ENERGY SAVING COST CURVES FOR THE CASE OF THE GERMAN BUILDING STOCK

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Motivation

In order to curb climate change, the European Union (EU) has set a long-term aim to reduce greenhouse gas (GHG) emissions by 80-95% below 1990 levels by 2050. The EU has proposed a 40% goal for the reduction of GHG emissions by 2030, together with targets of 27% for both renewable energy and improved energy efficiency. Buildings play an important role in meeting the EU climate targets, in particular in Germany, the largest economy of the EU, where the building sector accounts for 40% of final energy use and for about one-third of GHG emissions.

Adopted as part of the Energiewende (Energy Transition) in 2010/2011, the Federal Government has set national goals to reduce energy consumption for heating by 20% by 2020 and non-renewable primary energy consumption for space heating and hot water by 80% by 2050, compared to 2008 levels. In addition, it aims for a 14% share of heating and cooling generated from renewable sources by 2020. Energy efficiency is the second pillar of the Energiewende and has been higher on the political agenda ever since the revision of the Renewable Energy Sources Act (EEG) was adopted in 2014. Currently, however, Germany is not on track to achieve its 2020 GHG emissions reduction target of 40%. In the 2013 report to the European Commission on GHG emissions projections and national programmes, the Federal Government reported a projected 33-35% CO2 reduction.

Research questions

In this context, this paper analyses the potential and related costs of energy savings in the German building sector.

- What are the costs and energy saving potentials up to 2030 for renovating the building stock, for the case of Germany in various building categories from an investor's point of view?
- What is the impact of various framework conditions like energy prices, subsidies, technological learning, transaction costs and interest rate on the results?
- Which methodological aspects and presumptions drive the results and what has to be taken into account when deriving energy saving costs curves?

Method

The starting point for the analysis in this report is the categorisation of the German building stock according to a number of about 4450 representative building segments. The energetic refurbishment potential for each of these reference buildings is then assessed, for three renovation levels: *standard*, *moderate*, and *ambitious*. The methodology adopted in this study has been to focus on comprehensive renovation of the building envelope combined with the replacement of the heating system. Partial renovations or single measures are not considered. The associated costs and energy savings for each of the three renovation levels for each reference building is calculated compared to a reference case of renovation without any thermal improvement of the building envelope. Least cost renovation options for each reference building for a given set of economic conditions are identified for every building segment. The results (costs and energy savings) for these building segments are summarized into building clusters in order to draw them in a transparent way in energy saving cost curves. It is important to note that the resulting energy saving cost curves represent the perspective of an investor, i.e. taking into account different economic side conditions, policies, energy taxes, expected payback periods, rate of return etc.

General approach

In order to develop energy saving cost curves for the building stock – and thus to better understand the impact of different policies on the economic attractiveness of renovating different types of buildings – the following steps were undertaken:

1. Consider the current stock of buildings and factor in stock changes (e.g. demolitions, conversions) over the modelling period to 2030;
2. Define a number of different renovation packages, resulting in various levels of improvement in the building's energy performance.
3. Calculate delivered energy demand of each reference building after renovation by means of the corresponding module in Invert/EE-Lab. This calculation module is based on the standard monthly, stationary energy balance approach defined in EN13790.
4. Calculate energy savings per building as the difference of the delivered energy demand for each renovation package and the energy demand of the reference system
5. Calculate levelized costs of heating energy service c for these renovation
6. Calculate additional costs for heating energy service in building class j with renovation package i compared to reference renovation package.
7. Define a set of economic parameters affecting the cost effectiveness from the perspective of the investor (e.g. energy prices, interest rate or development of investment costs). These can be varied in order to generate different scenarios.
8. Identify and select the least cost renovation package for each building segment.
9. Calculate costs of energy savings for those least cost renovation packages as the ratio of additional costs and energy savings;
10. Plot the data on an Energy Saving Cost Curve by representing every relevant renovation package and building class combination. In this step, a clustering of building segments is carried out in order to allow a reasonable graphical representation.

Applied models

The Invert/EE-Lab model

The Invert/EE-Lab model is a dynamic bottom-up simulation tool that evaluates the effects of different promotion schemes (in particular different settings of economic and regulatory incentives) on the energy carrier use, CO_2 reductions and costs for RES-H and renovation support policies. Furthermore, Invert/EE-Lab is designed to simulate different scenarios (energy carrier prices, insulation, consumer behaviours) and their impact on future trends of renewable as well as conventional energy use on a national and regional level (see also www.invert.at, Müller 2014, Kranzl et al 2014).

