurbish their buildings to invest in more efficient refurbishment packages with a larger potential of savings or similar savings in a more cost-effective way. The shares of packages P1 to P4 are therefore distributed between packages P1 to P15. In this case the refurbishment rate remains mainly the same as in the baseline scenario but the refurbishment depth is increased.
2. Building owners which are not implementing energy-renovation measures in the baseline scenario are driven to take simple and cost-effective energy efficiency measures. The share of P0a and P0b is therefore decreased and the share of efficiency relevant packages is increased. In this case, the refurbishment rate is increased and the measures include small improvements of the refurbishment depth.

These two pathways were applied as post processing steps for the baseline scenario, giving the option to "migrate" the share of packages P1 to P4 considered for the baseline scenario, to a limited selection of packages from P1 to P15 (destination packages).

However, this migration is restricted in a way that not all potential migration options are applicable: e.g. a building from package one (for which refurbishing the window only is foreseen) cannot migrate to a package six, where all building elements are improved (see Table 2 for more details on the migration pathways). For this reason, other potential solutions might exist for the selection of shares of packages and measures, based on different selection criteria.

In general, the destination packages were chosen to allow that the building elements (e.g. walls or window) of the baseline package were also included in the new package. FORECAST-Residential calculates the shares of the packages for each building category taking into account the need for maintenance of the building elements involved in the package and the cost-effectiveness associated with the particular characteristics of the building element and the proposed package. When buildings only need wall refurbishment or a change of windows, it is unlikely that such buildings undergo refurbishment of other building elements. Therefore, the destination packages are mainly more efficient versions of the original packages, but in some cases, highly cost-efficient packages are included in the options even though they do not include all the building elements of the original package.

For the cases where no renovations are carried out in the baseline (P0a), migration to very expensive packages is unlikely due to considerations of financial investors and behavioural aspects[5]. Therefore, migration is foreseen to go for the cheapest and most cost-effective packages (P14 & P15). For P0b, the cases where no energy renovations are implemented but the façade is painted, it seems reasonable to expect that some of these cases can be persuaded under specific conditions to include some efficiency improvements of the wall (or to change

5. As shown in (Rose *et al.*, 2016), net present value of deep refurbishment is not always positive, depending on country specificities. Therefore, if no refurbishment is selected in the baseline scenario, deep refurbishment is unlikely due to net present value considerations and the selected pathways considered in this study.

the windows) given that they are already investing money in scaffolds and work that need to be done for painting anyhow. Then the extra costs would be mainly the insulation material, the consideration of façade connections points and the extra hours of labour. Thus, P0b can migrate to packages P9 or P11. By migrating buildings from P0a and P0b to other packages, an increase of the energy-effective retrofit rate is modelled. To give a full overview of potential migrations, the combinations of packages are shown in Table 2.

The combination of packages shown in Table 2 sets the frame for the calculation of the potential energy savings for the different efficiency targets. By incrementing the shares of the most cost-effective packages until the next 5 % saving step is reached, the cost curves are generated. Although it is not a net annual cost (since fuel costs savings are not included), the (annualized) investment costs per kWh saved is a reasonable proxy of the cost-effectiveness of the packages. With this value, a ranking of "cost-effectiveness" was built to be used as a guideline for the optimum combination of packages for the saving steps. Several iterations are made until the optimum value is found. However, some assumptions were introduced to keep the scenarios within reasonable margins.

For example, in this cost analysis, migrating the share of cases where no renovations are carried out (P0a) to do cost effective renovations like insulating the roof and floor (P14 and P15) are the options with the best cost-effectiveness. From a mathematical point of view, to achieve additional cost-effective savings compared to the baseline scenario, one should start by migrating the maximum share from P0a to P14 or P15, which means to "convince" all the building owners that are not implementing renovation measures in the baseline scenario to at least insulate the roof and or basement, which is not very realistic. It seems reasonable to first take the cases where the buildings are already undergoing some refurbishment measures to go for higher standards, given different barriers and hurdles for home owners to invest in energy efficiency in the first place (see (Jakob, 2007) or (Ebrahimigharehbaghi *et al.*, 2019)). However, such additional measures are not sufficient to achieve high additional savings and therefore, the most cost-effective option (P0a to P14 or P15) is implemented gradually according with the saving step considered.

