Pathways towards achieving a climate-neutral building stock in Germany

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Abstract

The German Climate Change Act (KSG) defines a sector specific reduction target for the building sector for 2030 of 67 million tonnes CO_2eq achieving climate neutrality by 2045. In a scenario analysis this paper examines the extent to which greenhouse gas emissions (GHG emissions) in the building sector in Germany can be reduced by 2045 through current and additional policy instruments. Therefore, a trend scenario is modelled to quantify the target gap by 2030 and 2045. Second, a cost-optimal transformation path for complete reduction of GHG emissions until 2050 from a sector-coupled perspective is modelled (target scenario). For the trend scenario the bottom-up simulation model Invert/ee-Lab is used to map the exploratory development of the building stock based on the current political framework and individual decisions of building owners. The target scenario is modelled with an optimisation approach using the energy system model REMod, which represents the whole energy system and determines a target system considering CO_2 reduction targets and the remaining CO_2 budget. Coupling both energy models enables a comparison between the simulation of actors' decisions and the resulting diffusion of heat supply systems and building renovation with the target system, in order to identify possible field of actions to reduce GHG emissions. In the third part, additional policy instruments are suggested for closing the gap between trend- and target scenario with the impact being modelled in a policy scenario. In the trend scenario a gap of 21 million tonnes of CO_2eq results in 2030 compared to the target defined in the KSG. In 2045, 31 million tonnes of CO_2eq remain, which is 91 % less than in 1990. The target scenario outlines a pathway to achieve decarbonisation of the building stock by 2045, already reducing GHG emissions to 52 million tonnes CO_2eq until 2030. The ambitious target requires a consistent change to renewable heat supply and heat grids as well as an increase in renovation rates.

Introduction

The vision for a climate-neutral future covers almost all sectors and is in line with the goals of the Paris Agreement. Climate neutrality is associated with a reduction in greenhouse gas emissions (GHG emissions) of 95 % compared to 1990 across all sectors (European Commission, 2019). The German Climate Change Act (KSG) defines a sector specific reduction target for the building sector for 2030 of 67 million tonnes CO_2eq achieving climate neutrality or zero emissions by 2045 (Bundesregierung, 2021). Against this background, this paper investigates the GHG emission savings in the German building sector that can be achieved with the current policy framework by 2030 and 2045 and derives a cost-optimal transformation pathway for a complete reduction of GHG emissions from an overall system perspective. Furthermore, this paper examines the extent to which GHG emissions in the building sector can be reduced by 2030 and 2045 through current and additional policy instruments.

Methodology

For the purpose of this paper, a trend scenario and a target scenario are derived applying the energy system models Invert/ee-Lab (Steinbach 2015, Müller 2015) and REMod (Henning and Palzer 2014). The combination of both models allows to map not only the building sector and the associated investment decision processes in detail, but also the necessary developments in the other energy consumption and supply sectors to achieve complete decarbonisation. In the final part of the paper, a policy scenario examines the impact of several policy measures on GHG emissions in a sector specific approach from a micro-economic perspective with the model Invert/ee-Lab. The policy scenario addresses the key elements identified in the scenario comparison relevant for achieving the sector targets. The focus of the policy scenario is on achieving the target in 2030, as this year marks an important milestone on the path to climate neutrality.

The trend scenario models the exploratory development of the building sector on the basis of the current regulatory and policy support framework and the individual investment decisions of building owners influenced by them. For this purpose, the agent-based bottom-up simulation model Invert/ee-Lab is used. The basis of the model is a detailed representation of the building stock according to building types, construction period and states of renovation with relevant building physics and economic parameters, including the technologies for providing space heating, hot water, and air conditioning. Based on this, the heating and cooling energy demand is determined, considering user behaviour and climate data. The investment decision in technologies and efficiency measures is determined in the INVERT Agents module, considering investor-specific decision-making calculations and obstacles as well as energy source potentials. With Invert/ee-Lab it is possible to analyse the impact of different policy instruments like national promotion schemes and regulatory measures and design variants on the expansion of renewable energies in the building sector in scenarios (Steinbach, 2015).

The target scenario is calculated with the energy system model REMod, which represents the entire energy system. The model determines a cost-optimal system composition in compliance with hourly supply security under the specification of a CO_2 budget and CO_2 targets for specific years, considering the building sector, industry, transport, and the energy industry. The model input variable in REMod is the target of the annual CO_2 budget across all sectors, according to the Climate Change Act. As a result, this can lead to the sector-specific target of the building sector (according to the definition of the KSG) not being met because more CO_2 is saved in another sector.

