Germany's path towards a nearly climate-neutral residential building stock: A techno-economic comparison of greenhouse gas mitigation strategies

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Abstract

14% of the total national CO_2 emissions are caused by heating systems in the residential sector. To meet the overall CO_2 reduction target (-40% in 2020, -80% in 2050), the German Federal Government has set a target in its "Energiewende" concept for Germany's building stock to be nearly climate-neutral by 2050 focusing mainly on thermal insulation measures. It is unclear, however, whether this preferred option is the cost-effective strategy.

Different strategies for reducing energy demand and CO_2 emissions from residential building stock up to the year 2050 were investigated. These strategies comprise the Federal Government's energy concept measures, on the one hand, and alternative paths and options using more renewable gases and innovative heating systems, on the other.

The calculations are based on a dynamic simulation model that simulates the residential building stock in detail. The model simulates the effects of various energy-efficiency measures, such as thermal insulation and improvements to heating systems.

The results show that there are alternative strategies which can lead to a climate-neutral building stock. Alternative strategies focusing on an early replacement of heating systems, an increased use of renewable energy, and a forced use of innovative heating systems are cost-effective than strategies which mainly focus on thermal insulation measures. The sensitivity analyses show the robustness of our results.

Keywords

Building stock, thermal insulation, dynamic simulation model, CO_2 reduction, heating system, energy efficiency, renewable energy

1. Introduction

In order to limit global warming to less than 2°C, the EU has committed itself to reducing greenhouse gas emissions by 2020 by 20% compared to 1990 levels and as part of the plans for reducing emissions in industrialized countries to cutting them by 2050 by 80–95% compared to 1990 levels [EU-Rat, 2009]. Buildings are responsible for 40% of total energy consumption and 36% of CO_2 emissions in Europe [EU-COM, 2008]. Improving energy efficiency and an increased use of renewables are therefore decisive measures to ensure a decrease in the EU's dependence on energy imports, the use of fossil energy, and CO_2 emissions. Key parts of the European regulatory framework in this context are the Energy Performance of Buildings Directive (EPBD) [EPBD, 2002], and its recast [EPBD, 2010]. The recast EPBD established the obligation that all new buildings should be nearly zero-energy by the end of 2020.

These targets were confirmed in Germany by the German Federal Government's Energy Concept [Bundesregierung, 2010]. The German Federal Government aims to reduce emissions by 2020 by 40% and by 2050 by 80% compared to 1990 levels. The decision in favour of an accelerated nuclear power phase-out means that climate protection and energy efficiency in the buildings sector are becoming increasingly important [BMWi, 2011]. The private building stock is extremely important here, as it currently accounts for approx. 14% (124 million tonnes) of national CO_2 emissions and 23% (space heating and hot water) of final energy consumption in Germany [AGEB, 2013]. For the buildings sector, the aim is to achieve a climate-neutral building stock by 2050 by reducing the primary energy consumption of existing buildings by 80%. A key aspect here involves enhancing the energy efficiency of buildings by implementing additional thermal insulation measures. Such implementation will be promoted by regulatory measures (e.g. Energy Saving Ordinance) and diverse incentive programmes (e.g. KfW programme for energy-efficient construction and refurbishment). The new German Energy Saving Ordinance (EnEV 2014) came into force in 2014. Therefore, the standard for the construction of new buildings is being raised. From 2016, the maximum primary energy demand of a new building will be 25% lower than the level currently required under EnEV 2009. The amended EnEV 2014 provides for the introduction of a climate-neutral standard for new buildings by 2020 based on primary energy consumption rates [EnEV, 2013].

To achieve a climate-neutral standard for new buildings, different regulatory approaches have been adopted in the EU members states [Annunziata et al., 2013]. A comparison of the definition and introduction of this standard in EU member states can be found in [D′Agostino, 2015]. The cost-optimal design of nearly zero-energy buildings is investigated using simulation-based approaches in [Ferrara et al., 2014a, Ferrara et al., 2014b] for a single-family house in France and in [Pikas et al., 2014] for office buildings in Estonia. Starting with new buildings, this climate-neutral building standard will be implemented in Germany using individual renovation road maps that will begin in 2020 and be expanded to cover existing residential and non-residential buildings by 2050.

Many studies [EWI et al., 2014, EWI/gws/Prognos, 2010, Hoier & H., 2013, Kirchner et al., 2009, Matthes et al., 2013] that deal with reducing CO_2 in the buildings sector in Germany focus solely on the efficiency strategy favoured by the Federal Government. In [McKenna et al., 2013], a bottom-up model is used to analyse the importance of improving the energy efficiency of buildings to achieve the ambitious targets in Germany. Only through intensified policy measures that include the renovation of single-family houses will it be possible to meet the Federal Government's targets. A cost analysis is performed only in a few cases here [Pikas et al., 2015].