INVESTMENT COSTS

The total investment cost for tapping the energy savings potential corresponds to the addition of the costs needed to implement the final share of packages for each of the 14 HRE4 countries. The cost of each package is the agglomeration of the particular costs for the renovation of the different building elements involved. These costs depend on the energy improvement (the improved U-value from one measure to the other), whether additional costs are associated by either accounting for additional material only or by including additional labour cost, etc. Costs are expressed in € per m^2 of energy reference area.

For the calculation of costs of insulation material, the cost of rigid foam insulation material (EPS) is used as baseline assumption (Hinz, 2015). However, assuming high efficiency improvements implies thick material applications, sometimes even double layering of insulation plates. Such application would come with additional costs for special fixation systems and additional labour efforts. Choosing other materials would therefore prove more cost efficient overall. With our approach we may slightly overestimate the total investment cost.

In overall terms, for walls, roof and basement, the costs are calculated based on the German study on labour and material costs for refurbishment measures (Hinz, 2015) and then adjusted for the different countries by a cost index derived from data on labour costs across the 14 HRE4 countries (EUROSTAT, 2015).

For windows, the costs are calculated using a formula derived from statistics from Switzerland (Jakob *et al.*, 2006), taking the U-value of new windows as reference. These costs include all the expenses related with the renovation (insulation material, scaffold, paint) depending on the scope of the renovation chosen for each element.

It is important to emphasize that only the total additional investment costs are considered, see Figure 4 for the schematic calculation of additional costs per measure. This includes also the migration of packages: when the original share of package "x" from the baseline scenario is reduced to increase the share of package "y", the costs that were assigned in the baseline scenario to implement package "x" are accounted for in the costs needed to implement the share of package "y".

Also, when the refurbishment rate is increased (pathway 2, reflecting change of shares of P0a and P0b), cases are calculated where the renovations are carried out with the purpose of improving the energy performance of buildings. In this respect, the costs calculated for the baseline scenario and for the additional savings, only include cost parameters for the building elements and not for the painting. However, it is extremely difficult to increase the overall refurbishment rate in reality and the social cost of increasing the refurbishment rate is not considered in the cost curves.

RESIDENTIAL SPACE COOLING

Space cooling demand in the residential sector is expected to increase in the future (Fleiter *et al.*, 2017), although from very low levels today. To limit energy demand growth in the future, highly efficient equipment is needed and specific requirements

Table 2. Combinations for package's share migration.

Original Package	P0a	P0b	P1	P2	P3	P4
Possible actions	stay in package P0a or migrate to packages P14 or P15	stay in package P0b or migrate to packages P9 or P11	stay in package P1 or migrate to packages P10, P2 or P8	stay in package P2 or migrate to packages P11, P3 or P12	stay in package P3 or migrate to packages P5, P11 or P4	stay in package P4 or migrate to packages P5, P6 or P7

