German Energiewende – different visions for a (nearly) climate neutral building sector in 2050

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Abstract

The building sector plays an important role for the goals of the German *Energiewende* (energy transition). In order to contribute to the *Energiewende* adequately the building sector has to be almost completely decarbonised in the long-term. Our analysis investigates how the German building stock can be transformed into a nearly climate-neutral state by 2050.

Using a stock modelling approach based on a typology of the German residential and non-residential building sector we develop different visions (target states) of what a nearly climate-neutral building stock could look like. All developed target states achieve the overall goal of reducing the non-renewable primary energy demand in 2050 by at least 80 % with respect to 2008. In order to span a broad target corridor, the target states differ in the two central target dimensions: efficiency (reduction in final energy demand), and energy/technology supply mix (especially the herein contained share of renewable energies). Additionally, using the energy system model REMod-D the interactions of the building stock, as defined by the different target states, with the energy system as a whole are investigated.

We explore the differences between a target state focussing on efficiency measures (all buildings which in principle can be renovated are refurbished to the maximum extent possible) and a target state where efficiency is partly compensated for by an increased use of renewable energies. We learn that from a cost perspective no clear recommendation can be derived as to which target state should be given priority. This means that other criteria become more relevant, such as social acceptance regarding the different measures, or the challenges that arise from rolling out additional renewable energy capacity on top of the expansion of renewable energy that is necessary to achieve the climate goals in other sectors (e.g. electricity generation, transport).

Based on our analysis we develop policy recommendations aimed at achieving the long-term targets.

Introduction

The federal government of Germany aims at realizing a "nearly climate-neutral" building stock by 2050. The plan is "that buildings will only need very little energy and that the remaining energy needs will mainly be met by renewable energy sources" (BMWi 2010).

The technical feasibility of both climate-neutral renovations and climate-neutral new buildings has been shown by various demonstration projects. However, a vision is lacking of how the entire stock of residential and non-residential buildings should be constituted energetically in order to reach the 2050 target. The relevant questions concern, amongst others, the required level of buildings' energy standards, the mix of energy sources and supply technologies, the associated costs as well as how the building sector as both energy consumer and energy producer will interact with the entire (transformed) energy system in the long run.

In our paper, we explore different target states of how a nearly climate-neutral building stock could be realised in 2050. The target states are parameterized as to reflect a rather broad corridor of future states in terms of two central dimensions, the reduction in final energy demand (efficiency) and the composition of the fuel and technology mix (mainly the share of renewables).

Methodology

DEFINITIONS AND ENERGY ACCOUNTING FRAME

The definition of the term "nearly climate-neutral" building stock leaves room for interpretation. The term "very low energy demand", for instance, does not clarify whether this refers to the useful energy demand, the final energy demand, or the primary energy demand. Additionally, the meaning of "low" is not explicitly quantified.

For the purpose of our analysis a nearly climate-neutral building stock is defined by

- a non-renewable primary energy demand (PE_{NR}) for the thermal conditioning of a building that is 80 % lower than that of the 2008 reference year, and
- a remaining, very low final energy demand, which is mainly supplied by renewable energy sources, i.e. by more than 50 %.

The building stock entails all buildings in the residential, commerce, trade and service sectors as well as industry.

For the energy accounting all fluxes of primary energy are considered that are used for the thermal conditioning of a building. This includes the primary energy required for space heating, sanitary hot water generation and ventilation as well as supporting energies, e.g. to run a circulation pump. For non-residential buildings, energy for lighting and air conditioning is also accounted for. In this regard, the primary energy demand is calculated using the methodology laid down in the German building code (Energy Saving Ordinance, *EnEV*) and underlying technical standards[1]. Deviating from the building code the final energy demand is calculated according to the standard set by the official energy balance (energy balance for national energy statistics) which accounts for all energy forms. This includes solar thermal energy as well as ambient energy made available by means of a heat pump[2]. The only exceptions are heat recovery (HR) units, which are treated like an energy efficiency measure that reduces the final energy demand. Figure 1 shows the schematic energy flux diagram, which forms the basis of the energy accounting.

BUILDING STOCK MODELLING

A stock modelling approach based on a typology of the German residential and non-residential building sector is applied to analyse indicators such as final and primary energy demand, CO_2-emissions and costs.

Building typology

For the calculations, the entire building stock is represented by 19 building types – nine for residential buildings and ten for non-residential buildings.

- Residential buildings are subdivided into three size classes which are single- and double-family houses (SDFH), small and medium-sized multi-family houses (SMH/MMH), and large multi-family houses (LMH). The building types are further subdivided into three age groups (pre-1949/1949–1994/post-1994) whose energetic characteristics in their originally built state differ strongly.
- For non-residential buildings (NRB) the shape, the energy characteristics of the building envelope and, in particular, the building's usage all have an influence on the building's energy consumption. There are six different usage types, of which four are subdivided into two age classes (pre-1984/post-1983). The six different usage types are (I) residential buildings with mixed use, (II) education, office and administration buildings, (III) commerce and industry buildings, (IV) trade/service and surgery buildings, (V) hotels, restaurants and hospitals, and (VI) other (sports, cultural).

Building typology data are mainly based on Destatis 2013, IWU 2012, Loga et al. 2012, Loga et al. 2011, Diefenbach/Loga 2011 and Diefenbach et al. 2010 for residential buildings and Schlomann et al. (2011), BMVBS (2013), BMVBS (2011) for non-residential buildings.

To describe the building stock's expected future heating demand three energy standards of thermal insulation are considered:

1. Non-renovated buildings ("non-renovated").
2. Renovations according to the EnEV in 2009 for newly built buildings with an increase in that standard by 25 % ("fully renovated").
3. Renovations according to the standard for passive houses ("fully renovated plus").

The two renovation standards "fully renovated" and "fully renovated plus" are characterised by the following U-values.

The energetic standards of newly built buildings are treated in the same way as the renovation standards.