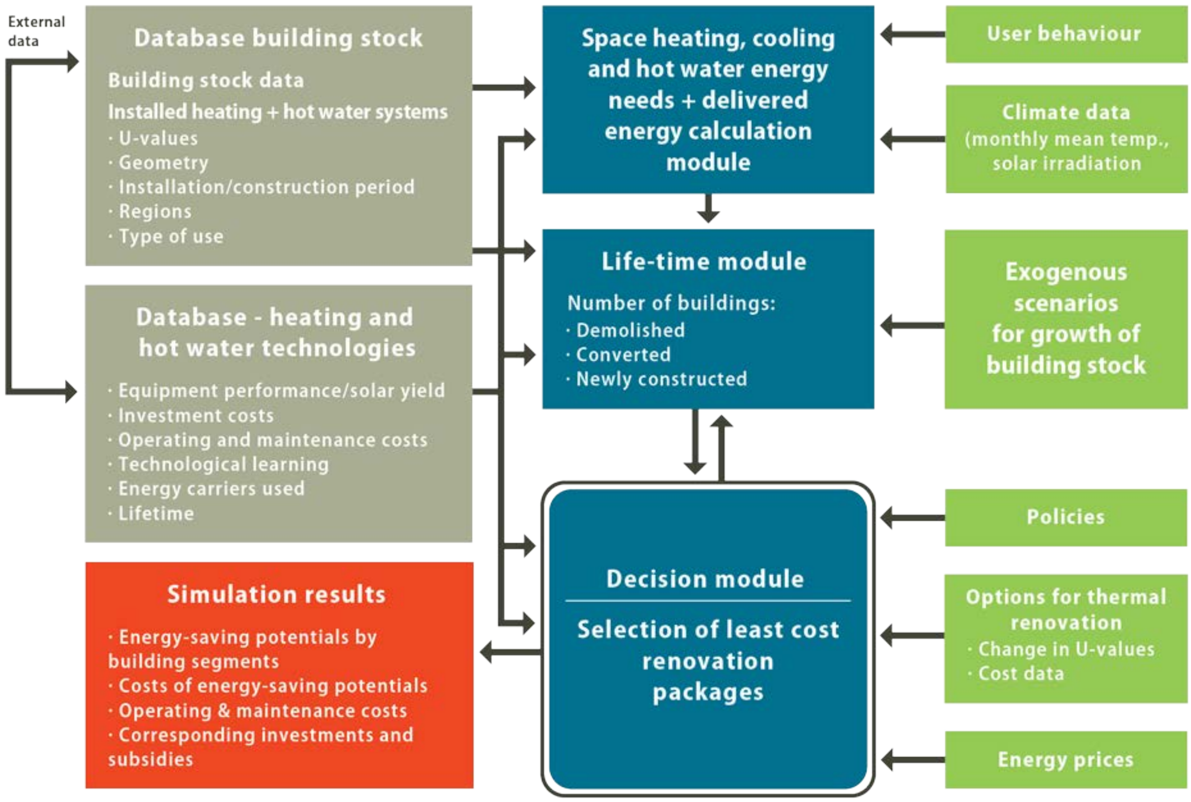


Figure 1: Structure of the Invert/EE-Lab model as applied in this study for deriving Energy-Saving Cost Curves

Sources: Müller 2014, Kranzl et al 2014

The energy needs and demand calculation module implemented in the Invert/EE-Lab model uses a monthly energy balance, quasi-steady-state approach (EN-ISO 13790, 2008), (Pöhn et al., 2007), (ÖNORM B 8110–5:2009, 2009), (ÖNORM B 8110–6:2009, 2009), (ÖNORM H 5056:2009, 2009)) enhanced by explicitly distinguishing between using and non-using days and in case for ventilation between average day (16 hours) and night (8 hours) outside air temperatures. Buildings are implemented as single zone buildings. Behavioural aspects, such as dependency of the energy needs for heating on the thermal quality of the building envelope or the heated area of dwellings are implemented based on (Biermayr, 1998), (Born et al., 2003), (Loga et al., 2003). A more detailed description of the model is given in (Müller, 2015), (Kranzl et al., 2013).

ESCC Plot Tool

The tool for deriving Energy Saving Cost Curves (ESCC) makes use of the results derived from the model Invert/EE-Lab. The ESCC plot tool has been developed by BPIE as an add-on to the Invert/EE-Lab with the purpose of displaying the results in the form of ESCCs. The tool utilizes the standardized format of delivered Invert/EE-Lab's model outputs that are used as inputs to the BPIE ESCC tool. The code aggregates input by building category and vintage in order to display the weighted average renovation costs and energy savings for each building category. The aggregated values are plotted according to the Marginal Energy Saving Cost Curve format with energy costs or savings on the vertical axis and energy savings on the horizontal axis. Additionally, the tool aggregates and provides the shares of renovation depths for envelope measures, heating technologies used, total investment requirements and the total value of subsidies.

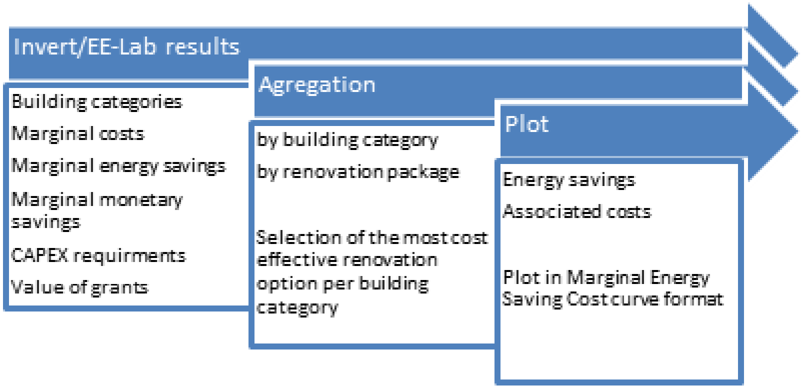


Figure 2. Process of deriving energy saving cost curves in this paper

System boundaries and methodological aspects

- We included following technologies in our analysis:
  - Space heating and hot water systems: Solar thermal collectors, PV and heat pumps. Natural gas condensing boilers were taken into account as reference system. District heating and biomass heating systems were excluded from the analysis because this would have required a spatial disaggregation (in case of district heating) and biomass potential restrictions (in case of biomass) with additional methodological challenges and distortions in developing the energy saving cost curves.
  - Renovation of the building envelope: different insulation thicknesses of ceiling, façade and floor as well as window replacement. Three different renovation depths were taken into account.
- Not every feasible energy saving measure has been considered in this study. For example, the important role that district heating, co-generation (heating and electricity) and tri-generation (heating, cooling and electricity) can play in reducing GHG emissions has not been explored.
- Only comprehensive renovations which result in installation of both fabric and heating measures are considered. Such renovations can be effected in one stage, or alternatively in a number of carefully planned and co-ordinated stages. Partial renovations are not considered. Additional savings, not shown in the scenarios, will be achieved in cases where only the heating system or certain building components (e.g. windows) are replaced.
- All scenarios run to 2030. This is a sufficiently long timescale for the full impact of policies to be witnessed; yet not so long as to necessitate unrealistic assumptions to be made about longer term technological developments and evolution of costs/prices that may radically change the economic landscape for building renovation. Clearly, within the period to 2030, it would only be possible to renovate a proportion of the existing stock, so the results presented below should not be considered as being the limits of what can be achieved in terms of energy savings and GHG emissions reductions from the existing building stock.[1]

The results present the full impact of the renovations undertaken under a particular scenario through to 2030, rather than an annualised rate. For example, the quoted energy savings will occur from 2030 onwards, once the full complement of buildings has been renovated. The investments and subsidies represent the total requirement for all renovations to 2030, but at today's prices (reduced according to the learning curve applicable under a given scenario). Likewise, net savings (which might be negative or positive) cover the energy cost savings over the lifetime of the measures, less the total investor contribution to the investment.