This paper investigates alternative strategies and scenarios that could help Germany to achieve its goal of climate-neutral residential building stock. The effects of forced thermal insulation versus the increased use of innovative heating systems and renewables are examined. The impacts are analysed using the dynamic bottom-up model JEMS-BTS[1], which details the German residential building stock

[1] JEMS-BTS = Jülich Energy Modeling Suite - Building Stock and Technology Simulation Model for Space Heating and Hot Water Supply

and installed heating systems using a regionalized approach. It also allows an extrapolation by incorporating re-investment cycles. Scenarios are compared based on primary energy consumption and CO_2 emissions. Costs are compared using the actual cash value of each strategy.

The first section describes the modelling approach used. This is followed by a description of the scenarios with the most important assumptions. Finally, the model-based results are compared by outlining and discussing the potential for increasing efficiency and for decreasing CO_2 emissions as well as costs.

2. Methodology

In order to quantify the potential of efficiency to produce space heat and hot water with higher efficiency, building stock models are used in most cases. For the scenario analysis, the model JEMS-BTS has a particularly high importance. It is a physical bottom-up approach to simulating energy consumption in residential buildings [Foucquier et al., 2013, Kavgic et al., 2010, Rysanek & Choudhary, 2013]. Building stock characteristics must be known in order to estimate the impact of energy-efficiency measures on the stock. To efficiently model the energy consumption of building stock, in a methodological approach similar to that in [Mata et al., 2014], a building stock simulation model was developed for Germany [Hansen, 2011, Hansen et al., 2014, Markewitz et al., 2012]. Using the bottom-up modelling approach in [Asadi et al., 2012], the dynamic simulation model JEMS-BTS extrapolates energy consumption based on the type of building, construction year, climate region, and energy carriers used to the regional and national levels and combines statistical calculation methods with technical and physical calculation methods. For the simulations, an extensive, regionalized building stock database was integrated into the model. It models the residential building stock in Germany based on typologized residential building types, sizes, and age classes including heating and hot water systems as well as corresponding energy conditions. Analyses in [Engvall et al., 2014, Gonçalves et al., 2013] show that energy consumption for heating depends significantly on the age of the building, type of building, and ventilation as well as on the age of the installed heating system. JEMS-BTS can be used to aggregate measures for single buildings in chronological sequence on the stock`s level. The modelling approach described in [Asadi et al., 2012, Ma et al., 2012] enables the simulation of all potential combinations of technical measures concerning the thermal insulation of the building envelope and improvements to heating systems. The development of buildings’ energy requirements over time and the projection of technical options are simulated in the form of scenarios.

The potential for energy efficiency improvement is modelled for each building type using a probabilistic approach for the renovation timing (Weibull-distribution). This methodological approach allows the simulated ageing processes to be used to determine the renovation frequency for each building component. By setting a rate of energy efficiency improvement, the potential for saving energy and reducing CO_2 can be determined for each building type and projected onto the building stock. This approach is expanded to include the calculation of cost-related impacts and the determination of strategy costs [Krause et al., 2011, Markewitz et al., 2012].

In determining the potential for energy savings, the impacts of rebound and prebound effects, which cannot be neglected in an assessment of efficiency potential [Bourrelle, 2014, Hens et al., 2010, Madlener & Alcott, 2009, Sunikka-Blank & Galvin, 2012], must also be considered. The reasons listed by the authors are that efficiency improvement may eventually stimulate energy consumption [Achtnicht & Koesler, 2014] (rebound) and the fact that [Galvin & Sunikka-Blank, 2013] non-insulated houses have a lower and insulated houses a higher energy consumption than the theoretical calculations suggested (prebound). In order to take these effects into account, JEMS-BTS uses consumption values for space heating and hot water supply, e.g. those in [Diefenbach et al., 2010, Walberg et al., 2011], to determine the building's initial energy baseline and it exploits the potential for improvement using the rate of energy efficiency improvement similar to [BMVBS, 2013], for example. Based on these findings, the research in this paper analyses the energy consumption for space heating and hot water supply in residential buildings, taking particular account of the dynamic developments of demographic change and socio-economic factors.