Energy and technology mix

It is very difficult to foresee the development of the technological portfolio for the coming 35 years. In the case of the building sector this holds true for predictions about the relevance of power-to-gas, power-to-heat, gas-driven heat pumps or fuel cells. The development of the target states is therefore based on a conservative approach, which only makes use of technologies that are already established today. For residential buildings five basic heating technologies are considered which are:

1. Gas condensing boilers
2. Wood/pellet condensing boilers
3. Electric heat pumps
4. Gas-driven combined heat and power units (CHP)
5. District heating

1. DIN V 18599:2011, Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung (Energy efficiency of buildings – Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting); DIN 4108-6:2003-06, Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 6: Berechnung des Jahresheizwärme- und des Jahresheizenergiebedarfs (Thermal protection and energy economy in buildings – Part 6: Calculation of annual heat and annual energy use); DIN EN ISO 832:2003-06: Wärmetechnisches Verhalten von Gebäuden - Berechnung des Heizenergiebedarfs – Wohngebäude (Thermal performance of buildings – Calculation of energy use – Residential buildings); DIN V 4701-10:2003-08, Energetische Bewertung heiz- und raumlufttechnischer Anlagen – Teil 10: Heizung, Trinkwassererwärmung, Lüftung (Energy efficiency of heating and ventilation systems in buildings – Part 10: Heating, domestic hot water, ventilation).

2. If the final energy demand is calculated according to EnEV, ambient forms of energy (essentially solar thermal heat and ambient heat) which are produced in close proximity to a building are set to zero.

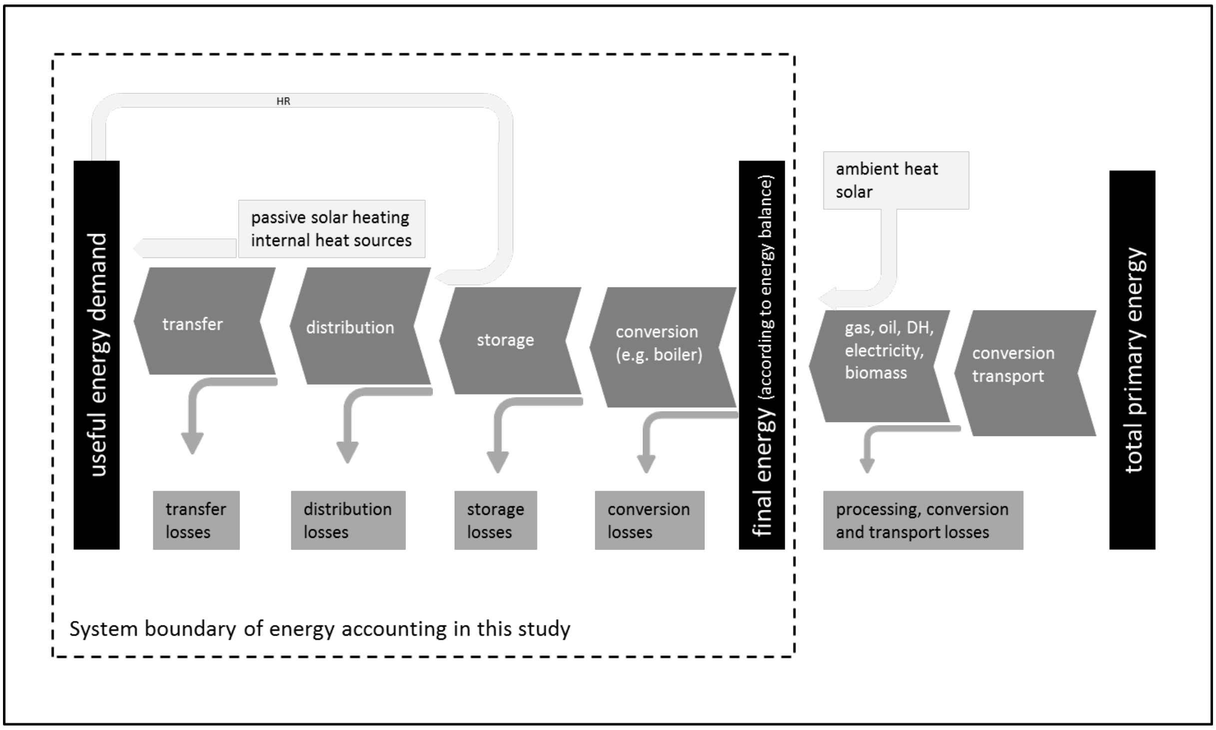


Figure 1. Schematic energy flux diagram.

Table 1. U-values characterising the two renovation standards.

		Fully renovated	Fully renovated plus
U-value external wall	W/(m²*K)	0.29	0.10
U-value roof	W/(m²*K)	0.21	0.10
U-value floor	W/(m²*K)	0.37	0.20
U-value window	W/(m²*K)	1.37	0.70
g-value window	W/(m²*K)	0.63	0.45
U-value doors	W/(m²*K)	1.89	1.35

Source: Own assumptions.

All heating technology options are considered in combination with ventilation systems with or without heat recovery (HR), as well as with or without the usage of solar thermal energy. The solar thermal system is solely used for sanitary hot water. Buildings that are renovated according to the standard "fully renovated plus" always feature a heat recovery system.

For non-residential buildings four heating technologies are considered:

1. Gas condensing boilers
2. Electric, reversible heat pumps
3. Gas-driven combined heat and power units (CHP)
4. District heating

All heating technology options in non-residential buildings are considered with or without photovoltaic panels (electricity self-consumption).[3] Since the generation of cooling, ventilation as well as lighting all have to be accounted for in non-residential buildings according to the Energy Saving Ordinance (EnEV), parameters for these types of energy usage are introduced, e.g. for the generation of cooling through absorption cooling machines.

A restriction applies to the use of wood for the future heating supply in buildings. According to UBA (2014), the potential of sustainably-sourced wood-like waste material (including from industry) in 2050 amounts to 85 TWh/a. This therefore presents the upper limit of energy from wood that can be used in residential buildings (for non-residential buildings, wood-based heating technologies are not included in our chosen typology).