[1] In the model Invert/EE-Lab the renovation rate is derived based on the lifetime of buildings and building components and the corresponding age structure of the building stock. Thus, different age categories show different renovations rates. The cumulated share of renovated buildings in the period from 2015-2030 varies between about 15% and 37% for different building segments. This is equivalent to an annual renovation rate from below 1% for newer building segments and up to 2.3% for older building segments.

- Within each building category there are a range of buildings, some of which will be more amenable to renovation than others. The results plotted in the results section represent an average across that building category. If a building category is cost effective overall, it does not necessarily mean that comprehensive renovation of all buildings of that type will be cost effective. Likewise, a building category that is overall not cost effective may include some buildings which are cost effective to renovate under the given set of economic conditions.

Scenario settings and basic assumptions

In order to generate different possible views of the future, a number of economic factors that are relevant to investors have been identified and used as variables in the generation of different scenarios. These are described and summarised in Table 2.

Technological learning reflects the cost reduction due to technology diffusion and as a result of increased volumes of sales. Historical evidence of such reductions is plentiful, with perhaps the best known example being the reduction in the cost of photovoltaic panels (PV). In the model, the following learning, in form of cost reduction, is used. As can be seen, they are differentiated according to technology, reflecting its maturity. In deriving learning effects, we took into account relevant recent literature, in particular (Manteuffel et al., 2014), (Henning et al., 2013), (Fernandez-Boneta, 2013).

Table 1: Cost reduction applied for specific technologies

Technology	**Cost reduction in 2030 compared to today's prices**		
Scenario assumption	*low*	*central*	*high*
Solar thermal	3%	6%	9%
PV	13%	25%	38%
Heat pumps	3%	6%	9%
Ambitious renovation of building envelope	8%	15%	23%
Moderate renovation of building envelope	5%	10%	15%

The cost effectiveness from the investors' perspective is estimated in a number of different scenarios based on permutations of economic factors, to illustrate different policy measures that government might reasonably consider applying to stimulate the renovation market. The selected scenario parameter variations are described in Table 2 and Table 3.

Table 2: Overview of scenario variables

Item	Description	Scenario variables	
Subsidy level for building envelope measures	Grants, implicit value of loan, or other external financial support as a % of total capital investment	low	0%
		central	10-25% (R1= 0%; R2 =10%; R3 = 25%)
		high	20%-35% (R1 = 0%; R2 = 20%; R3 = 35%)
Subsidy level for heating and hot water system measures		low	0%
		central	10-20%
		high	25%-40%
Transaction costs	Costs associated with preparatory work, planning costs, approvals, etc., including staff time, expressed as a % of total capital investment	central	5%
Discount rate	Cost of borrowing to finance energy saving investment	low	2%
		central	4%
Learning and cost reduction until 2030	The impact of future price reductions resulting from factors such as increased sales volumes, more efficient installation procedures, improved productivity or R&D resulting in new and better ways of saving energy	central	6-25%
Energy price increase until 2030	Increase in the real retail price of energy from 2015 to 2030	central	1.1% /year

Building stock and cost related input data

Building stock data

The starting point for the analysis is the categorisation of the German building stock according to a number of representative building typologies. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the disaggregation as used in the model. In total, 4459 reference building segments are differentiated according to the physical characteristics of the building structure and the installed heating systems. The level of building classes is relevant for the differentiation of the energy performance of building envelopes. Residential buildings are represented by 285 different classes, non-residential buildings by 70 classes. Building classes are distinguished in terms of building type (e.g. single-family houses, apartment buildings, office buildings, etc.), as well as construction period and presence of existing renovation measures. The resulting building typology has been applied in previous studies and scientific analysis by Fraunhofer ISI and TU-Wien ((Dengler et al., 2011) (Kockat and Rohde, 2012), (Steinbach and Schultmann, 2015), (Steinbach, 2015).

For the presentation of the results, buildings are aggregated in the following categories shown in Figure 3, which shows the final energy demand for space heating and domestic hot water in the year 2014[2].