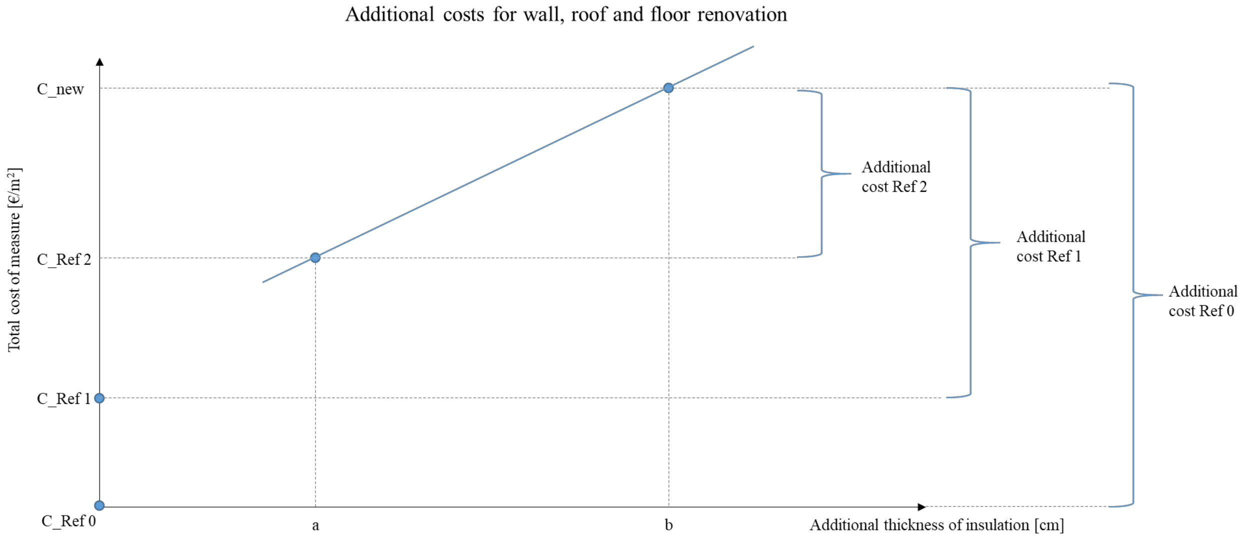

Figure 4. Calculation scheme for additional costs for migrating from one package in the baseline (C_Ref 2) to additional savings (C_new). C_Ref 0 for no refurbishment, C_Ref 1 for overhaul.

are defined in the Ecodesign Directive (European Commission, 2012). As space cooling in the residential sector is mainly defined by decentral cooling systems rather than centralized cooling devices, further cost considerations are not included in this analysis.

Additionally, depending on the buildings structure, the materials/installation and on the devices used, cooling demand can vary significantly. For buildings with good insulation values, passive measures such as closing blinds during the day or opening windows overnight helps reducing cooling demand in the future. Such efficiency measures are often depending on behavioural aspects and are therefore only described in qualitative terms. Other passive measures such as shading from trees or cool paints are not considered due to their partially countereffects between summer (lowering cooling demand and winter (increasing heating demand).

Results

The additional savings potential in the residential sector depends on the assumptions made to calculate the underlying baseline scenario. As introduced above, for new buildings, the NZEB standards are included in the baseline and therefore the savings potentials on top of the baseline for buildings after 2020 are limited. However, for existing buildings, which are needing refurbishment in the coming years due to their age structure and energy performance, additional savings are available (see (Fleiter et al. 2017; and Harmsen et al. 2017) for more details on the achieved baselined demand development and the energy savings potential). In this work, we calculate an additional 350 TWh savings on top of the baseline scenario until 2050 given the respective assumptions.

In the following text, the results are presented for the cost curves as an overview of the 14 countries together and for selected countries specifically, highlighting findings relevant for all countries or country groups. It is important to mention that the "costs" reflected in the figures correspond to the total investment of the measures, and not the annualized cost nor the net cost. The lifetime of the measures, the operational & maintenance costs, and the benefits perceived as energy carrier savings and reduced distribution losses have not been considered so far to display net cost curves. This explains why the "cost" per delivered energy saved appears so high compared with other traditional cost-curves.

Compared to the baseline scenario, additional efficiency gains can be achieved if buildings undergoing refurbishment, target higher efficiency gains as well as when more buildings are undergoing refurbishment measures. Depending on the targeted extra savings, the mix of extra measures varies to achieve such targets (see Figure 5). Additionally, the construction period of the buildings also has a high impact on the applicable set of measures and therefore, the renovation depth. As for each country the building stock has a different age distribution, the results for each country vary. To understand the development of the shares of the different refurbishment packages, Figure 5 is depicting the shares for each building period for all 14 countries until 2050, clustered for the different additional saving targets.

Based on the distribution of refurbishment packages applied in the baseline scenario, Figure 6 at the left shows the additional cumulative investments needed in the 14 countries to achieve 25 % lower energy demand in 2030 compared to the baseline in 2030. For the analysis of the additional cumulative investments needed in 2050 to reduce energy demand by 25 %, results are shown in Figure 6, right.