Regarding energy supply, we would gain additional degrees of freedom via the possibility of importing electricity based on renewable energies, biomass as well as more synthetic gases generated via renewable energies, and thereby reduce the pressure of rolling out more renewable energies within Germany. Because of uncertainties about the actual import quantities, we opt for a conservative approach and leave out the import of renewable energies altogether.

3. For the analysis of the impact on the energy system on-site PV generation is considered to contribute to the RES share of the overall electricity mix.

ENERGY SYSTEM MODELLING

Additionally, we analyse how the building stock in different target states interacts with the energy system as a whole. This analysis is using the REMod-D model, which integrates the topology of energy producers, converters, storage devices and consumers of the whole German energy system. The basic functionality of the REMod-D model is based on a cost-based optimisation of an energy supply system, whose energy-related CO_2 emissions do not exceed a specified target value and/or target pathway. The optimisation target is to size all generators, stores, converters, and consumers at minimum costs such that the energy balance of the overall system is met in every hour. This means that besides environmental sustainability and cost-effectiveness, the model also addresses security of supply through time-resolved simulations which ensure the energy demand is met each hour throughout the entire year. A detailed description of the model is provided by Palzer (2016), Henning/Palzer (2014) and Palzer/Henning (2014).

COST CONSIDERATIONS

Cost calculations are done from a building owner's perspective. However, some parameters (e.g. the economic impact of a subsidy scheme) are chosen in such a way that they deviate from a strict microeconomic perspective. For instance, in the case of an energetic renovation for which in principal there are subsidy schemes available, the subsidy scheme is not taken into account, even though it strongly affects the profitability of the renovation. Cost calculations are based on 2012 prices. The normalization on this price basis is done via related price indices. Net present values are calculated based on the technical life time of the different components.

The analysis of costs includes investment costs associated with the building's energetic standard (e.g. costs for an energetic renovation of components of the building's envelope or the supply technology) as well as operating costs (e.g. energy costs, costs for maintenance) that depend on the building's technological configuration and its energetic standard. Investment costs for the building's envelope are subdivided into incidental costs (that would occur anyway irrespective of whether a renovation is combined with any form of energetic modernization) and costs associated with renovating to a higher energetic standard (additional energy related costs). Energy costs reflect energy prices for end consumers. Three different energy price scenarios are used (low/intermediate/high). All cost data used for the analysis including their sources are documented in Bürger et al. (2016).

Results

DEFINITION OF TARGET STATES

The overall reduction goal, based on the non-renewable primary energy demand (PE_{NR}) can be illustrated by means of different sector configurations (target states). The two central and intertwined dimensions for those target states are the reduction in final energy demand (efficiency of the building envelope and heating system) and the composition of the sources of the final energy (the share of renewable energies in particular). For our analysis, we choose three different target states that are parameterized as to reflect the broadest possible corridor of future states in terms of these two central dimensions.

All three target states fulfil the primary energy reduction goal with respect to the reference year 2008 (PE_{NR} minus 80 %), whilst differing in the before-mentioned dimensions. Due to a lack of an unambiguous definition, however, it is unclear to what degree the three target states are consistent with the vision of a nearly climate-neutral building stock (see above). This holds true, in particular, for the qualitative requirement that "buildings have a very low energy demand". By contrast, the requirement that "the remaining energy demand is predominantly covered by renewable energies" is met in all three target states, as long as the renewable energy fraction of electricity generation and district heating generation is included.

The basis for the progression towards the target states is the replication of the status quo building stock using the developed building typology. In order to do so, we calibrate each building type according to their status quo distribution of thermal insulation standards and technology options. The calibration is based on different reference values such as the final energy demand of residential and non-residential buildings according to AGEB (2013), the specific final energy demand per building type and age class according to e.g. dena (2015) and BMVBS (2013) or the technology mix according to Destatis (2012). However, it has to be noted that especially for non-residential buildings the data situation for the status quo is still poor. This refers to e.g. areas and technology distributions. In addition, there is a big knowledge gap concerning the renovation activities that are taking place outside of the public subsidy schemes.

The target states are also based on the developed building typology, but taking into account assumptions for the demand for floor area in 2050, the distribution of insulation standards as well as the technology options. The following target states were developed (Table 2).

- The final energy consumption of the residential buildings' target states is reduced by 40 % (RB target state -40 %), 55 % (RB target state -55 %), and 70 % (RB target state -70 %) with respect to the status quo. The RB target state -70 % therefore mainly emphasizes efficiency. For RB target state -40 %, in contrast, the final energy consumption is reduced less, which leads to higher shares of renewable energies in order to achieve the superior goal of PE_{NR} of -80 %.
- The non-residential buildings' constitution does not allow for such a high reduction in final energy consumption. Therefore, their target states are guided by the maximum possible reduction in final energy consumption. The final energy savings range from 25 % (NRB target state -25 %) via 35 % (NRB target state -35 %) to 45 % (NRB target state -45 %).

There are many different restrictions when it comes to energetic renovations of buildings. Restrictions for installing thermal insulation, for instance, can be found for nearly all buildings. These restrictions are typically found for protection-worthy facades (heritage conservation), geometrical limitations due to walkways and passage ways, or cellar ceilings, that are too low[4]. As a consequence, not all buildings can be renovated to the highest renovation standard. In order to take account of this effect, all 2050 target states have a base of buildings that can-

4. For a detailed systematization as well as impact analysis of such restrictions see Jochum et al. (2012).

Table 2. Central assumptions of target states.

	Residential buildings			Non-residential buildings		
Rate at which new buildings are being built	decreasing from 0.85 % in 2015 to 0.2 % in 2050			constant at 1.35 % annually		
Rate at which buildings are taken out of use	constant at 0.3 % annually			constant at 1.35 % annually		
Floor area development by 2050	+ 7 %			± 0 %		
Target states	Target state -70	Target state -55	Target state -40	Target state -45	Target state -35	Target state -25
Reduction in final energy consumption by 2050	-70 %	-55 %	-40 %	-45 %	-35 %	-25 %
Reduction in non-renewable primary energy demand (PE_{NR}) by 2050	-80 %	-80 %	-80 %	-80 %	-80 %	-80 %

Source: Own assumptions.