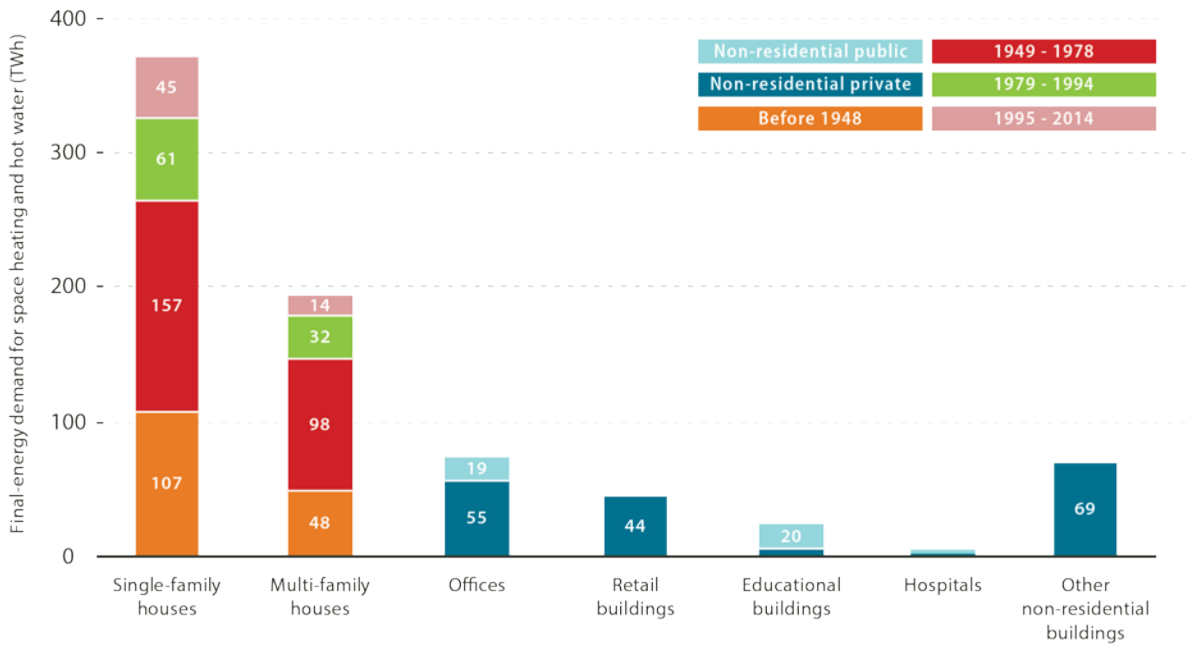


Figure 3: Final annual energy demand for space heating and hot water clustered in the building categories used within this project

The target value for the ***Standard*** refurbishment package assessed in this study is defined by the requirements of the *Energy Saving Ordinance* on existing buildings in case of major renovation. The ***Moderate*** refurbishment package meets the target of a *KfW efficiency house 100* with regard to the energy performance of the building envelope, while the ***Ambitious*** package corresponds approximately to the highest *KfW efficiency house 55* level of performance.

Required investments for renovation packages – building envelope

Figure 4 distinguishes potential efficiency measures applied to the building envelope according to specific investments per surface area of each building component in relation to the thickness of the insulation material[3] and in relation to the U-Value for window replacement, respectively.

[2] Since the data on buildings are partly based on the year 2010, results for 2014 have been extrapolated applying the Invert/EE-Lab simulation model and calibrated with the end-use energy balance.

[3] The thicknesses discussed here do not refer to a specific type of insulation, but instead are based on an average across a range of products available on the market.

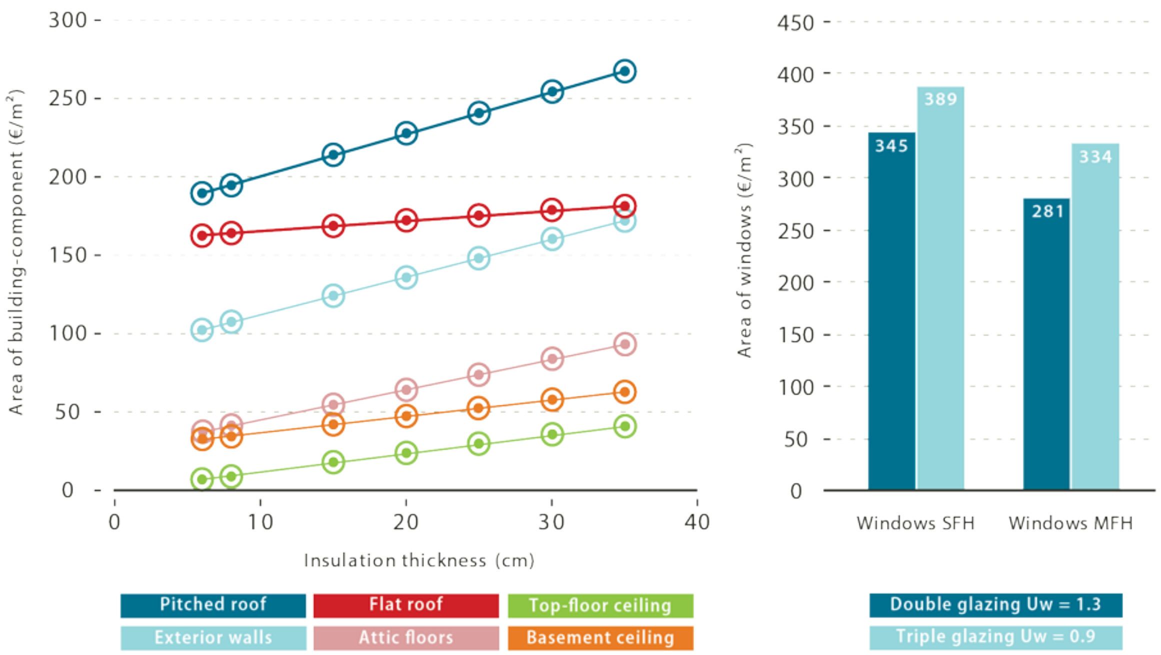


Figure 4: Specific investments of a range of energy efficiency measures on the building envelope, based on an average of different insulation products available for each application

Source: (Hinz, 2011)

The illustrated values represent the investments in terms of a full cost calculation for the energy retrofits, including material, transport and labour costs. The data are based on the evaluation of projects that have actually been implemented, while various insulation materials have been converted to an equivalent insulation thickness with a thermal conductivity value amounting to 0.035 W/(m*K) (Hinz 2011).

The cost effectiveness of the energy retrofit depends significantly on whether the investment includes concurrent implementation of energy retrofit measures alongside maintenance measures such as essential replacement of a building component (e.g. roof repair[4]). Assuming such works are undertaken simultaneously, only the additional efficiency measures are taken into consideration in the evaluation of the cost-effectiveness of building renovation.

The resulting specific investment costs for the renovation packages needed to achieve the three efficiency standards considered in this analysis for the reference buildings are taken from (Steinbach and Schultmann, 2015). Non-energetic investments account for 32 % of the total investment for the *Standard Renovation* package on average, weighted by floor area.

Results

In the following, we will present the resulting energy saving cost curves for three cases (according to the assumptions documented in Table 3), followed by an overview of sensitivity calculations, resulting from a variation of each of the parameters listed in Table 2.

[4] For a detailed description of the conventional retrofit measures that would in any case be implemented (regardless of an energy retrofit or a normal refurbishment), please refer to Hinz (2011).