The energy system model uses metaheuristic optimisation to determine the systemic cost minimum on the basis of a CO_2 target (in the years 2030–65 % compared to 1990 and in 2050 -100 %) as well as a CO_2 budget of 7.45 Gt CO_2 for the time span 2020 until 2050). The strength of the model lies in the simultaneous representation of the building, energy, transport, and industry sectors, as well as the property of optimising a future energy system on the transformation path - every year until 2050, whereby the energy balance is maintained on an hourly basis. The minimum-cost system composition is optimised under the constraints of supply security and climate protection (represented by the CO_2 reduction target). Modelling sector coupling options is of particular importance in REMod. Thus, electricity demand of heating technologies, technologies for the provision of process heat or the battery-electric vehicles are not included as predefined time-series but are also subject to optimisation. Thus, the resulting demand profile is determined by the model. In this way, many relevant technologies that can be coupled are interlinked in the model and interactions between the sectors influence the result of the optimisation. With regard to the development of energy demand in buildings, the depth of renovation and the renovation rate are determined on the basis of the model, as well as the expansion of heat supply systems. The replacement or renewal of technologies is based on the technical service life. Due to the properties of the system model, the technologies are selected in such a way that the cost-optimal system solution results (Henning & Palzer, 2014).

The primary input parameter of REMod is a given cross-sectoral CO_2 budget for energy, industry, transport and building sectors with the aim of finding the cost-optimal pathway. In the study, an overall reduction of 65 % of CO_2 emissions by 2030 was specified. Due to the fact, that the agricultural sector is excluded from the calculations of REMod, the underlying CO_2 budget deviates from the current applicable Climate Change Act[1].

Due to the model descriptions, it can be seen that Invert/ee-Lab represents the building stock in great detail and follows a simulation approach modelling the technology choice based on individual investment decision making of building owners. REMod considers the building sector more aggregated and optimises the technology choice from an overall system perspective. In order to derive disaggregated results not only for the trend scenario but also for the target scenario, the REMod scenario results are disaggregated using Invert/EE-Lab (see Figure 1). For this purpose, the Invert/ee-Lab model is applied without the agent-based simulation but with a newly incorporated accounting module, whereby the resulting market shares and renovation rates are not simulated endogenously but defined exogenously as model input based on the results of the REMod. Therewith, a direct link between the system model REMod and the building sector model Invert/ee-Lab has been established.

In the context of this study, coupling these two energy models serves the following objectives: the approach enables a comparison between the explorative simulation of actors' decisions (micro-perspective) of building owners and the resulting technology diffusion of heat supply systems and building renovation with the cost-optimal target system from a macro-perspective. This approach allows to identify and analyse possible action gaps to achieve the CO_2 reduction targets under the set political framework.

The scenario analyses are subject to various framework parameters. These include forecasts of population development,

1. With regard to the target scenario, it should be noted, that the study was originally based on the 2019 sector target of 70 million in 2030 and achievement of carbon neutrality in 2050 (BMWK, 2019). With the amendment of the Climate Change Act in 2021, the Federal Government has tightened the climate protection targets and anchored the goal of greenhouse gas neutrality by 2045 (Bundesregierung, 2021). GHG emissions of all sectors are to be reduced by 65 percent by 2030 compared to 1990.

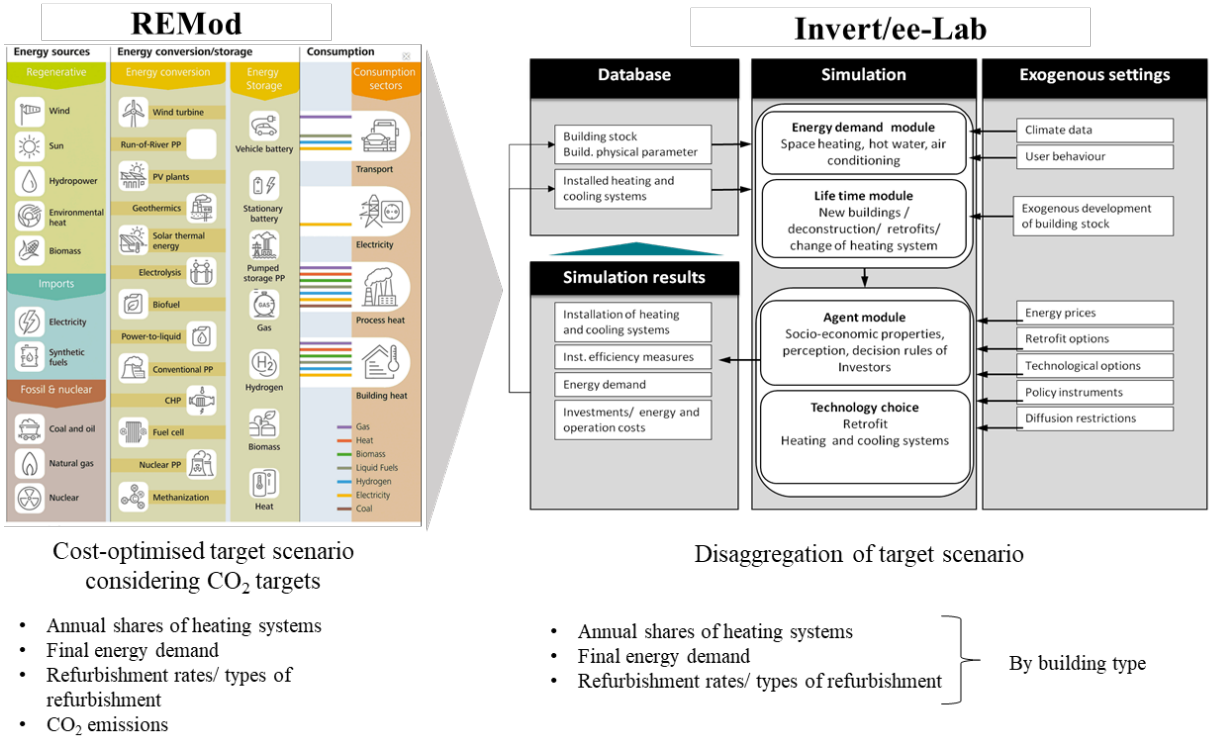


Figure 1. Coupling of REMod and Invert/ee-Lab for disaggregation of target scenario results.