2.1 Definition of the scenarios

For the scenario analyses up to 2050, three scenarios were defined (see Table 1). In the "business as usual" (BaU) scenario, the impacts of measures and efficiency standards already in place are extrapolated. This applies to national regulatory instruments such as EnEV 2014 and the Renewable Energies Heat Act (EEWärmeG), as well as the provisions of the EU Energy Performance of Buildings Directive. Additionally in the BaU scenario, in accordance with the EU Buildings Directive, all new buildings must be nearly zero-energy buildings from 2021 onwards. The current renovation rate of the building envelope remains over the last few years at around 1%/a [BMVBS, 2013] until 2020 before gradually increasing moderately to 1.5 %/a in the subsequent period up to 2050. Old heating systems are replaced predominantly with conventional systems. In contrast to the BaU scenario, the "enhanced thermal insulation" (TI) scenario assumes that the measures for the buildings sector as defined in the Federal Government's Energy Concept are implemented in full. The focus here is on pushing building renovation. A renovation road map is introduced to progressively transfer the nearly zero-energy building standard for new buildings to existing buildings. Key elements are the doubling of the rate of energy efficiency improvement to 2%/a from 2020 onwards and a tightening of the EnEV efficiency standards for existing buildings. Furthermore, higher incentives are offered within the CO_2 Building Renovation Programme and energy contracting is expanded to enhance savings potentials in the rental accommodation sector. Old heating systems are replaced at the same rate as in the BaU scenario, namely 4%/a.

In addition to these scenarios, an alternative scenario was also defined. In the "modern heating systems" (MHS) scenario, the BaU scenario is taken one step further by assuming that measures and instruments applicable to buildings are supplemented by expanding the Renewable Energies Heat Act (EEWärmeG) to include existing building stock. This alternative MHS scenario assumes a renovation rate in line with the BaU scenario and also concentrates on the intensified use of modern and innovative heating systems as well as an increased use of renewables. In addition, the use of local and district heat is taken into account mainly by stepping up network densification. In contrast to the BaU and TI scenarios, the MHS scenario assumes a shorter average renewal cycle of 20 years (technical renovation cycle) instead of 25 years (market renovation cycle) for heating systems. Another important feature is that natural gas is more heavily substituted with admixtures of CO_2-free gases, such as biogas and hydrogen produced from wind. We assume that biomethane feed in and hydrogen production will play a more important role in the MHS scenario (Figure 1). To achieve the goal of 80% CO_2 emission reduction an enforced use of renewables in all sectors is necessary. According to the study of VDE [VDE, 2012] 30 TWh surplus electricity are expected until 2050, which can be converted to hydrogen. In 2050 the share of renewable gas (biogas and hydrogen) amounts 26%

2.2 Underlying data

The scenario calculations are based on the initial thermal state of buildings in 2012 and demographic development up to 2050 according to variant V1 of the Federal Statistical Office's 12th coordinated population projection for Germany [Destatis, 2010]. On this basis, the German Sample Survey of Income and Expenditure (EVS) [Destatis, 2008] and household projections in Germany [DESTATIS, 2007] are used to derive the dynamics of household structure and the demand for living space. Accordingly, the demand for living space increases continuously despite a declining population. It is expected that living space as of 2012 totalling 3.62 billion m^2 will increase to a total of 3.87 billion m^2 (inhabited living space with vacancies) by 2050 despite the decline in the residential population to 69.4 million in the same period (see Table 2). This is explained by the increasing number of single-person and two-person households as well as the higher amount of living space per person. This increasing consumption of living space appeared in the past across all age groups [IDW, 2009]. If we include living space in new buildings constructed in the period 2012–2050 amounting to 0.87 billion m², the inhabited living space increases by 7% to 3.67 billion m² in 2050. With respect to the development of the vacancy rate, it is assumed that it will rise slightly by 2050 from the current figure of 5.1% to 6.1%. The calculations also assume a constant annual demolition rate of 0.2% accross the entire period.

In addition to these input parameters, the energy prices assumed in the scenarios are an important factor (see Table 3). Energy prices are assumed to develop in line with the same trend in the scenarios in [EWI/gws/Prognos, 2010], which are also used as the basis for the Federal Government's Energy Concept. Accordingly, a continuous increase is assumed in energy prices. For example, the annual rate of increase for light heating oil for private households is approx. 1.8%. With the exception of the price for gas mixtures, identical energy carrier prices are assumed for all scenarios. As the share of renewable gas varies in the scenarios, the prices of the gas mixtures also differ.

In order to extrapolate the heating system structure up to 2050, replacement rates for heating systems are defined. The replacement rate describes the technology-specific substitution rate for heating systems that must be replaced due to age. The combination of replacement rates and the age structure of relevant inventories is used to calculate the current stock of heating systems.

In the BaU and TI scenarios, it is assumed that most of the oil heating systems are replaced but that at least 20% of these oil systems will remain in 2050. Furthermore, it is assumed that these oil heating systems are increasingly replaced by a mixture of gas systems, biomass boilers, and electric heat pumps. In addition, it is assumed that micro-CHP units will begin to penetrate the market. It is assumed that heating systems run on natural gas are replaced from 2020 onwards by gas heating systems only. The highest replacement rates of 52.5% in 2050 apply to gas-fired condensing boilers with solar technology.