Until 2030, we estimate for all 14 countries additional investments of approx. €600 billion to achieve additional 25 % energy savings. As one can observe, until 15 % additional energy savings, the measures are getting costlier by each 5 % step (increasing slope due to the selected number and type of refurbishment packages), since more expensive measures are needed to achieve such reductions, including for some countries a slight increase of the refurbishment rate. Thereafter, additional savings are not achieved by retrofitting buildings deeper but

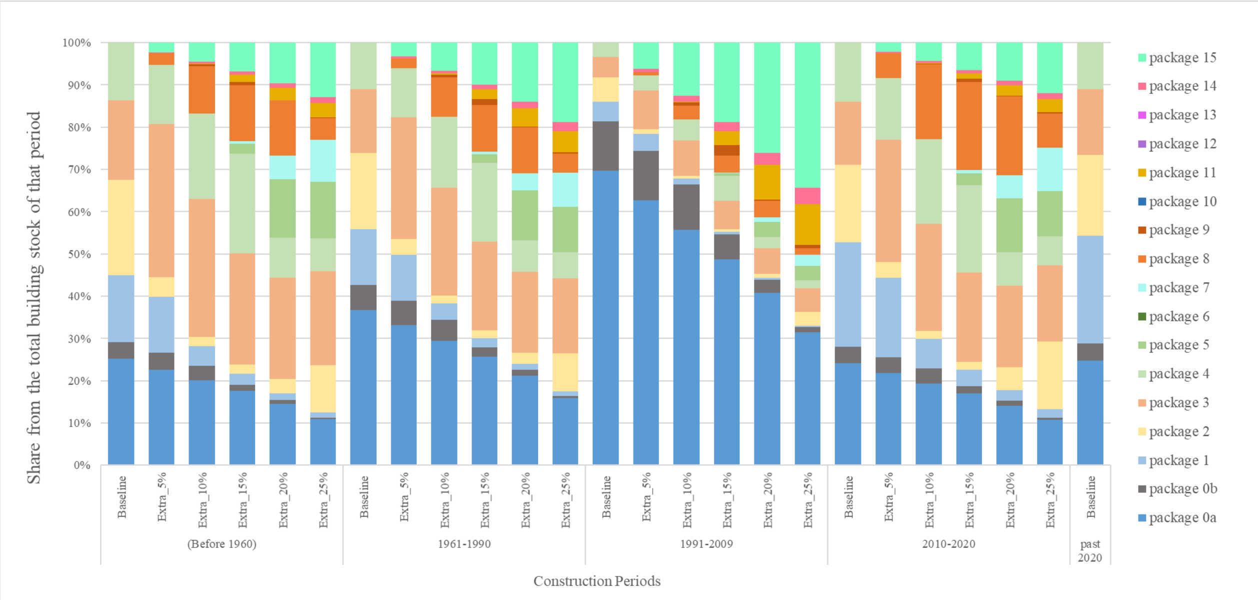

Figure 5. Percentage share of renovation packages for different saving targets for residential buildings for all 14 countries for the year 2050.