residential space development, energy price development and development of the CO_2 price as well as temperature changes due to climate change. In detail, the data is described in Steinbach et al., 2021 and Repenning et al., 2021. Among others, the development of the CO_2 price is an important input factor. Starting from €25 in 2021, the CO_2 prices increases to €125 in 2030 and €275 in 2040 (nominal prices).

Determination of the target gap in the building sector

FINDINGS OF THE TREND SCENARIO

In the trend scenario, GHG emissions of the building sector of around 88 million tonnes of CO_2eq result in 2030 (see Figure 2). The results show that for achieving the sector target according to the Climate Change Act in 2030 there is a target gap of around **21 million tonnes of CO_2eq**. The current measures are therefore far from sufficient to achieve the 2030 targets. With the current policy measures, the target of 2030 is achieved in 2035.

In 2045, GHG emissions of 31 million tonnes of CO_2eq remain, which means that also in the long-term, the current policy measures are not sufficient to achieve the Climate Change Act nor carbon neutrality of the building sector. Nevertheless, very high savings can already be realised with the existing policy measures. In 2050, GHG emissions will only amount to 19 million tonnes of CO_2eq, which already corresponds to a reduction of around 91 % compared to 1990.

As the figure shows, fossil heat supply remains the central technology in the trend scenario until 2030. From then on, there will be a fuel switch from natural gas and heating oil to biomass, solar thermal energy, and heat pumps.

The reason for the increasing decline after 2030 is in particular due to the increase in energy prices with rising CO_2 price. With regard to the installation of renewable energies, heat pumps play a decisive role. While today the heating market is dominated by gas- and fuel oil-fired heat supply systems with a market share of more than 80 % (in 2020) (BDH, 2021), the market share of these technologies also decreases in the trend scenario until 2050. At the same time, a total of about 7 million additional heat pumps will be installed and 6 million connections to heat grids will be made until 2050. The refurbishment activity in the trend scenario is determined by the natural replacement and maintenance cycles, the existing funding instruments and the energy and CO_2 price development. By 2030, the renovation rate increases to 1.5 %, after 2030 the refurbishment activity increases and a renovation rate of 2.5 % is reached. With regard to the energy performance standards of renovation measures, the model differentiates different renovation packages from standard renovation in accordance with the requirements of the German Building Energy Act (BMWi, 2019; Buildings Energy Act, 2020), to moderate ambitious renovation and ambitious renovation[2]. In the trend scenario, mostly standard renovations are carried out. However, the share of ambitious renovation measures increases significantly in the period after 2030 due to higher energy and CO_2 prices.

2. Moderate ambitious and ambitious renovation package represent different energy performance standards defined with the Efficiency House standards subsidies by the Federal Development Bank (KfW).