In the alternative MHS scenario, it is assumed that old oil and gas heating systems are replaced by a mix of gas heating systems, electric heat pumps, biomass boilers, and local and district heating systems. It is also assumed that more heat pumps and micro-CHP units are installed as replacements for oil and gas heating systems. The substitution rate for gas heating systems in 2050 is based on the assumption that every third heating system is replaced with a micro-CHP unit.

3. German Residential Building Stock

The residential building stock in 2012 is based by the results of the 2011 census [Zensus, 2013] and is made up of around 39.7 million dwellings, which are distributed across 18.5 million residential buildings. Almost 83% of residential buildings (15.3 million) are single-family and multifamily houses. Residential buildings with more than two dwelling units account for 17% and comprise 21.2 million dwellings [Destatis, 2013]. The total living space in residential buildings is currently 3.62 billion m^2.

Figure 2 shows the existing stock broken down into building types and age classes which are divided into architectural building periods. It can be seen that more than two-thirds of today's stock was built before the first German Thermal Insulation Ordinance (WärmeschutzV) came into force in 1978. The greatest share of existing living space is made up of the building age classes 1958–1968 and 1969–1978 which account for 636 million m^2 and 579 million m^2, respectively. Since the introduction of EnEV in 2002, only 7% of living space had been newly built by 2012.

Table 1. Definition of scenarios.

	BaU	TI	MHS
Policy instruments for building renovations	Updating of existing policy instruments	Implementing of energy concept	Measures (like BaU) and extension to the mandatory use of renewable energy in refurbished buildings
Energy efficiency standards	EnEV 2014 for existing buildings; EPBD 2010 requires all new buildings to be nearly zero-energy by the end of 2020	Tighter requirements for existing buildings (2020 and 2030: + 30%); EPBD 2010	EnEV 2014; EPBD 2010
Refurbishment rate of building envelope	1.0%/a and from 2020 moderate increase to 1.5%/a in 2050	Doubling the current rate up to 2%/a by 2020	1.0%/a and from 2020 moderate increase to 1.5%/a in 2050 (like BaU)
Renewal rate of heating systems	4%/a	4%/a	5%/a, increased use of innovative heating systems

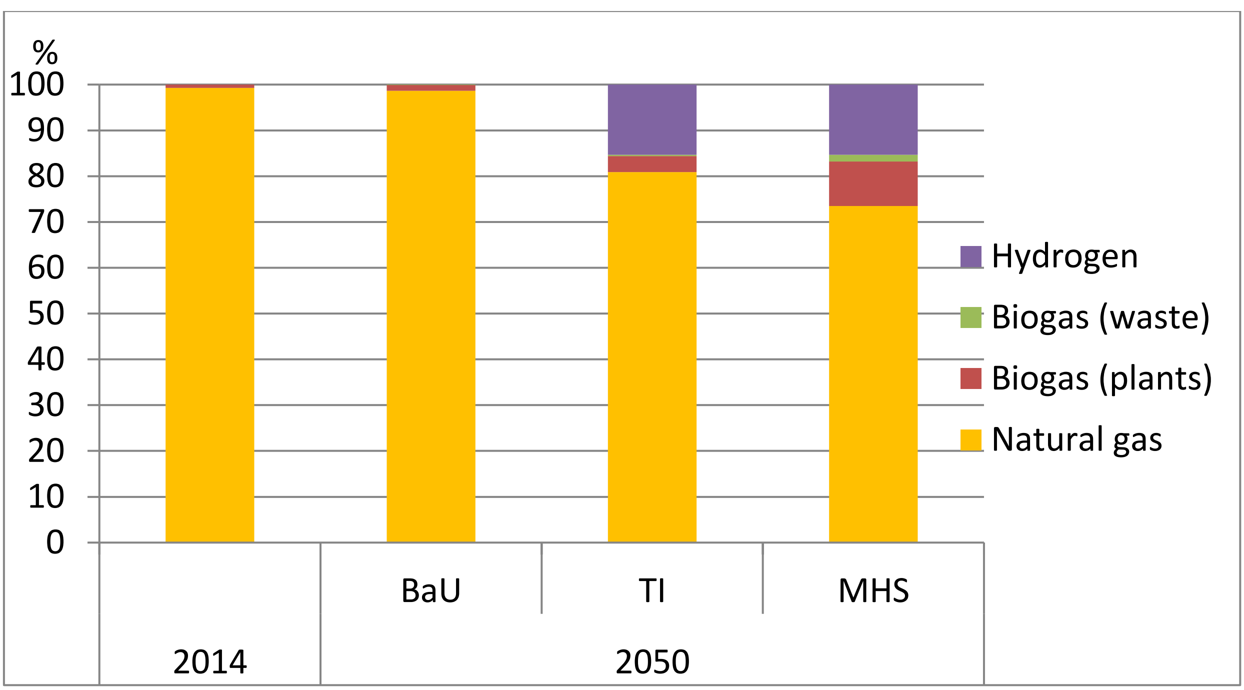

Fig. 1. Gas composition in 2050 in Germany.