Table 3: Overview of scenario parameters applied in the scenarios

Scenario	Subsidies	Transaction costs	Discount rate	Cost decrease to 2030	Energy price increase to 2030
Business as usual	10-25%	5%	4%	6-25%	1.1% /year
Low subsidies	0%	5%	4%	6-25%	1.1% /year
High subsidies	20-40%	5%	4%	6-25%	1.1% /year
Low interest rate	10-25%	5%	2%	6-25%	1.1% /year

Scenario 1: Business as Usual

This scenario assumes the prevailing *central* economic conditions in Table 2 are maintained throughout the period in question. Under the Business as Usual scenario just over half of the building categories are located above the line and thus not cost-effective (without consideration of the co-benefit). Non-residential building categories hold the most cost-effective potential for retrofits, notably hospitals, educational facilities, retail and private offices. It is noteworthy that, within the residential sector, only older dwellings built before 1948 exhibit a cost-effective potential for renovation – these are the ones with the highest specific energy demand, as illustrated in Figure 5. However, it should be recalled that we consider full renovation packages only. There would undoubtedly be single measures or partial renovations that deliver cost-effective benefits, even though they would achieve lower savings. Assuming investors only take up cost-effective renovations, the total investment required amounts to €97 billion, of which €19 billion is public subsidy. When co-benefits are valued in the economic appraisal, total investment increases to €235 billion, of which subsidies account for €41bn[5].

[5] Subsidies are related to the level of investment. They do not rise in exact proportion to the investment, since the mix of measures changes according to the specific input parameters, and different measures attract different levels of subsidy – see table 6.

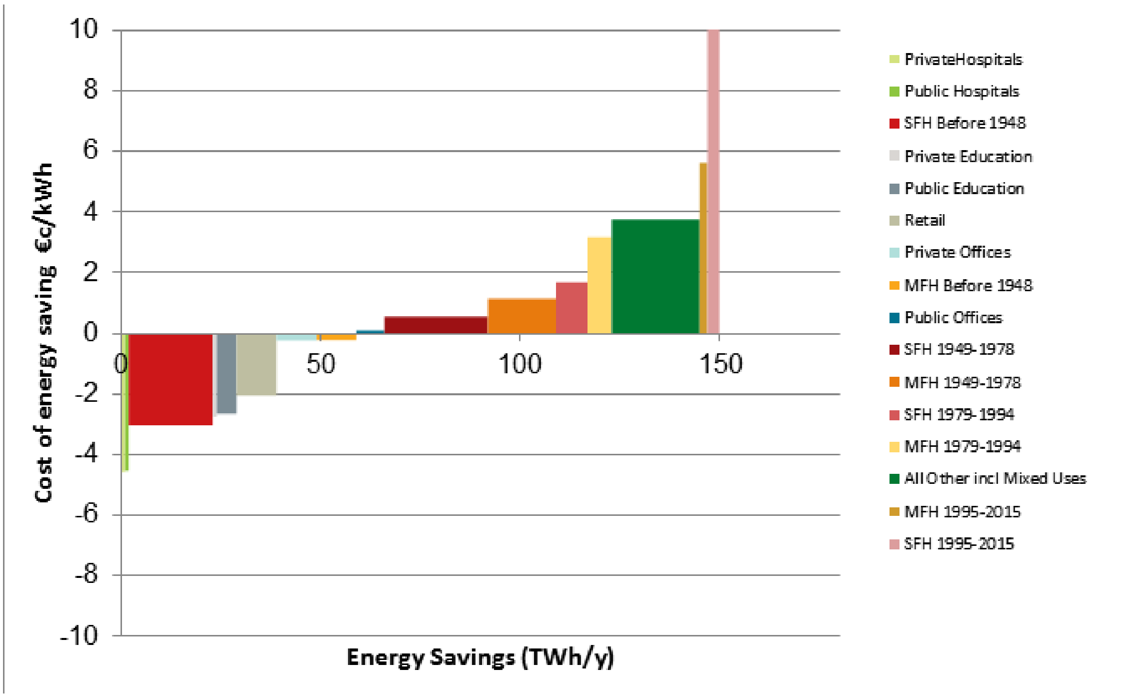


Figure 5: ESCC– Business as Usual scenario

Scenario 2 and 3: No Subsidies vs. High Subsidies

In this section, we show the results under low subsidies (i.e. no subsidies, Figure 6) and under high subsidies (Figure 7)[6]. The first scenario shows the impact of current subsidies. Without these subsidies (and no change in other framework conditions) a considerably smaller amount of energy savings would be economic, only 28% of the overall potential compared to 40% in the BAU scenario. The result also shows that the current subsidies do not only trigger renovation activities, but also contribute to avoiding lock-in effects: The type of implemented renovation activities in the “no-subsidy scenario” is less ambitious and thus locks these buildings for more ambitious renovation packages until 2050.

[6] Taking into account the values documented in Table 3.