Table 3. Share of buildings that can't be renovated (regarding the floor area of non-renovatable buildings in their respective status quo).

Building's age class	SDFH	SMH/MMH/LMH	Non-residential buildings
pre-1949	10 %	20 %	2.5–10 % (depending on the building's usage)
1949–1994	5 %	5 %	
post-1994	0 %	0 %	

Source: Own assumptions.

not be renovated. These buildings represent both buildings that cannot be refurbished due to restrictions and buildings that can only be renovated partially. The non-renovatable base differs between different building types and age classes. The relatively high base value for multi-family houses of age class "pre-1949", for instance, reflects the share of *Gründerzeit* (Wilhelminian style) buildings, whose facades are insulation-restricted.

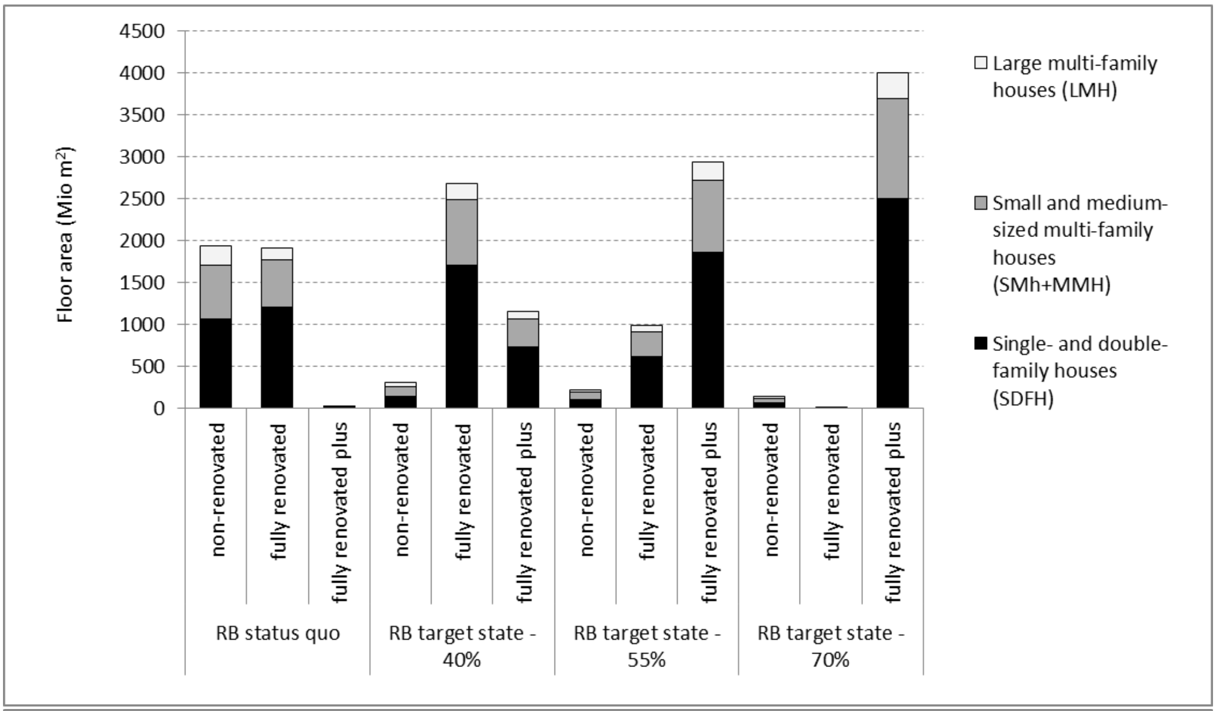
Regarding the future distribution of heating supply technologies, we assume that the relative number of buildings connected to district heating (DH) networks remains fairly constant with respect to the status quo, i.e. district heating is not increasing in our scenarios. In residential buildings, the share of wood-pellet condensing boilers is limited by the maximum available potential of wood (about 85 TWh according to UBA 2014). The number of gas-driven CHP units increases moderately. The collector area increases on average by a factor of 4.5 by 2050. Consequently, the essential levers to pull when it comes to heating technologies are the respective shares of gas condensing boilers and heat pumps.

Figure 2 shows the distribution of the floor area (residential and non-residential buildings) for each renovation standard in 2050. The higher the reduction in final energy consumption, the stronger is the increase in floor area for the renovation standard "fully renovated plus". In the case of target states RB -70 % and NRB -45 %, all principally renovatable buildings are renovated to the "fully renovated plus" standard, with only the base of non-renovatable buildings remaining untouched.

Target states for the building stock as a whole are derived from combining the respective target states of residential and non-residential buildings. The combined target state of RB target state -70 % and NRB target state -45 % achieves the highest combined reduction in final energy consumption of nearly -60 % (see Figure 3). This means that the final energy consumption can at the most be reduced by 60 %. In order to achieve this, the majority of residential and non-residential buildings must be transferred into the renovation standard "fully renovated plus" which is more ambitious than newly built buildings under EnEV need to achieve. In other words, all buildings that in principle could be renovated need to be refurbished with passive house components and include a heat-recovering ventilation system. In view of the rather long investment cycles in the building sector this means that renovation with passive house components needs to start immediately.

Combining the two intermediate target states of residential and non-residential buildings (RB target state -55 % and NRB target state -35 %, respectively) results in a combined final energy reduction of nearly -50 %. Doing so for the two target states with the smallest reduction in final energy consumption (RB target state -40 % and NRB target state -25 %) yields a combined reduction of roughly 35 %. Thus, the long-term transformation goal for the entire building sector with respect to the reduction in final energy consumption is defined by a corridor, which ranges from a reduction of 35 % to 60 %.