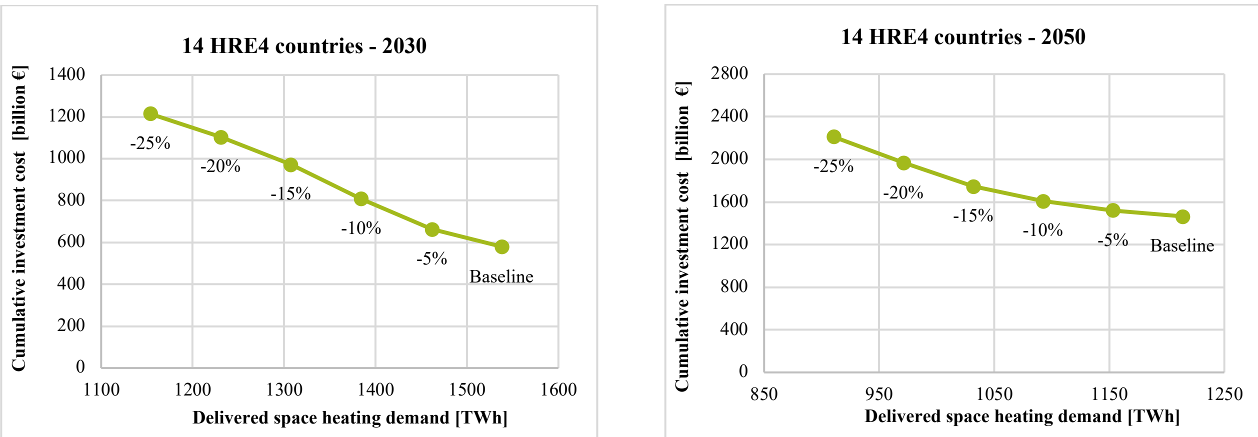

Figure 6. Summarized investment curve for the 14 core countries of the study for 2030 and 2050 in the residential sector. Cumulative investments for all countries.

rather additional buildings need to be refurbished which did not undergo such measures in the baseline (i.e. increasing the refurbishment rate). This allows for more cost-effective options and therefore lower specific costs. However, one should keep in mind that the hurdle of increasing the refurbishment rate is high (i.e. motivating building owners to implement energy effective refurbishments instead of just overhaul measures) and most likely needs additional policy support or even financial incentives which is not accounted for in this cost curve. Until 2050, the cumulative investment only slightly increases to approx. €700 billion compared to 2030, whereas other refurbishment packages are needed to achieve the respective savings. Additionally, until 2050, measures are getting costlier with each 5 % increase of the savings target, indicating that more costly actions are needed.

By recalculating the savings target of -25 % energy demand by applying only the standard refurbishment packages from the baseline scenario, it was found that the average refurbishment rate of the building stock would need to be increased to 4 %–5 % per year to achieve such savings until 2030. This average rate would be reduced to 1.5 %–2 % if the additional savings needed to be achieved by 2050 only. However, these high refurbishment *rates* in 2030 are coming along with a low refurbishment *depth* since the additional measures for migrating from packages P0a and P0b to P14 and P15 only includes the insulation of floors and roofs (see Table 1 for information on the named packages). Additionally, it is unlikely that such high refurbishment rates until 2030 will be achieved across Europe as it would need at least a doubling of respective economic businesses such as construction, planning and engineering based on trained employees amongst other barriers (see (Camarasa *et al.*, 2015)). Therefore, the refurbishment rate alone does not appropriately describe extra efforts needed to achieve higher savings. Only in combination with the renovation depth one can derive specific conclusions. By 2050, the share of buildings, which have undergone refurbishment measures in the baseline compared to 2015 is higher as in 2030 and therefore, the potential for achieving substantial additional savings by increasing the refurbishment depth by one "unit" is higher. Therefore, the declining trend of the investment curve is not observed any longer (see Figure 6 at the right).

On country level for 2030, these general trend developments of the cost curves can be observed as well, although not all countries show identical patterns. In the case of Spain, (see Figure 7) one can observe a similar decline of the gradient of the cost curve. However, other countries such as France do not show such declining investment costs in 2030. This is related to the country specific refurbishment rates, the current building status and the age distribution of the building stock. In France, the refurbishment rate is higher (approx. 0.8 % in 2015, (Fleiter *et al.*, 2017)) as in Spain (0.4 % in 2015) and therefore, by improving the refurbishment measures by one standard, more efficiency gains in relative terms can be achieved. In Spain, where the overall building stock has also lower performance standards, the energy demand is also less dependent on heating degree days. Therefore, to achieve the defined savings, only improving refurbishment measures by one "unit" is not sufficient and therefore, more buildings need to undergo simple refurbishment measures.