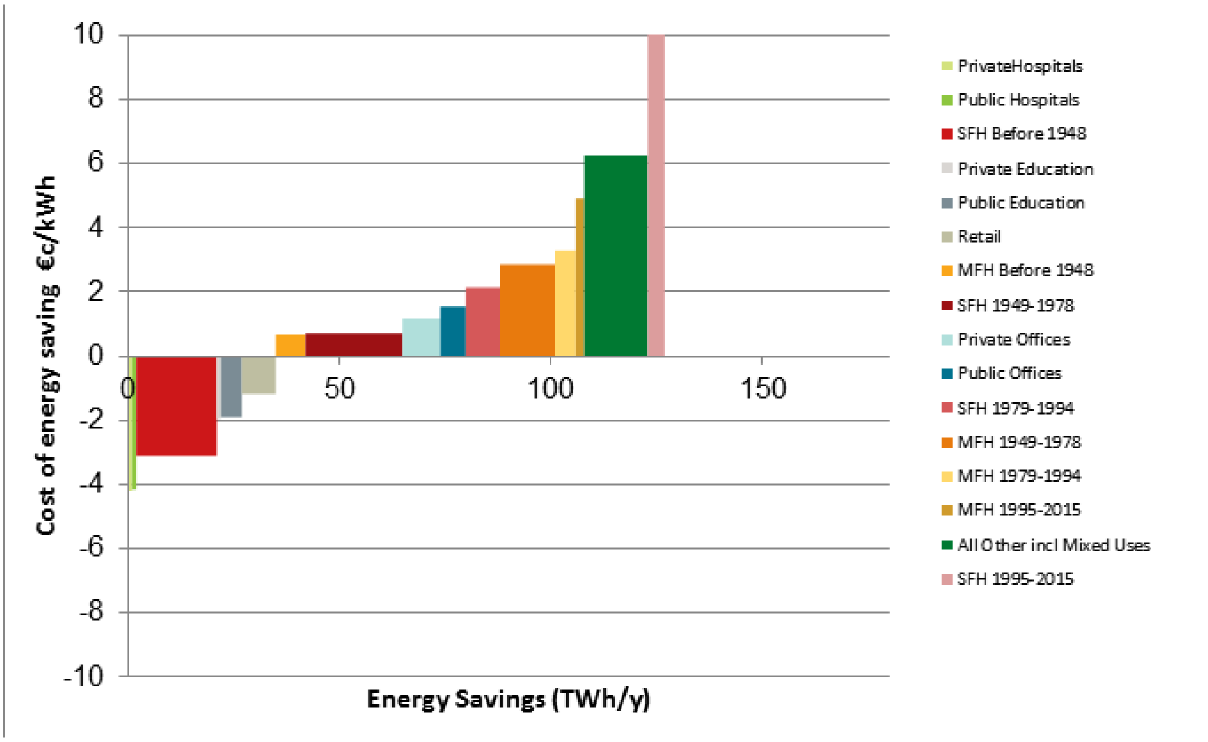


Figure 6: ESCC– No Subsidy scenario

Compared to the Business as Usual scenario, the additional incentive in the High Subsidy scenario is to increase the level of subsidies to the *high* values seen in Table 3, namely for fabric measures: R1 = 0%; R2 = 20%; R3 = 35% and for space heating and hot water systems 25-40%.

The impact of applying the higher subsidy rates can immediately be seen. Compared to the Business as Usual, there is a general shift down (i.e. more cost-effective) and right (i.e. higher energy savings) in the Energy-Saving Cost Curve. The following additional building categories become cost-effective: public offices and residential buildings (both single and multifamily) constructed in the period 1949-1978. Total energy savings increase from 150 TWh/year to 167 TWh/year (not including the co-benefit). The fact that net savings across all building categories are positive, at €1.2 billion, means that a “bundling” approach of transferring the surplus from cost-effective buildings to the non-cost-effective ones could achieve the total energy saving potential in a way that delivers net cost savings for all building category owners. Clearly, the higher subsidy rate comes at a higher cost to the public purse – up from €50 billion in the Business as Usual scenario to €106 billion in this High Subsidy scenario.

However, the challenge is also to avoid free-rider effects: Those buildings with already quite negative energy saving costs also receive the increased subsidies leading to even higher profit from building renovation. In order to reduce the impact on public budgets and increase the probability that increased subsidies will be realized such free-rider effects should be avoided. This could be achieved by mandatory bundling of projects or tendering.