Not only do the two extremes of the target corridor differ with respect to the final energy savings, but also with respect to the final energy supply mix (see Figure 3). Due to the higher thermal insulation requirements, about 47 TWh more gas may be used in target state -60 % in comparison to target state -35 %. This is caused by the fact that for target state -60 % a higher proportion of realizing the overall primary energy goal is achieved by ambitious measures to reduce the final energy consumption. In contrast, target state -35 % requires almost twice as much final energy from renewable sources (incl. the renewable share



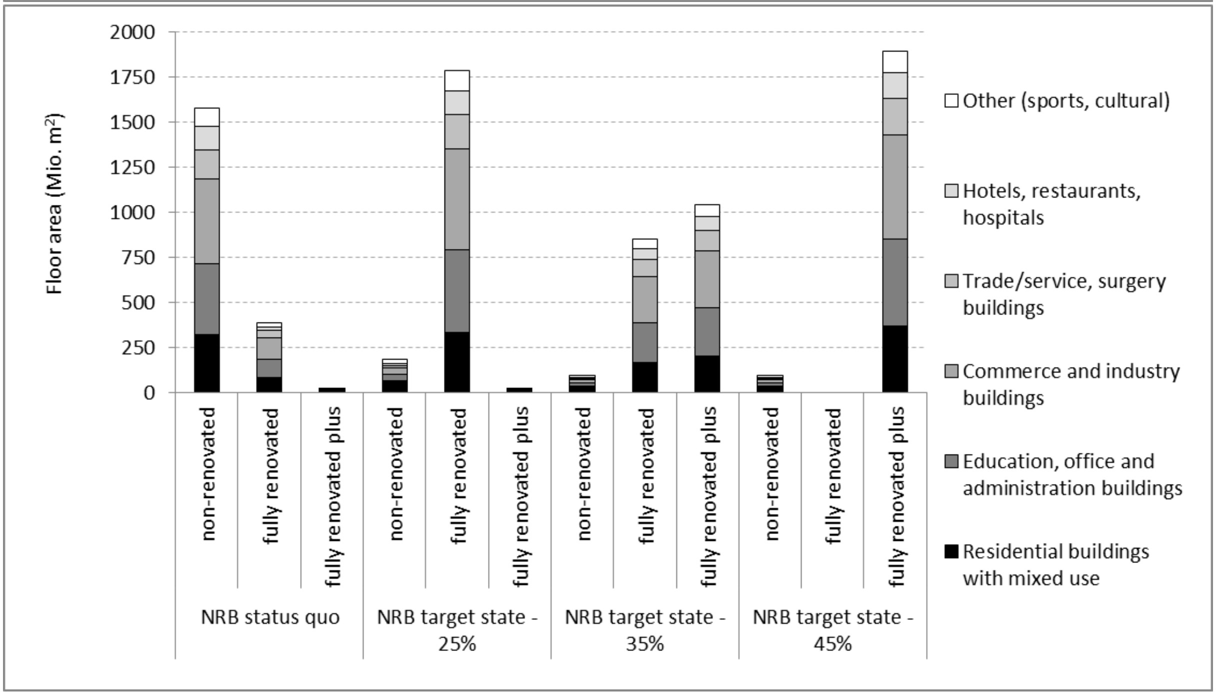


Figure 2. Floor area distribution of the different renovation standards in residential (top) and non-residential buildings (bottom). Source: Calculations by Öko-Institut.

of the electricity and district heating demand) in order to reach the PE_{NR} -80 % goal.

Additionally, target state -35 % shows a strong increase in electricity demand (covering electricity to operate heat pumps, electricity for running the ventilation, pumps and lighting in non-residential buildings). Target state -35 % and target state -60 % differ by around 55 TWh, i.e. the electricity demand of target state -35 % is 55 TWh higher than in target state -60 %[5]. The primary energy factor for electricity used for our analysis implicitly assumes a high share of renewable energy sources. The increasing share of renewables in the electricity mix is reflected by the primary energy factor for electricity that decreases from 2.4 in 2014 to about 0.4 in 2050. The higher demand for electricity in target state -35%, therefore leads to higher pressures on increasing the capacity for renewable electricity generation.

Figure 4 shows the development of key energy-related parameters for the three target states of the building sector as a whole. The development of the final energy consumption is the only parameter showing strong differences between the three

5. For comparison: in Germany in 2015 electricity produced from renewable energy sources amounted to 196 TWh (BMWI 2016).