Table 2. Input data.

	2012	2020	2030	2040	2050
Population (million)	80.5	79.9	77.4	73.8	69.4
Private households (million)	40.7	40.9	40.6	39.3	37.7
1	16.5	16.8	17.0	17.1	17.1
2	14.0	14.6	14.9	15.0	15.2
3	5.1	4.8	4.4	3.6	2.7
4	3.7	3.5	3.2	2.8	2.2
5 and more	1.3	1.2	1.1	0.8	0.5
Persons per household	1.99	1.95	1.91	1.90	1.84
Living space (billion m^2)	3.62	3.68	3.83	3.88	3.87
New construction (billion m^2)	0.00	0.16	0.40	0.65	0.87
Inhabited living space (billion m^2)	3.43	3.34	3.24	3.01	2.80
Vacancies (%)	5.1	5.2	5.5	5.8	6.1
Living space per person (m^2)	44.7	46.1	49.5	52.6	55.8
Living space per household (m^2)	88.9	90.0	94.3	98.7	102.7

Table 3. End-user prices for private households (including VAT).

	2012	2020	2030	2040	2050	Δ 2012–2050
			ct/kWh			%/a
Gas (BaU)	6.6	7.0	7.6	8.1	8.7	0.7
Gas (TI)	6.6	7.0	7.6	8.3	9.5	1.0
Gas (MHS)	6.6	7.0	7.7	8.6	9.9	1.1
Oil	6.9	8.5	10.1	11.9	13.4	1.8
Briquettes	4.6	4.2	3.9	3.7	3.4	-0.8
District and local heat	7.7	8.4	9.0	9.6	10.2	0.7
Pellets	4.2	4.6	5.2	5.8	6.4	1.1
Electricity	25.1	26.9	28.8	30.8	32.5	0.7
Electric heat pumps	19.4	20.7	22.2	23.7	25.0	0.7

Almost 84% of the final energy demand of private households in 2012 is due to the production of space heating (69%) and hot water (15%). The temperature-adjusted final energy consumption of private households for space heating and hot water in the period from 1990 to 2013 decreased by approx. 14% compared to 1990 levels to 2,097 PJ. The initial thermal state of residential building stock can be characterized according to building age classes and installed heating systems based on the final energy consumption determined from the thermal insulation of residential buildings. In accordance with the analyses of the data basis in [Diefenbach et al., 2010] and the level of modernization in [Walberg et al., 2011], the level of thermal insulation in residential buildings can be determined for 2012 according to building type and age class. Consequently, in 2012, more than 50% of the 18.5 million residential buildings had no or insufficient thermal insulation. A further 30% had at least a partially insulated building envelope and less than 20% of residential buildings were fully insulated. According to the distribution of existing living space, the age classes 1958–1968 and 1969–1978 have the largest quotas of residential buildings which simultaneously have the worst insulation.

In addition to the quality of measures to insulate the building envelope, the installed heating systems are also essential in characterizing final energy consumption for space heating and hot water. According to statistical analyses and surveys, existing residential buildings were equipped with more than 23.2 million heat generators in 2012. At the end of 2012, installed heating systems in private households were dominated by 13.1 million gas heating systems. In 2012, some 4.0 million gas condensing boilers were installed in residential buildings. At the same time, more than two-thirds of existing boilers in 2012 were technically inefficient and allowing for a mean replacement cycle of 25 years they can also be classified as antiquated and in need of renewal [BDH, 2013, DEPV, 2013, Shell & BDH, 2013, ZIV, 2013]. Therefore, replacing heating systems has huge potential for energy efficiency.

4. Results

4.1 Final energy consumption

Final energy demand for space heating and hot water decreases considerably in the three scenarios for the period from 2013 to 2050 (see Fig. 3). The energy demand for heat and hot water supply in residential buildings drops by 35% by 2050 in the BaU scenario compared to the energy demand of 2012. This drop is due to the demolition of older buildings and the construction of new energy-efficient housing as well as the energy-efficient renovation of old housing stock. Overall, the energy demand in the BaU scenario is reduced by 730 PJ by 2050. Accounting for almost 600 PJ, natural gas is the dominant energy carrier.