For 2050, a similar pattern exists as for 2030 on country level. In countries with already high standards today, very ambitious additional savings can only be achieved if the refurbishment rate can be increased (see Figure 8). From our analysis, we expect country specific refurbishment rates which are between 50 % and 100 % higher as compared to the baseline scenario. Therefore, we estimate a declining cost curve for Finland to achieve additional savings between 20 % and 25 %. As explained before, this is based on the assumption that the refurbishment rate can be increased and cheap options are chosen for such additional measures.

For Spain (see Figure 8, on the right), declining cost curves for high efficiency targets are not observed, given the fact that increasing the refurbishment depth is dominating the applied measures compared to additional costs from increasing the refurbishment rate. Since more buildings are undergoing refurbishment in 2050 as compared to the year 2030 already in the baseline scenario higher savings can be achieved by improving the quality of the measures implemented in the baseline scenario, i.e. implementing higher standard refurbishment packages

In general, Figure 6 to Figure 8 for the built environment do not always show exponential shape of cost curves when targeting larger savings. This is defined by the availability of refurbishment packages and the implemented pathway of measures allowing for more cost effective savings to be implemented later

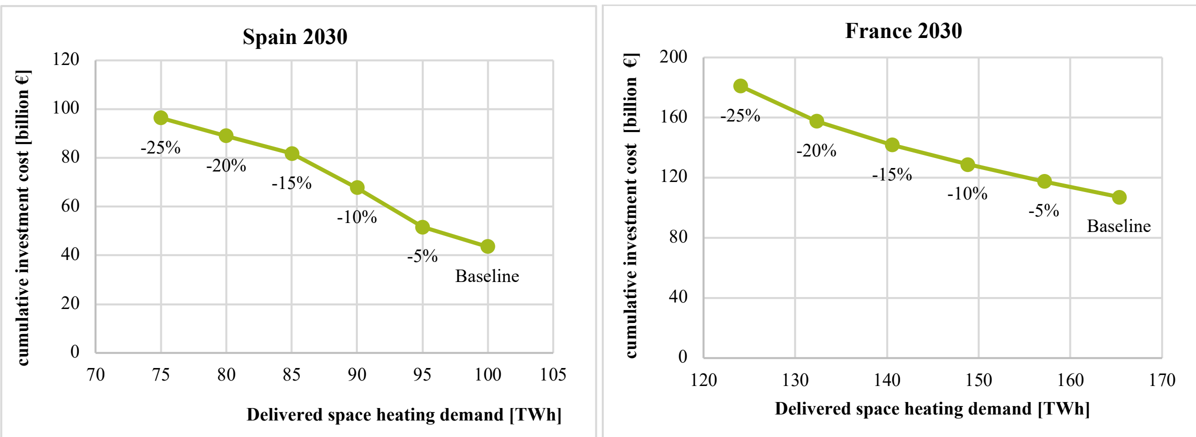

Figure 7. Investment curve for Spain and France for the year 2030 in the residential sector.

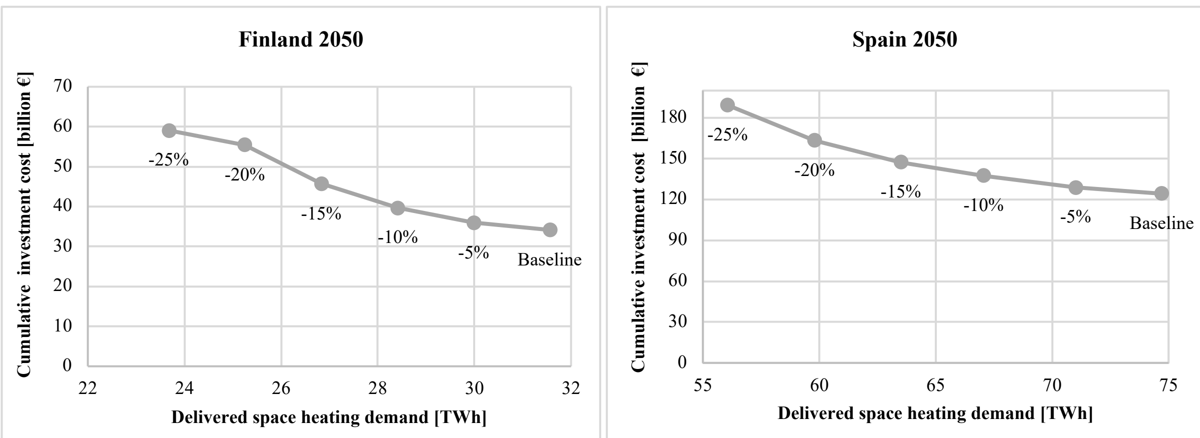

Figure 8. Investment curve for Finland and Spain for the year 2050 in the residential sector.