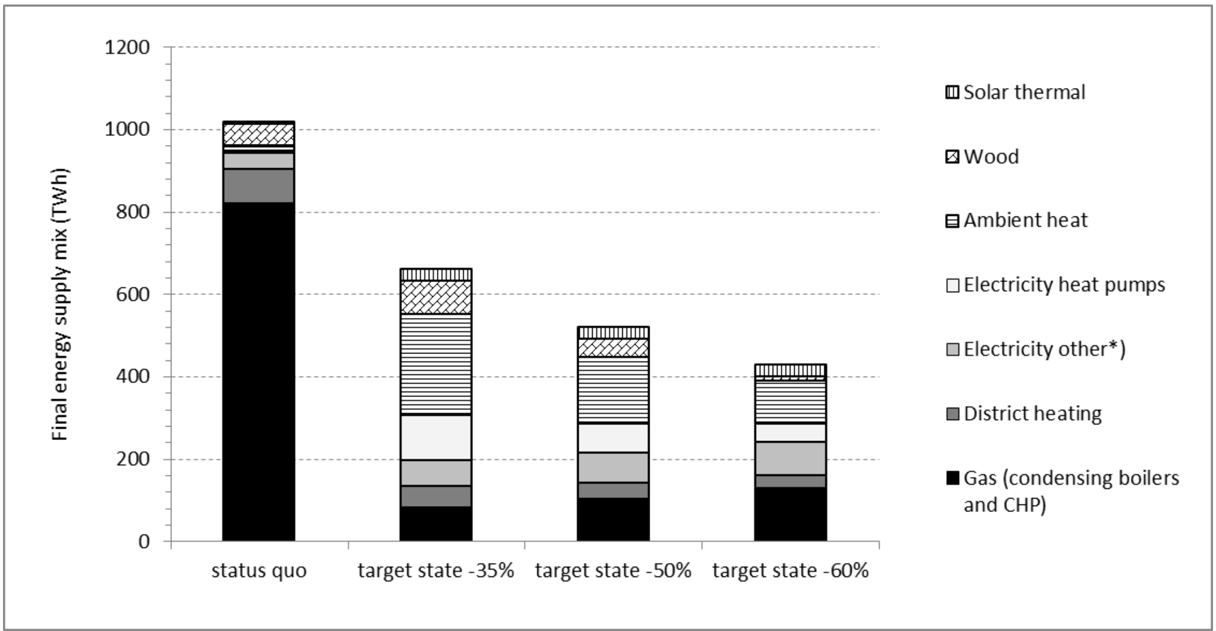


*Figure 3. Final energy supply mix (according to the Energiebilanz) for the three target states of the entire building sector. Source: Calculations by Öko-Institut. *) "Electricity other" includes electricity for running the ventilation, lighting in non-residential buildings, and the electricity needed for running the boilers/pumps etc.*

transformation pathways. Regarding PE_{NR} and CO_2 emissions, the three transformation pathways are almost identical. CO_2 emissions caused by the building sector decrease by 82 % with respect to the status quo for target state -60 %, and by around 83 % for the other two target states. The CO_2 emissions accounting here include emissions from electricity generation required for the thermal conditioning of buildings (e.g. electricity for heat pumps, or ventilation systems) that are typically being accounted for in the energy conversion sector. The same is true for district heating.

The build-up of a market for renovations that is able to supply energetic renovations in the required volumes and depth, needs a certain time lead. Relevant in this context is that a considerably greater volume of renovations is realized at a sufficiently high quality level. Especially for the ambitious renovation levels, the quality of the renovation is of utmost importance. The question therefore is how quickly the necessary capacities can be built up, in particular in the craftsmen trades. Therefore, we assume that renovation rates increase slowly between 2014 and 2020, before reaching a magnitude of 2 % per year from 2021 onwards. The relatively moderate increase in renovation rates leads to pathways of final and primary energy that show a considerable decrease only after 2020. The stronger decrease in primary energy relative to the decrease in final energy until 2020 is based on the fact that the coming years will experience a stronger switch to CO_2 saving heating technologies compared to the increase in thermal insulation measures.

Figure 5 shows the progression of annual costs for the three target states of the entire building sector. The annual costs include the annualised investment costs as well as running costs such as energy costs and costs for maintenance. The annual costs shown in the figure cover all residential and non-residential buildings. The annual costs increase from around €210 billion in 2015 to a maximum of €250–258 billion in 2040, before decreasing again by 1 % by 2050. The annual costs are slightly higher for the two target states with higher energy efficiency saving ambitions than for the one with lower ambitions (target state -35 %). The difference in costs, however, is very small. Considering the great uncertainties, which many assumptions that had to be made during the calculations are based on, it is difficult to derive robust statements as to which target state should be given priority from a cost perspective.

When dividing the residential buildings' total annual costs for the intermediate energy price path by the total floor area, we obtain specific costs of around €28/m² in 2015 and €35/m² in 2050. This equals an increase of about 23 %. For the low energy price path the specific costs rise from €28/m² in 2015 to around €33/m² in 2050, which equals an increase by 18 %. For the high-energy price path the specific costs reach a maximum of €37/m².

The interaction of the three sector-specific target states with the entire energy system and their compatibility with the overall Energiewende goals is analysed by using the REMod-D model (see above), which integrates the entire energy system. All scenarios are based on an overall CO_2 reduction of the entire energy system of 83 % compared to the Kyoto reference year 1990. Three groups of scenarios were analysed, namely:

a) Fixed target states with fixed final energy savings as well as a fixed distribution of technologies (reflecting the parametrisation of the three target states developed within the above described bottom-up approach),

b) Target states with a fixed degree of final energy savings, but – differing from the fixed technology mix of the above described target states – a freely heating technology distribution in buildings,

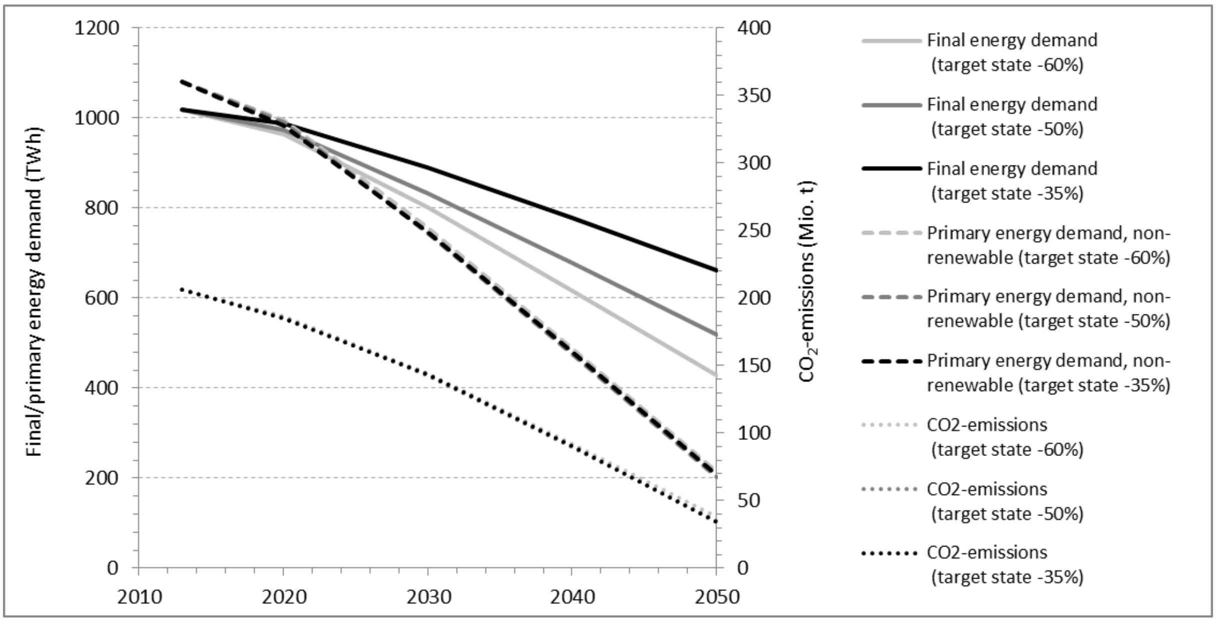


Figure 4. Key energetic parameters of the transformation pathways for the entire building sector. Source: Calculations by Öko-Institut.