The calculations for the TI scenario show that doubling the rate of energy efficiency improvement to 2% per annum combined with a tightening of energy efficiency standards compared to the situation in the BaU scenario are the main factors that lead to a saving of more than 560 PJ by 2050. Overall, the heat demand up to 2050 in the TI scenario decreases by a further 27% compared to levels in 2012. The energy demand therefore drops to approx. 800 PJ by 2050.

The largest decrease among the energy carriers by 2050 was ascertained for the use of natural gas, which drops by almost 710 PJ. Heating oil consumption drops by 450 PJ and in 2050 only a residual demand of 16 PJ for heat and hot water supply in private households needs to be covered by heating oil. Power consumption is reduced by almost 115 PJ and the use of district heating by a total of some 80 PJ by 2050. By adding biogas to conventional natural gas, this renewable gas mixture covers around 3% of the final energy demand in 2050 with 22 PJ. The share of renewables excluding renewable gases is successfully increased by more than 400 PJ by 2050.

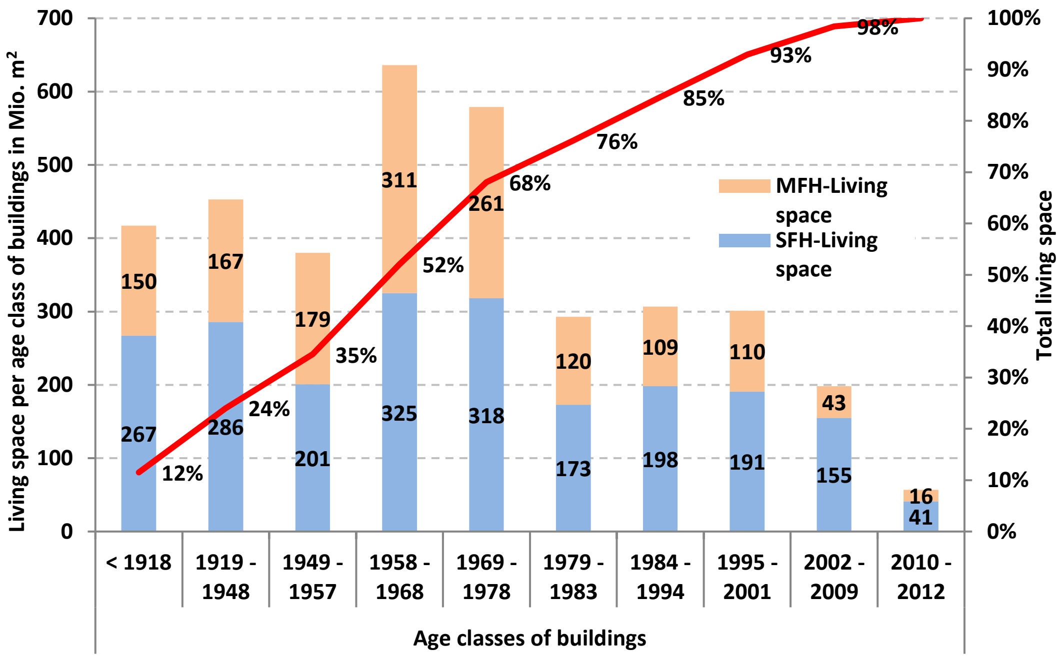

Fig. 2. Residential building stock 2012.