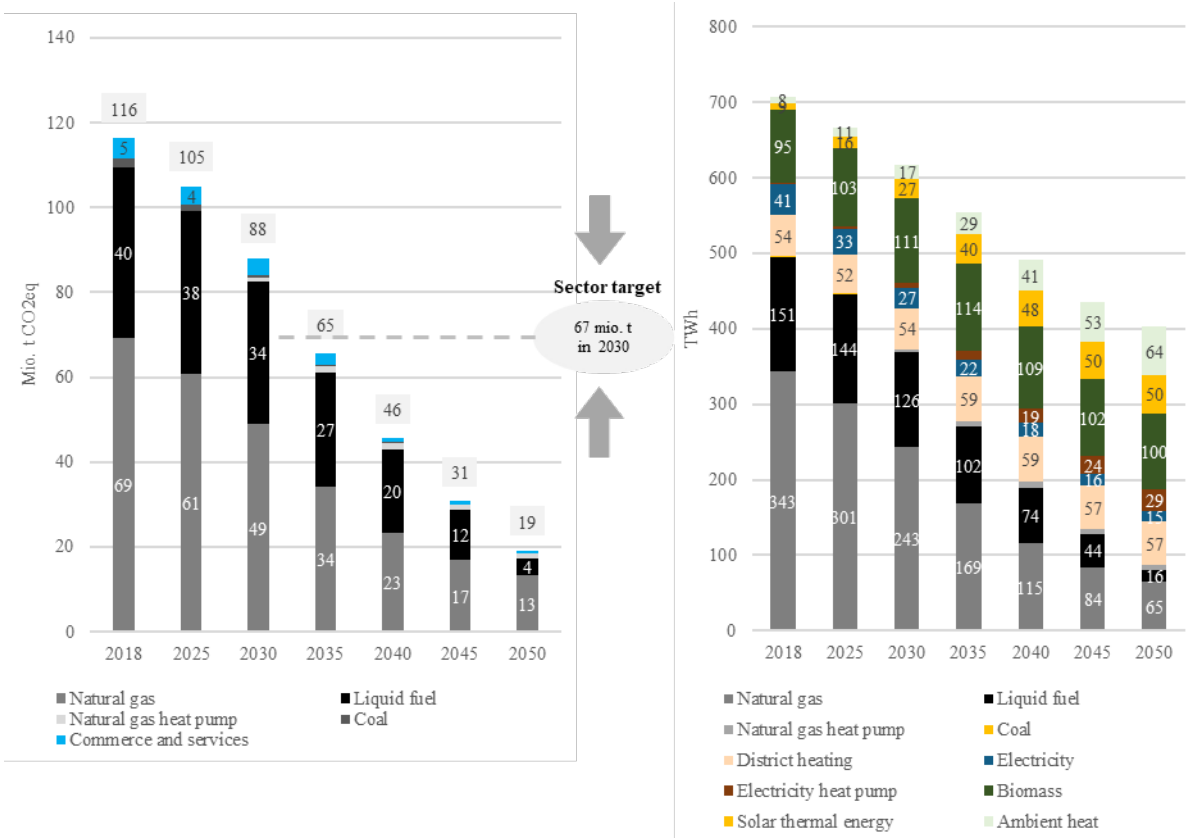


Figure 2. Resulting GHG emissions and final energy demand in the trend scenario from 2018 to 2050. In this context, the GHG emissions include not only the thermal conditioning of buildings in the household and tertiary sectors, but also further emissions from the combus.

FINDINGS OF THE TARGET SCENARIO

In contrast to the trend scenario, the target scenario outlines a cost-optimal path to achieve complete decarbonisation of the building stock by 2045. Despite the input parameters based on the Climate Change Act of 2019, Figure 3 shows that in 2030, GHG emissions of the building sector already amount to only **52 million tonnes CO_2eq**, which exceeds the revised sector target by **16 million tonnes CO_2eq**. Furthermore, due to the overall systemic view, a nearly climate-neutral building stock can be achieved in 2045 in the target scenario. The optimisation model always reduces GHG emissions at the point where it is most economical. The emissions can therefore deviate from the targets of the German Climate Change Act, as the REMod model performs a whole-system optimisation and sets cross-sectoral targets rather than sector-specific targets.

As also shown in Figure 3, in the target scenario there is a continuous switch to RES heat supply. Natural gas as today's dominant energy sources for heating will be replaced mainly by electricity and ambient heat used by heat pumps and district heating resulting in a share of nearly 82 % by 2050. The use of hydrogen for space heating and domestic hot water is less important with a share of nearly 15 % by 2050. By 2050, the number of installed heat pumps will increase to 19 million. Only marginal shares of heat are provided via synthetic gases or biogas, as these energy sources are primarily used in other sectors and, against the background of cost-effective optimisation, are not drawn to relevant shares in the building sector. The disaggregation of the results of the target scenario with Invert/ee-Lab demonstrates that the expansion of heat pumps and district heating as drivers of target achievement is taking place across all building types and vintages. Gas heat pumps powered by biogas and synthetic methane and hybrid systems that can be operated with electricity or gas are primarily installed in new buildings. On the other hand, district heating and a smaller share of biomass heat supply systems and fuel cells are primarily installed in (renovated) older buildings.

With regard to the renovation measures, higher renovation rates are required already in the near future in order to achieve the sector target – by 2030, the renovation rate increases to an average of 1.6 %. This changes significantly from 2030 onwards, as the renovation rate levels off again here (2030–2040 to 1.46 %) to comply with the CO_2 target and then remains constant at around 1 % until 2050. In these years, a lower renovation rate in combination with the use of heat pumps and connections to heat grids is sufficient to reduce emissions in the building sector. The average renovation rate across all years is 1.37 %.

MAIN FIELDS OF ACTION RESULTING FROM THE TARGET GAP

From the comparison of trend and target scenario relevant findings can be derived that are relevant for closing the target gap and thus aligning additional policy efforts. When comparing the trend and target scenario it becomes clear, that renewable heating technologies are the backbone for achieving