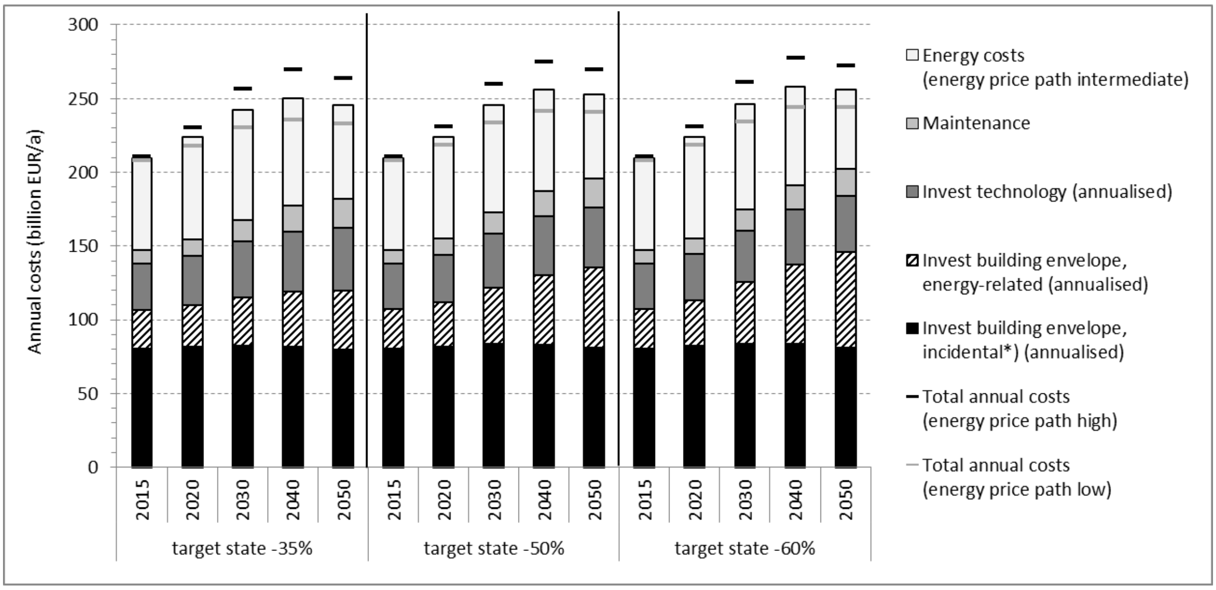


*Figure 5. Annual costs of the transformation pathways for the entire building sector. Source: Calculations by Öko-Institut. *) Incidential costs are costs that would occur anyway irrespective of whether a renovation is combined with any form of energetic modernization.*

c) An entirely free optimisation, in which the reduction of the final energy consumption as well as the technology distribution in the building sector is determined by the model.

The entirely free optimisation under c) leads to a reduction in final energy demand by only around 20 % (as opposed to reductions of 60 %, 50 % and 35 % for the fixed target states). This is a consequence of the higher costs associated with target states that show more ambitious renovation activities. In addition to this the scenarios that allow for an optimisation of the technology mix arrive at different technology distributions compared with the fixed target states under a) (see Figure 6).

In the free optimisation scenario heat pumps clearly dominate the technology distribution, followed by district heating. This shift is a result of the greater capability of these technologies to interact with the electricity system. Decentralized gas boilers, CHP units or wood boilers are hardly present in the free optimisation scenario. Their fuels are mostly used in the other sectors, in particular in industry and transport. If those fuels were not available for these sectors, they had to be replaced by synthesized fuels, for which an additional energy conversion is necessary. The extra conversion, however, leads to higher energy losses, and, overall, to a higher demand in electricity in the energy system as a whole. From a system's per-