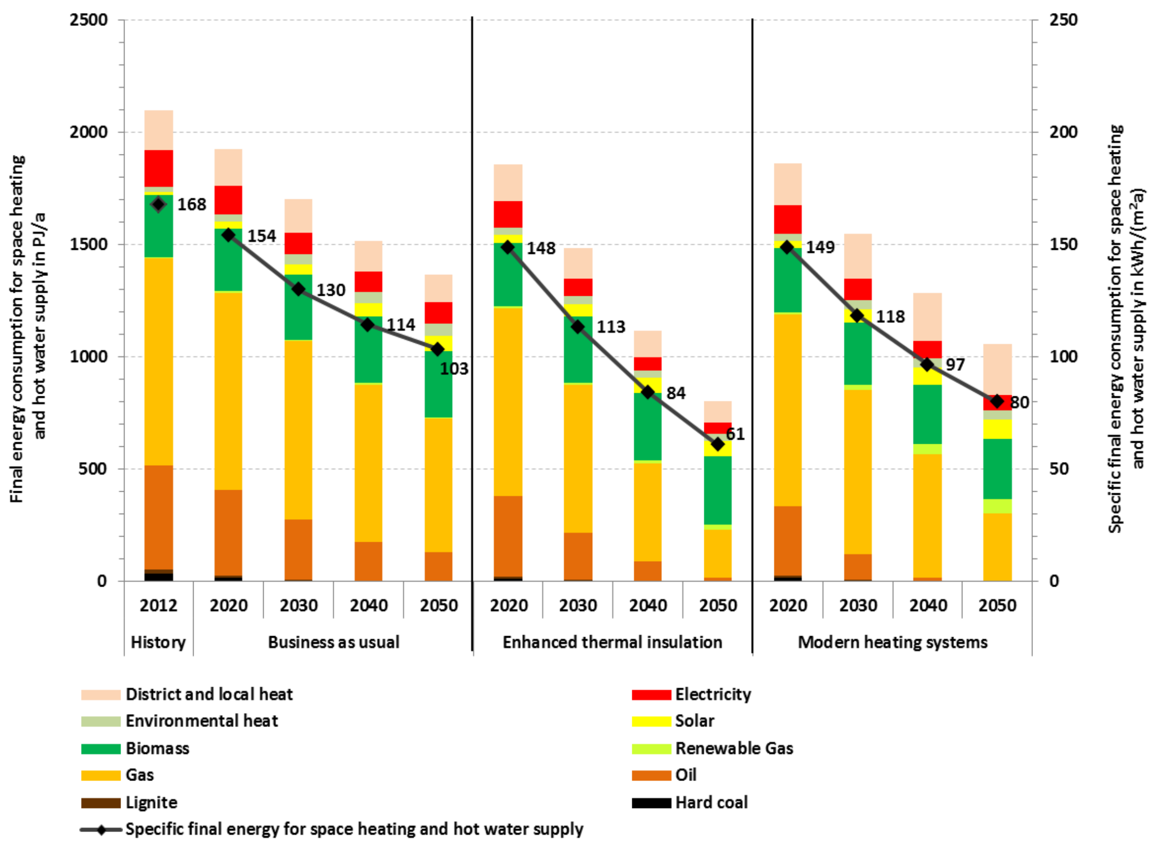

Fig. 3. Final energy consumption for space heating and hot water supply.

Heating oil consumption drops by 450 PJ and in 2050 only a residual demand of 16 PJ for heat and hot water supply in private households needs to be covered by heating oil. Power consumption is reduced by almost 115 PJ and the use of district heating by a total of some 80 PJ by 2050. By adding biogas to conventional natural gas, this renewable gas mixture covers around 3% of the final energy demand in 2050 with 22 PJ. The share of renewables excluding renewable gases is successfully increased by more than 400 PJ by 2050.

The building renovation measures and measures for increasing the efficiency of heating systems in the MHS scenario enable the 2012 final energy demand of households for space heating and hot water to be reduced by almost 50% (1,040 PJ) by 2050. The demand for heat up to 2050 therefore decreases by almost 310 PJ more than in the BaU scenario. However, the savings are lower in the BaU scenario than in the TI scenario. The additional savings in the TI scenario compared to the BaU scenario can be explained by shorter replacement cycles for heating systems and predominantly by the growing use of innovative heating systems such as micro-CHP units. Heating oil is completely replaced by other energy carriers by 2050. The use of conventional natural gas is decreased by 620 PJ by 2050. In contrast, the use of renewable gases is increased to 64 PJ by 2050 through the admixtures of H_2 and biogas. The renewable gas mixture has a share of 6% in the total energy demand in 2050. The power demand decreases by more than 90 PJ in total by 2050 and the energy demand for local and district heat increases by 17 PJ. The share of renewables from biomass, solar energy, and environmental heat increases by 27%.

An indicator for energy savings is the area-specific energy consumption for the production of space heating and hot water. The values shown in Fig. 3 apply to the entire residential building stock. The area-specific consumption decreases for inhabited living space from 168 kWh/(m^2a) in 2012 to 103 kWh/(m^2a) in the BaU scenario by 2050. Due to the measures in the TI and MHS scenarios, an area-specific demand of 61 kWh/(m^2a) and 80 kWh/(m^2a), respectively, emerges.

4.2 *Primary energy consumption and CO_2 emissions*

If the energy demand for space heating and hot water in the TI and MHS scenarios is calculated using the primary energy factors defined in EnEV [EnEV, 2013], then the primary energy consumption (PEC) can be determined. Fig. 4 shows that both scenarios achieve the 80% reduction envisaged in the Energy Concept by 2050 compared to levels in the base year 2008. Primary energy demand, therefore, drops by 80% in the MHS scenario (PEC-MHS) by 2050. In the TI scenario, primary energy demand is reduced by almost 84% in 2050. In addition, the emissions savings verify that CO_2 emissions produced by space heating and hot water supply of 28% in 2012 are decreased by 2050 in both scenarios by more than 80% compared to 1990 levels. The climate target of -80% compared to 1990 levels has therefore been exceeded in the MHS scenario (MHS-CO_2) where emissions are reduced by 88% and in the TI scenario (TI-CO_2) with a reduction of 91%. (Figure 4).