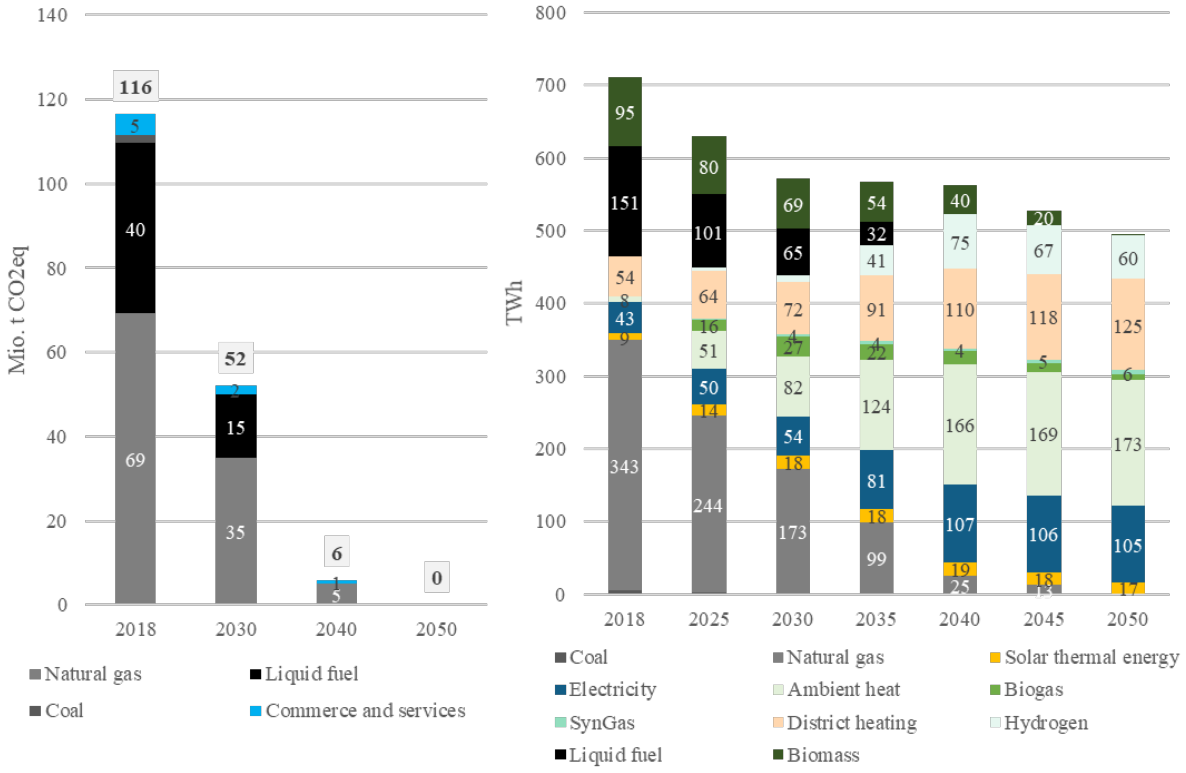


Figure 3. Development of final energy demand of target scenario from 2018 to 2050.

a climate-neutral energy system. The target will be achieved in particular through a consistent change to renewable heat supply and district heating. With regard to the refurbishment activities, in the trend scenario, refurbishment activities have a relatively high impact on reducing the final energy demand and therefore also on the GHG emissions. The renovation rate increases constantly until 2040 which results in lower final energy demand in the trend scenario. Based on the optimisation approach applied in the target scenario, an even more ambitious increase in refurbishment activity is no longer necessary after 2030 since decarbonising the heat supply has been achieved to large extent already until 2030 in order to meet the target. Furthermore, the system perspective of the target scenarios does not consider subsidies for renovation measures and uses wholesale energy prices without taxes, levies, and CO_2 prices. Therefore, very ambitious refurbishment measures without subsidies, taxes and levies on energy prices are "more expensive" in comparison to alternative measures in the system perspective, even if they are economically efficient from a micro-economic perspective in the trend scenario with high energy prices and subsidies. However, there are high uncertainties with regard to the development of energy prices, so that ambitious renovation measures should not only be interpreted as "no-regret" measures, but also as an opportunity to hedge against energy price increases and thus against an overall more expensive system for achieving the climate-neutral building stock. Due to the increasing interaction between the individual energy consuming sectors, an isolated analysis of the sectors has only limited validity. Comparing the modelled target- with the trend scenario, a striking CO_2eq-target gap of 36 million tonnes results. For the limited case of the building sector, the sectoral target should be achieved by 2030. However, it should be noted that any efforts beyond this will benefit the other sectors. As the analysis of the target scenario shows, the measures in the building sector are comparatively more cost-effective, which is why in the model analysis, the sector target is already significantly undercut in 2030.

Policy measures to close the target gap

This part of the paper assesses the impact of possible additional policy instruments with regard to GHG emissions reduction. The policy scenario is modelled with Invert/ee-Lab from the micro-economic perspective of the individual building owners. In order to close the target gap, ambitious policy measures are modelled in the scenario.

Table 1 gives an overview of quantified policy measures for closing the target gap. Most of the suggested policy measures address the fuel-switch from fossil to renewable energies in heat supply systems. In addition, the measures are aimed at increasing the renovation rate and deep renovation measures. It should be taken into account that the measures focus on achieving the sector target in 2030.

In addition to the stated policy measures, the solid biomass available in the model is limited so as not to exceed the sustainably available potential. Furthermore, the underlying CO_2 price exceeds the level of the previous trend scenario. In the policy scenario the CO_2 price increases up to €240 in 2030 and €440 in 2040. With regard to energy prices, a lower electricity price is considered due to the reduction of the levy through the Renewable Energies Act (German, EEG). Figure 4 shows the GHG

Table 1. Policy measures considered in the policy scenario.