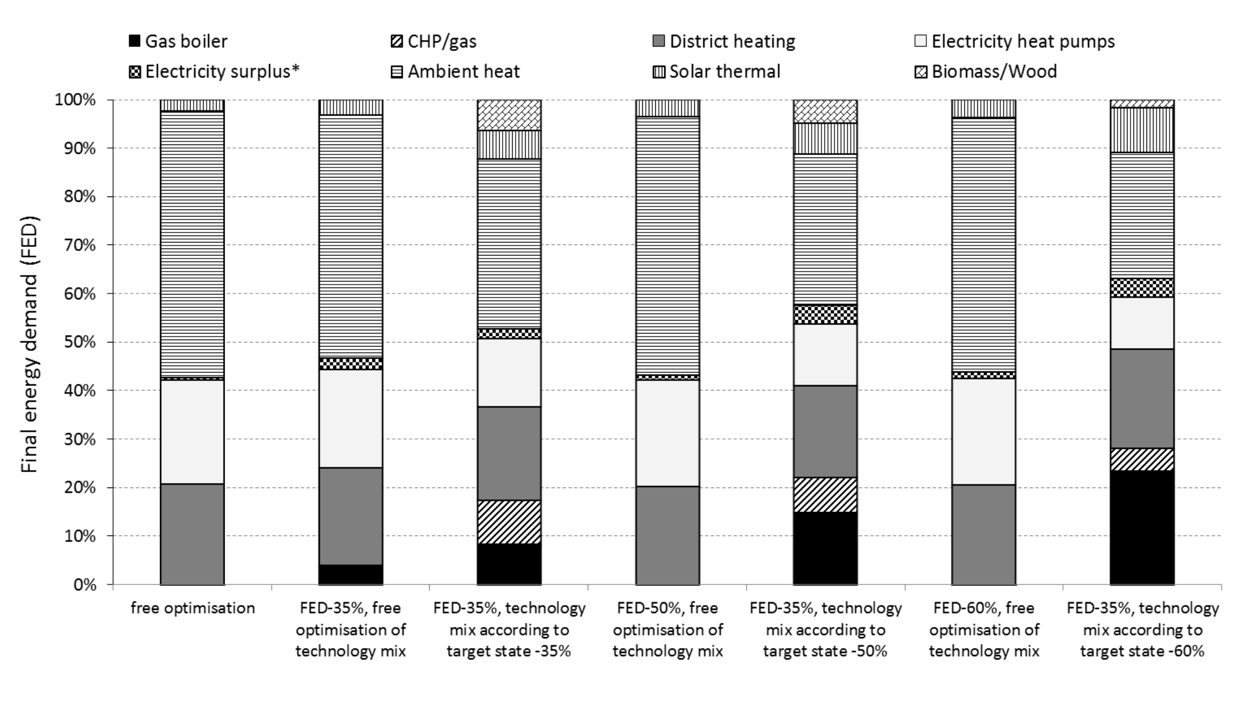


*Figure 6. Distribution of final energy consumption sources for heating in 2050 for different scenarios. Source: Calculations by Fraunhofer ISE. * Electricity surplus represents renewable electricity (RES-E) that is available in periods in which RES-E generation is exceeding the overall electricity demand and is used in direct electric heating elements.*

spective, it is therefore cheaper to use these fuels in the industry and mobility sector, and to generate low-temperature heat in buildings via heat pumps.

Different technology distributions also reflect different "decision perspectives". The technology distribution in the target states in which the reduction of the final energy demand as well as the technology mix is fixed (bottom up approach) better reflects the considerations of landlords and building contractors. Here, criteria such as energy generation autarky play a bigger role than a possible optimisation of the energy system as a whole.

Conclusions and recommendations

The analysis presented in this paper has been carried out before COP 21 in Paris. The Paris agreements call for a reduction of the global carbon output as to keep global warming to well below 2 degrees C. This implies that reducing CO_2 by about 80 % will not be sufficient, but that Germany should rather strive for a reduction goal of 95 %. Under such conditions and given the reduction challenges other sectors are confronted with (e.g. transport, industrial process-related emissions, agriculture), the building sector would need to be more or less completely climate-neutral by the middle of the century. This would imply even more mitigation efforts than described in our analysis.

The paper describes different visions for the building sector in the year 2050. The visions frame a corridor of how a nearly decarbonised building sector could look in future. The visions mainly differ in the level of effort to reduce the final energy demand and the level of decarbonisation concerning the energy supply. Since our analysis does not lead to a clearly preferable result of one of the three target states from a cost perspective, other criteria become more relevant when deciding which target state should be pursued. Amongst others, these are:

- The acceptance by society regarding the various measures on which the target states are founded. For target state -35 % this mainly concerns the societal acceptance for the roll-out of new renewable energy plants (mostly wind and solar PV) including the infrastructure that is required to integrate them in the energy system (e.g. expansion of the electricity grid). For target state -60 % it concerns the acceptance regarding the very profound renovation activities mostly relating to the thermal insulation of buildings.
- The challenges that arise from the increased roll-out of heat pumps regarding the interaction with the electricity system: heat pumps as a heating technology mostly use electricity at times of high electricity demand in other sectors as well as when photovoltaics generate comparatively little electricity. An additional aspect is noise emissions connected with the increased roll-out of air-source heat pumps.

In addition to these criteria further arguments suggest striving for that edge of the corridor that is characterised by high efficiency efforts (target state -50 % or -60 %). Each kilowatt hour of final energy that can be saved by any form of efficiency measure lessens the pressure on expanding renewable capacities. Moreover, a target state in which lowered efficiency efforts are compensated for by an increased use of renewables is bearing the risk of losing efficiency potentials. This is due to the rather long investment cycles that apply for most insulation measures (mainly relevant for the outer wall, roof and ceiling). The risk would become relevant if during the transformation process it turned out that the required renewable potentials were not available. In such a case the "missing" mitigation contribution would have to be delivered by efficiency measures many of which would have to be carried out beyond the typical reinvestment cycle.

Based on our analysis it can be identified in which areas the policy impact needs to be strengthened in order to achieve the long-term targets. For the transformation of the building sector towards climate neutrality the key levers are the depth and rate of building renovation as well as the decarbonisation of the supply technology. To become a success story all three levers would have to be addressed by political intervention. Important measures include[6]:

- Strengthening the efforts to significantly increase the refurbishment rate over the coming decade. At the same time, it must be ensured by appropriate measures that the refurbishment market is capable to deliver the growing refurbishment volume at high quality.
- Strengthening incentives or regulatory requirements that buildings are refurbished towards energy standards that comply with the long-term goals. A nearly zero-energy like standard should become the lead standard for renovations in the mid-term.
- Strengthening incentives or regulatory requirements for gradually shifting all conventional, fossil fuelled heating systems to renewables. At the same time implementing appropriate measures that aim at shifting heat distribution systems towards lower temperatures (that are more favourable for heat from solar thermal or heat pumps).
- Strengthening R&D efforts aiming at developing high-performance insulation material and insulation concepts (e.g. pre-fabrication of insulated façade elements) at low cost; in addition, R&D efforts for heat storage (thermal and thermochemical storage), efficiency of heating systems (e.g. of air/water heat pumps) and to lower the system costs of solar thermal collectors.
- Development of an allocation strategy for biomass which provides guidance in which sector (electricity, heat, transport etc.) which biomass fraction should be used in the future and how much biomass will be available for low-temperature heat demand in the building sector.
- Improving the knowledge about ongoing renovation activities (renovation rate, depth etc.) by developing and implementing a monitoring scheme on the basis of empirical data.

6. For a more detailed description of required policy elements for the transformation of the building sector see e.g. Hesse et al. (2016), Bürger/Klinski (2013) and Bürger (2013).

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