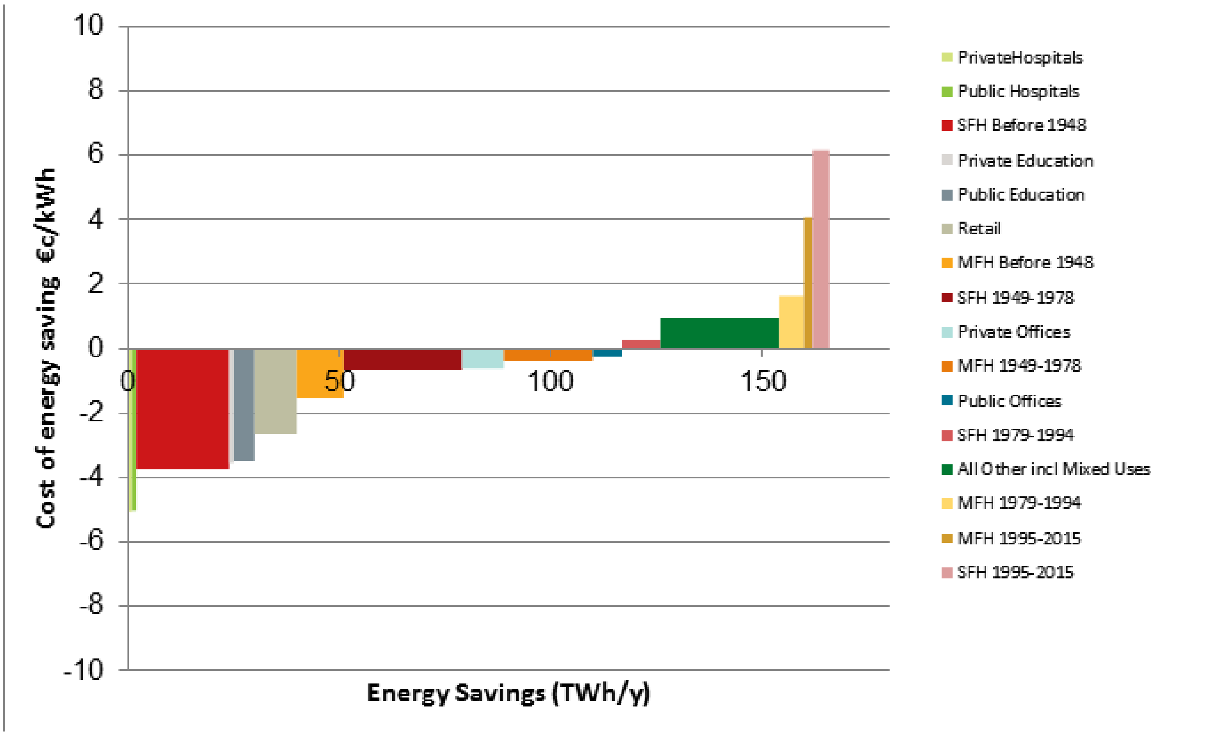


Figure 7: ESCC– High Subsidy scenario

Scenario 4: Low discount rate

The following scenario shows the impact of a low discount rate on the ESCC. A high uncertainty is related to the discount rate which is applied by investors. Currently, we can observe very low market discount rates. Some building owners may have money on their bank accounts with practically 0% real discount rate. Thus, if investors, the banking sector, pension funds etc. would identify the potential of thermal building renovation not necessarily as highly profitable but highly secure investment with still positive rate of return (e.g. 2% as suggested in this case), this could lead to a huge increase of economic energy saving potential compared to the central scenario: About 125 TWh, which is more than three quarters of the potential in this scenario is cost effective and more than 90% of the potential is achievable with costs below 0.2c/kWh energy saving.

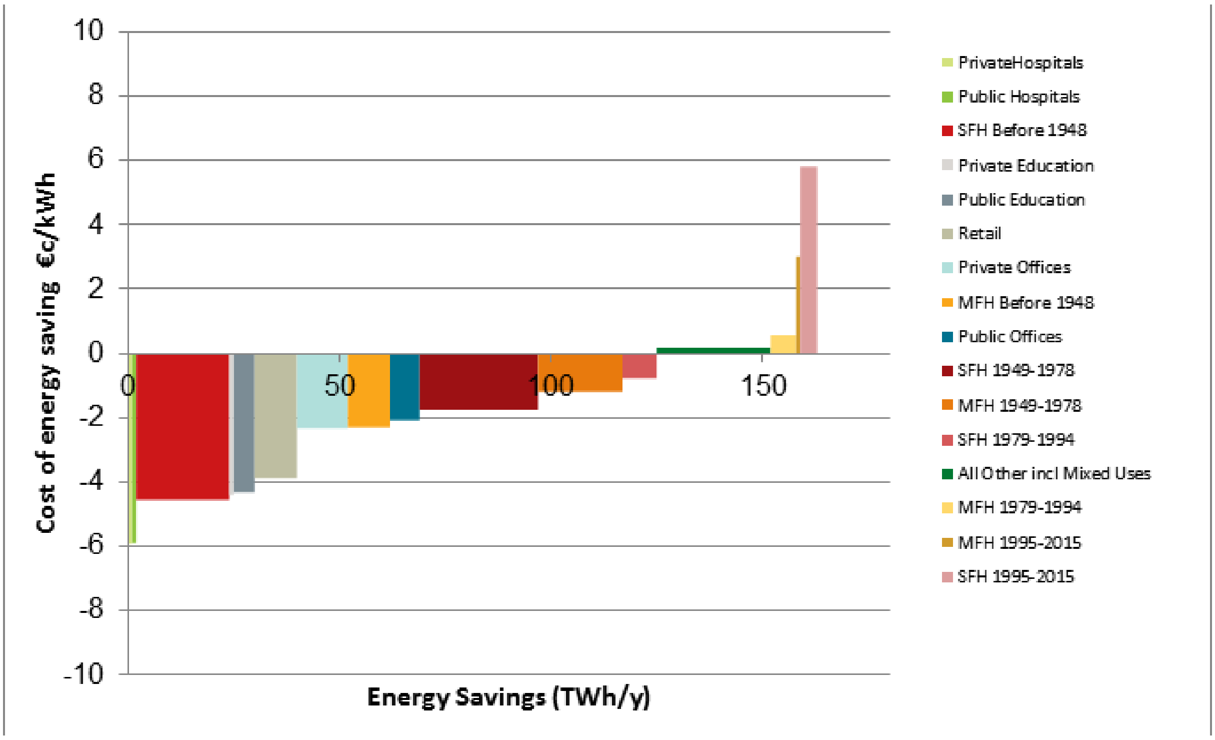
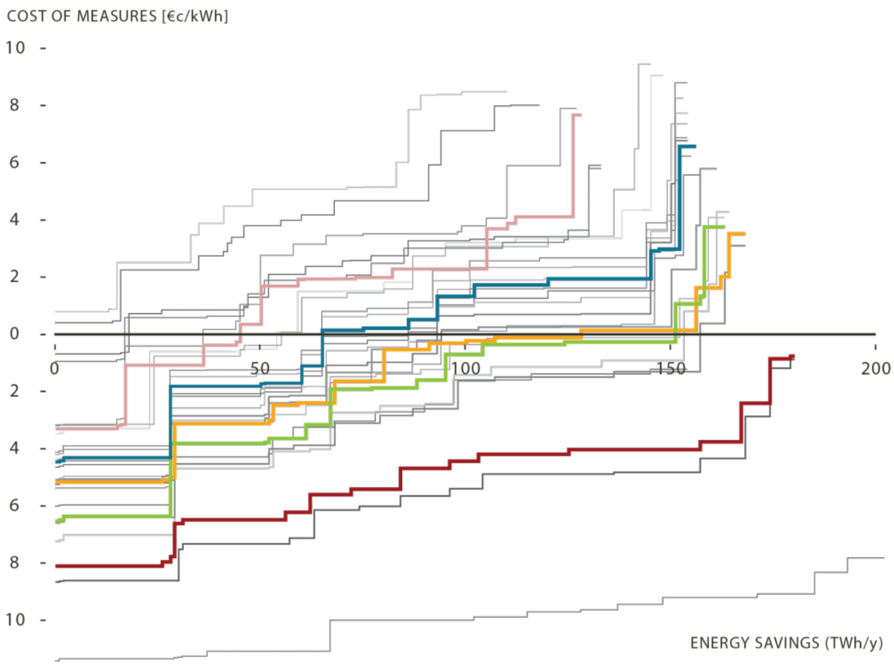


Figure 8: ESCC– Low discount rate scenario

Sensitivity analyses

The following figure shows the main results for a number of main scenarios and related sensitivity analyses within the limits of parameters shown in the table below the graph. Each band of the curves represents a building cluster, which will be described more detailed in the full paper. The coloured lines show the main scenarios which are discussed more intensively in the full paper. The blue line reflects the status quo conditions: current level of subsidies, medium transaction costs, medium discount rate, medium expected cost decrease of renovation activities, medium energy price increase. All these data are based on literature and previous studies.