Policy measure	Description
Further development of target-compliant minimum energy performance standards in combination with guaranteed subsidies to close gap to cost-optimal levels (delta-subsidy programme)	Up to now, minimum energy performance standards for renovation measures and new buildings are only defined based on cost optimal levels that do not represent the required energy standards for target achievement. Therefore, a clear pathway for tightening energy performance standards until 2030 is proposed in combination with a "delta-subsidy" program that provides a guaranteed subsidy if the minimum performance standard is not economic efficient. The scenario considers the following minimum energy performance standards: From 2023 on Efficiency house 55 for new buildings and Efficiency House 85 for existing buildings. From 2025 on Efficiency House 40 for new buildings and Efficiency House 70 for existing buildings.
Improved funding for ambitious energy-efficient renovations	The existing funding instruments within the framework of the federal funding for efficient buildings (BEG) is increased by 10 percentage points in the scenario from 2022 onwards
Abolishment of subsidies for fossil fuel system	In the scenario no financial support is provided for the installation of hybrid gas boilers or renewable-ready gas boilers as it is in the current subsidy programme of the BEG
Ambitious support programme for the market penetration of heat pumps	Attractive and temporary subsidy programme, for the installation of at least 1 million heat pumps in existing buildings with a subsidy rate of 50 % in the period 2022 up to 2025. Based on the higher subsides, a higher heat system replacement rate is considered
Obligation to use renewable energies in heat supply systems	Obligation to use renewable energies or heat grids from 2025. This excludes the use of both oil and gas boilers.
Increased increase in the CO_2 price and consideration of this in energy advice	The scenario also considers an increased CO_2 price within the National Fuel Emissions Trading System. Furthermore, it is assumed that energy advisors communicate increasing CO_2 price and taking it into account when calculating measure and advising consumers. For this reason, a perfect foresight of the future development of CO_2 prices over a period of 10 years is postulated in modelling in the investment decision making. By increasing the number of energy advisors and suitable support measures, it is assumed that the implementation rate of measures and thus also the renovation rate will increase.
Ban on the new installation of oil boilers from 2023	The ban on installing new monovalent fossil liquid and solid fuel boilers, scheduled for 2026, will be brought forward to 2023 and extended to all monovalent boilers for the combustion of liquid fuels. In addition, the permissibility of installing hybrid applications, i.e., the combination of oil/solid fuel boilers and renewable heat supply systems, will be narrowed down.

emissions and final energy demand of the policy scenario. With the help of the policy measures presented Table 1, the target gap can be closed in 2030.

Through the measures presented, GHG emissions can also be significantly reduced in 2045 compared to the trend scenario. In 2045, 9 million tonnes of GHG emissions remain that still need to be reduced through appropriate measures. Due to the obligation to use renewable energies in heat supply systems, heat pumps will be the prior installed heat supply technology from 2025. However, a significant increase in the number of newly installed heat pumps can already be observed from 2022. In contrast, a significant decrease in fossil heat supply systems can be seen.

Conclusion

This paper shows which developments are necessary to achieve a climate-neutral building stock by 2045. For this purpose, a trend scenario is developed considering the current legal and funding framework as well as a target scenario under the premise of an overall system optimisation of all sectors. Assuming a more stringent climate target, the target scenario reduces energy-related CO_2 emissions by 65 % by 2030 and by almost 100 % by 2045 compared to 1990. From the comparison of the trend and target scenarios, important findings can be derived with regard to the medium-term development and achievement of the sector target by 2030, as well as the measures required for the path to a climate-neutral building stock in 2045. Figure 5