due to behavioural aspects. Therefore, we only show one potential development and additional work is needed to derive the impact of other pathways.

Conclusions and outlook

The savings potential estimated in this analysis for the residential sector adds another 350 TWh of heat savings in the 14 states. The heat savings in the baseline scenario require an overall investment of approx. €1.500 billion, and another €600–€700 billion needs to be invested to tap the full heat savings potential identified for the residential sector.

In order to better understand what these significant investments in the built environment entail, it is worthwhile to focus on what HRE4 suggests about the residential sector. The majority of the extra savings revealed by this work for the residential sector are achieved by implementing more ambitious renovation measures than implemented in the baseline for buildings that undergo a renovation anyway. Further savings are achieved by increasing the refurbishment rate considered for the baseline scenario (i.e. doing renovations in buildings which are untouched in the baseline scenario or doing these renovations earlier than in the baseline scenario, i.e. in the period 2015–2030 rather than 2030–2050). As potential additional costs for increasing the refurbishment rate (e.g. subsidies) are not considered in this analysis, package migration to increase the refurbishment rate are underestimating specific costs. It is important to note that implementing only one of these strategies does not open up the full potential of additional savings which is in line with (Staniaszek *et al.*, 2013), where also a combination of increasing renovation depth and renovation rate is suggested to achieve long-term EU efficiency targets.

Limiting cooling demand growth will become more important for the residential sector in the future, especially in absolute terms, since a strong demand growth is expected. The implementation of stringent regulations for new equipment will help to achieve such savings at limited additional costs. Additionally, the integral planning of heating and cooling demand and supply in refurbishment and new building projects is of high relevance to deal with contradicting influences of building works. Site-specific adaptation of passive and active measures for influencing H&C demand (e.g. specific windows U- and SHGC-values, sun blinds, cooling and ventilation systems, etc.) is needed to effectively reduce H&C demand during the whole year.

In order to exploit all the additional H&C savings effectively, stronger policy instruments are required, which address missed opportunities in current policy and financial frameworks especially in terms of building refurbishment. For new buildings, the efficiency targets are clearly set, given the European wide Energy Performance of Buildings Directive (EPBD) as basis (EC, 2010). However, especially if one considers only the savings inherent in the baseline, there is clearly much to be done. At least a stringent implementation of the EPBD (EC, 2010) and the EcoDesign Directive (EC, 2009) in all European countries could further help decarbonising the H&C sector.

However, more focus has to be put on building refurbishment and new policy instruments. Such policy changes will need to address missed opportunities like the overly-high share of buildings which have been (or will be) renovated without any/sufficient energy efficiency improvement being implemented. They also must stimulate an increase in renovation actions which cover the entire stock of existing buildings in Europe, as well as the systems and processes within them. Currently, prohibitions or enforcements seem not to be available as political tools to implement faster target achievement, as most policies focus on subsidies, financial incentives and targets rather than excluding specific applications or technologies.

Therefore, the political discussion and country specific implementation of needed additional instruments is of high relevance to define needed overachieving of the current development trends. By including lessons learned from slow integration of European wide measures (Camarasa *et al.*, 2015), the uptake of effective policies however, can be improved. To do so, different countries have to carefully investigate their current building stock and its age distribution and refurbishment needs to select appropriate policies and support measures.

To help understanding the effectiveness of potential solutions and policies, accurate building stock data is needed. With our FORECAST tool we are able to provide such information and investigate more country specific aspects as well as evaluate potential implementation measures and their contribution to achieve needed efficiency targets in the future.

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