Limits	Subsidies	Transaction costs	Discount rate	Learning effects (cost reduction 2015-2030)	Annual gas price increase (2015-2030)
Lower	**0%**	**2.5%**	**2%**	**3-13%**	**0.27% per year**
Upper	**20% -40%**	**10%**	**10%**	**9-38%**	**2.28% per year**

Fig. 1 Energy Saving Cost Curves for the case of the German building stock. The table indicates the ranges of parameter variations.

Discussion

The level of ambition of renovation is heavily influenced by policies rather than by the market. Without the right policy signals, there is a serious risk that the building owners and investors will continue to focus on shallow renovations, effectively locking out the potential for the full energy potential to be realised, and, with it, a loss of economic benefit to building owners and the wider German economy. In the worst case, over half of all renovations could be shallow, whereas in the best case, over 70% could be deep;

Total annual energy savings of up to 180 TWh could be achieved by 2030, through a dedicated programme focused on deep renovation. This represents approximately 16% of current energy use in the building stock;

Non-residential buildings are generally more cost-effective to renovate than residential buildings; Among the residential buildings, those constructed prior to 1948, both single-family and multi-family, are the most cost-effective to renovate; The energy saving potential across all non-residential buildings is broadly equivalent to that across single-family houses of all age categories;

The least cost-effective building categories to renovate are the newer residential buildings, built to higher energy performance standards. One would not expect these new buildings to be renovated in substantial numbers in the period to 2030;

Total investment requirements over the period to 2030 vary considerably, between €100 billion and €500 billion, according to scenario, depending on whether co-benefit is included, and whether all buildings or only the cost-effective sectors are considered. This shows the big impact in investment – up to a factor of 5 – that choice of policy levers can have on the market for building renovation;

Establishment of a fund which bundles investments with varying cost effectiveness can substantially increase the overall level of renovation;

The greatest level of energy savings, and financial return to investors, would be achieved through a combination of financial/fiscal measures such as subsidies and energy prices, together with soft measures that reduce costs for investors by creating more favourable market conditions.

There is a limited pool of funds to be allocated under the German energy efficiency fund. In order to stimulate optimal investment and overcome the issue of free riders, a bundling approach is proposed. The bundling policy of the grant-making scheme would aim to transfer surplus economic gains from building categories with a high energy savings potential to building categories whose economic benefit is marginally negative. In this way, financial returns to free riders who have the financial capacity to undertake energy efficiency renovations are limited, and the surplus savings are distributed to beneficiaries who would otherwise be unable to do so. Our approach is indicated by a focus on financial transfers between building categories, but a renovations programme adopting this approach should also be taking into account social factors, which are excluded from the scope of our analysis. Through the bundling approach, the sharing of economic gains from the renovation of the most cost effective categories will allow borderline cost effective buildings to engage in renovation activities and maximise the overall energy savings. In practical terms, owners with investment capacity of buildings with significant economic energy savings potential would through the bundling approach receive smaller subsidies (either as direct payments, or low interest loans) compared to owners of buildings who also have significant energy savings potential but are only marginally uneconomic.

The economic evaluation of the subsidy levels under the KfW requirements should pass through a centralised system that will allow for a readjustment of the grant according to the bundling approach and based on the registered economic status and energy savings potential of the participating owners and buildings. Attention should be placed in the structure of the bundling system and its adjustment criteria in order to avoid irrational and socially unacceptable transfers of funds.

Several methodological aspects should be considered carefully in the interpretation of our work:

The energy saving cost curve developed in this paper represents the investors' perspective. A change in the side conditions (e.g. energy prices, subsidies, taxation) affects the economic viability of various renovation packages and thus might lead to a change in the least cost option for the investor. Thus, this approach allows the policy maker to assess the energy saving potential which can be exploited at certain cost levels and under various side conditions. This leads to the fact that a change e.g. in subsidies shifts not only the cost level of the energy saving cost curves (i.e. the height of the bars) but might also change the energy saving potential (i.e. the width of the bars).

While we think that this methodology is a very useful approach to show the impact of policy instruments and other side conditions on the economic viability of energy saving potentials, it is not possible to get the full energy saving potential, including the stepwise marginal additional renovation measures which exist to improve the energy performance of the building stock. A comparison of our results with another methodological approach for deriving energy saving cost curves or also CO2 abatement cost curves in the building stock would be very interesting and is left for further research work.

The definition of the reference system has an impact on the results. We only took into account the part of the building stock which has to be renovated due to lifetime restrictions until 2030. Thus, it is valid to assume that a renovation measure without any thermal improvement can serve as a reference system. However, we could also assume a thermal improvement according to the building codes as a reference system and only take into account those measures going beyond this reference renovation level. However, this analysis was beyond the scope of the work in this paper.

We focused on measures showing the impact of full renovation packages, i.e. renovation of the building envelope (including all building envelope components) and the space heating and hot water system. However, one could also think of measures including only certain parts of such full renovation packages, in particular only replacing the space heating and hot water system without a renovation of the building envelope. These measures also were not taken into account in this paper.

The numerous reference buildings taken into account in the input data and the modelling framework were aggregated to a limited number of building clusters. This was mainly done in order to allow for a clear and manageable visualisation of the energy saving cost curves. However, we are aware that the building clusters are not completely homogenous. This means that within each building cluster there are buildings with lower energy saving costs and buildings with higher energy saving costs. Thus, the way how we clustered the large number of reference buildings has an impact on the average values shown in the graphs.

Acknowledgements

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