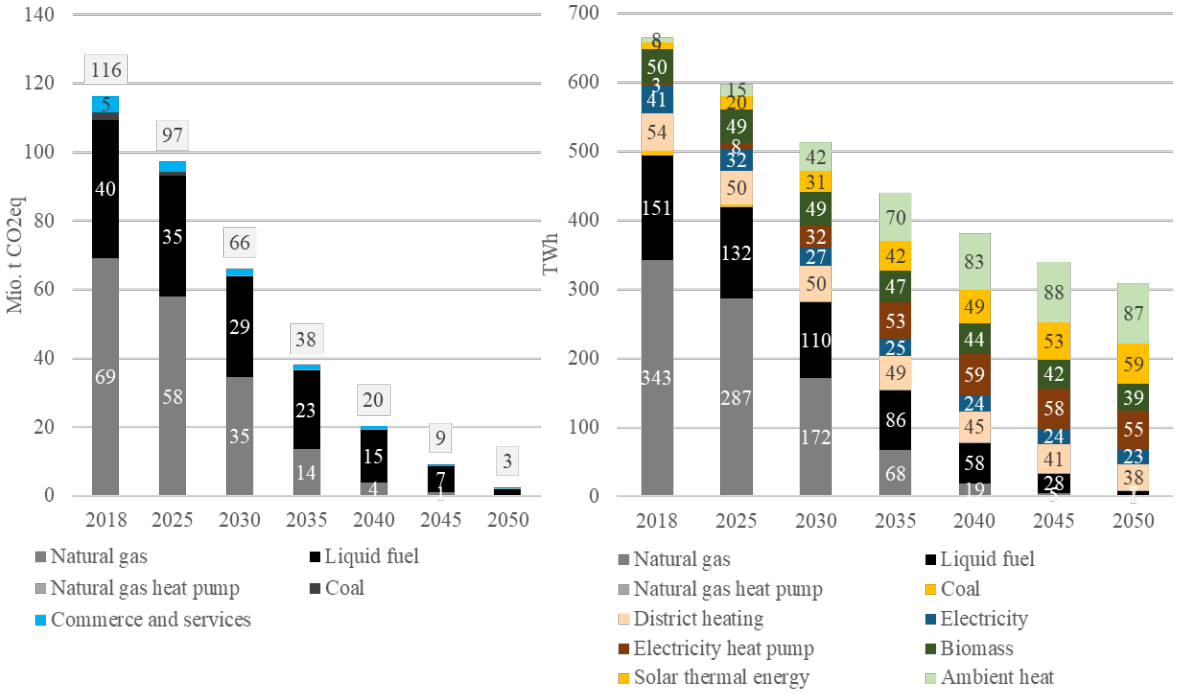


Figure 4. GHG emissions and final energy demand of policy scenario. Results excluding GHG emissions for appliances and processes in households.

compares the main drivers, refurbishment activities, installed heat supply systems and development of GHG emissions of the trend and target scenario.

The trend scenario pursues an explorative approach in order to investigate how the building sector will develop under the current framework conditions. The focus is on the decision-making processes of building owners for investments in building technology and efficiency measures, who are confronted with the respective technical and economic conditions as well as individual attitudes and obstacles. From a purely economic point of view, this approach can be described as a microeconomic analysis.

For the target scenario, on the other hand, a normative approach is pursued. This examines how targets can be achieved in a cost-optimal way from the perspective of the overall system. The approach is not at the level of the building owners, but rather at the macroeconomic level in the sense of a central planner. REMod maps all consumption and energy sectors and pursues an optimisation of the entire system. The approach thus does not claim to simulate reality, but to create a path that shows its systemic optimum for the energy sector while complying with the climate protection goals in all sectors.

As Figure 5 shows, the current measures are far from sufficient to achieve the 2030 targets. With regard to the required transformation from a trend development considering and updating the already existing measures to a cost-optimally determined target path in 2030 and 2045, the most significant difference lies in the faster conversion of the heat supply systems to renewable energies. While in the trend scenario mainly fossil-fuelled boilers will be installed in the period 2020 to 2030, in the target scenario the switch to heat pumps and heat grids in particular will be necessary to achieve the climate protection targets. By 2030, 5 million heat pumps will be installed in the target scenario, more than five times as many as in the trend scenario. The political instruments in the trend scenario thus do not have the necessary effect to initiate a rapid change in the heating market. The assumed development of the CO_2 price of €60/t on average in the period 2021 to 2030 is not yet sufficient. In addition, the current subsidy measures are not consistently aligned to the necessary conversion to renewable energies. Due to the promotion of hybrid heating systems, gas boilers in combination with solar thermal energy continue to be an attractive option from the perspective of building owners in the scenario because of the significantly lower investment costs. In order to achieve the high penetration of heat pumps in the target scenario, this is also made possible by low-threshold measures in the area of temperature reduction in buildings. Due to the increased share of renovated buildings and at the same time higher fossil fuel prices, the trend scenario also shows the change in the heating market for the period after 2030. Heat pumps are not only used in new buildings, but also have a higher market share than gas boilers in existing buildings after 2040. However, the change in the heating market comes too late for the 2030 target to be achieved. Despite the high momentum of renovation measures in the period after 2030, the climate-neutral building stock will not be achieved in 2045 in the trend scenario.

For the period up to 2030, the target scenario shows higher renovation activity, with higher shares for more ambitious renovation measures. In the period 2030 to 2050, the picture changes with regard to the renovation dynamics between trend and target scenario. In particular, due to the high CO_2 price of €195/t on average, the renovation rate increases in the trend

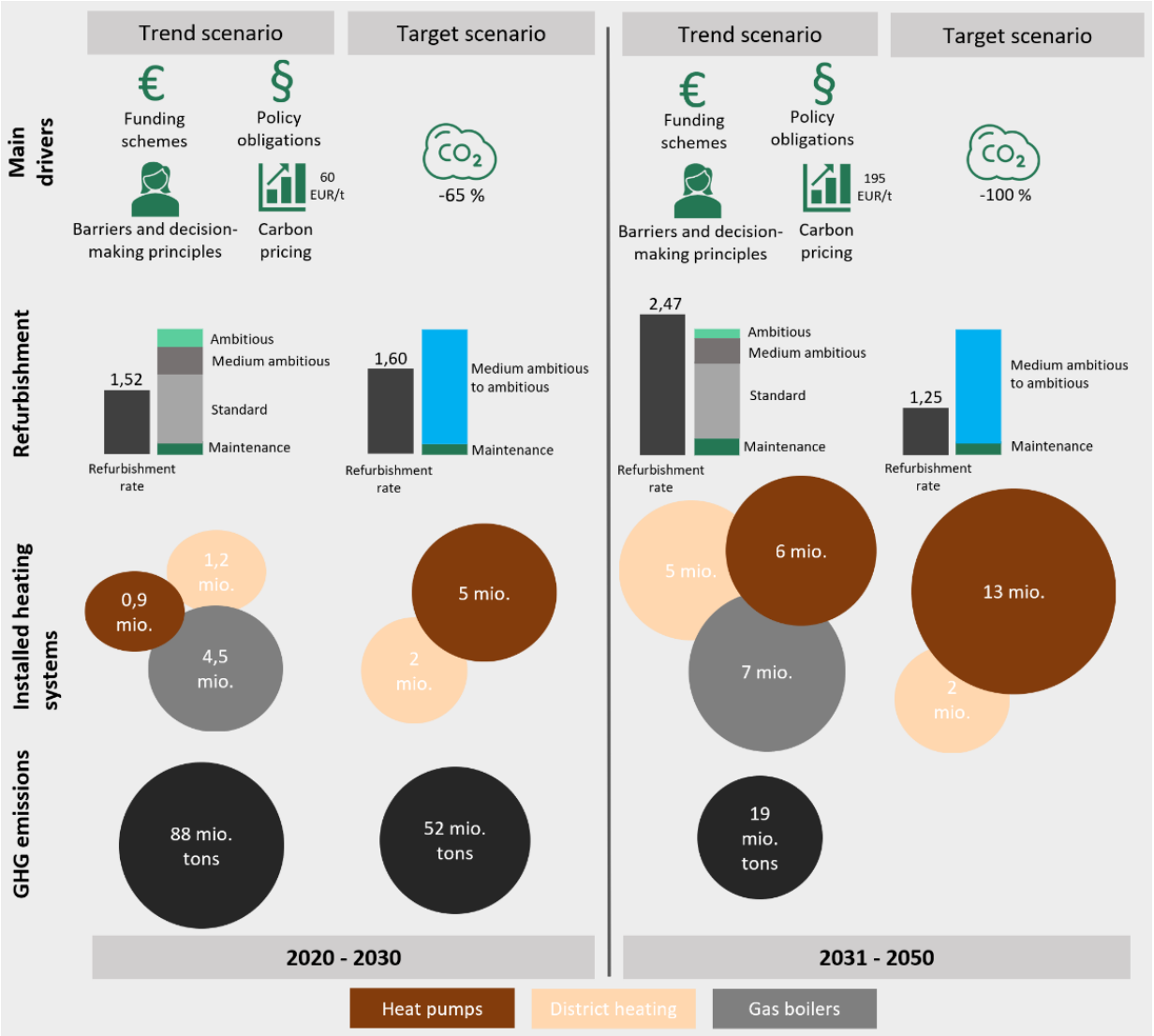


Figure 5. Summary and comparison of trend and target scenario.

scenario and is twice as high for the period as in the target scenario. The depth of retrofitting is also more ambitious in the trend scenario in the period after 2030. In the target scenario, higher renovation rates and depths are no longer necessary, as the decarbonisation of the building sector will already be achieved from 2045 due to the targets and the associated high dynamics in the changeover of the heat supply.

Therefore, it can be concluded that with regard to achieving the targets in 2030, a higher dynamic in the renovation rate and the heating replacement rate is required as a necessary criterion. Therefore, policy instruments are necessary that address the investment decision process at an early stage and not only when an investment appears necessary due to deficiencies in the building or the supply technology. That means, that in order to achieve the climate targets, investments in the building envelope and especially in heat supply systems, some of which will not be made until after 2030 in line with the maintenance cycles in the building sector, should be brought forward.

Despite the given subsidies mostly standard renovations are carried out in the trend scenario. This is due to the fact, that Invert/ee-Lab simulates decisions and takes into account individual decision criteria of building owners based on empirical surveys of decision behaviour.

In order to realise this target path, changes to the legal and funding framework are required to address the different barriers at the level of the individual actors in the building sector. The measures proposed in the policy scenario are aimed at converting the current fossil-based energy supply to renewable energy as well as increasing the refurbishment activity. The policy measures have the potential to reduce greenhouse gases to the extent that the target gap can be lowered in 2030. The decisive factors for achieving the target are the obligation to use renewable energies in heat supply systems, the more ambitious increase of the CO_2 price and the higher energy requirements in new and existing buildings. The assumed CO_2 price in 2030 is already almost at the same level as in the trend scenario in 2040. In addition, the more ambitious energy standards in combination with the increased subsidies for targeted refurbishment are pushing forward the refurbishment activities. In addition, the obligation to use renewable energy in heat supply systems makes the installa-

tion of heat supply systems based on fossil fuels very unattractive. In combination with financial support for renewable energies, the share of heat pumps in the market increases significantly.

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