In the BaU scenario, over the course of the scenario up until 2050, emissions are successively reduced. In 2050, the emissions reduction totals a good 120 million tCO_2 and emissions are thus 71% lower than levels in 1990. The measures for increasing efficiency and reducing CO_2 emissions that are already in place today and are extrapolated up to 2050 are responsible for this reduction. Climate protection targets set by the government, however, are not achieved in this scenario.

The measures in the TI scenario and the MHS scenario lead to greater CO_2 reductions than in the BaU scenario with figures of 35 million tCO_2 and 29 million tCO_2, respectively, by 2050. These figures also show that the Energy Concept measures have a greater impact on emissions than the measures in the MHS scenario. The main reason for this is higher building renovation rates compared to the MHS scenario.

Up to 2020, the reduction in emissions in the TI and MHS scenarios is of a similar magnitude to that in the BaU scenario because the measures in the TI scenario only begin to take effect after the rate of energy efficiency improvement is doubled in 2020.

4.3 Costs

The simulation model calculates the total investment costs and annual operating costs for the measures and on this basis assesses the annual costs of the scenarios from an end user's perspective. In order to calculate the net present value (NPV) the annual costs of the scenarios were discounted with an interest rate of 4% . The total costs (NPV) of the TI scenario are higher than those of the BaU scenario and at approx. € 75 billion are also higher than the equivalent figures in the MHS scenario at approx. € 26 billion (see Table 4). The main reason for this are the high investment costs for renovation measures, which due to the higher rate of energy efficiency improvement and the tightened energy efficiency standards are much higher than the investment costs in the MHS scenario. Doubling the rate of energy efficiency improvement, in particular, necessitates the implementation of measures beyond the usual renovation cycles, which in turn explains a considerable proportion of the higher additional investments. However, the energy savings in the TI scenario are considerably higher, which means that expenditure for energy is lower than in the MHS scenario. Overall, the reduced energy costs in the TI scenario cannot compensate the increased investments. The specific CO_2 avoidance costs in the TI scenario are approx. € 158/tCO_2 for cumulative CO_2 savings of 475 million tCO_2. In the MHS scenario, the specific avoidance costs in contrast are approx. € 58/tCO_2 for cumulative CO_2 savings of approximately the same magnitude at 445 million tCO_2.

4.4 Sensitivity analysis

A lot of assumptions are necessary to describe and calculate the scenarios described in the previous chapters. However, there are some key parameters characterising the scenarios. Key parameters are lifetime of heating systems, refurbishment outside the renovation cycle and fuel price assumptions, which might have a significant impact on the results. Taking this into account, we did a sensitivity analysis (Table 5) to get an advice about the robustness of the results.

S1: Impact of renewal rate of heating systems. If in S1 in the TI scenario, the replacement cycle for heating systems is reduced from 25 years on average to 20 years from 2020 onwards while the substitution rate is retained, then the energy costs in the period up to 2050 are € 47 billion lower. New heating systems with improved efficiencies replace old systems faster. However, this increase in the renewal rate from 4% to 5% per annum leads to additional investments of € 67 billion while simultaneously saving an additional 155 million tCO_2 bringing the total emissions saved to 630 million tCO_2. The additional costs in the TI scenario increase in S1 from € 75 billion to € 96 billion and the specific avoidance costs decrease to € 152/tCO_2.

S2: Impact of energy renovations within the technical renovation cycle. In S2, it is assumed for the TI scenario that energy efficiency improvements only occur within the technical renovation cycle. This assumption leads to a decrease in additional investments in thermal insulation of around € 70 billion and simultaneously the cumulative emissions savings drop to 266 million tCO_2. Reduced energy-efficient renovation activities increase the energy costs by € 20 billion by 2050, which causes the strategy costs to decrease by a total of € 50 billion. Overall, in S2 the specific avoidance costs drop to € 94/tCO_2. If sensitivity analyses S1 and S2 are combined, (which comes closer to the MHS scenario) then compared to the TI scenario the increased replacement of heating systems and thermal renovation of homes in the technical renovation cycle lead to emissions savings of 421 million tCO_2 and specific avoidance costs of € 107/tCO_2. In conclusion, S1 and S2 as well as the combination of S1+S2 show that the specific avoidance costs are consistently higher than in the MHS scenario.

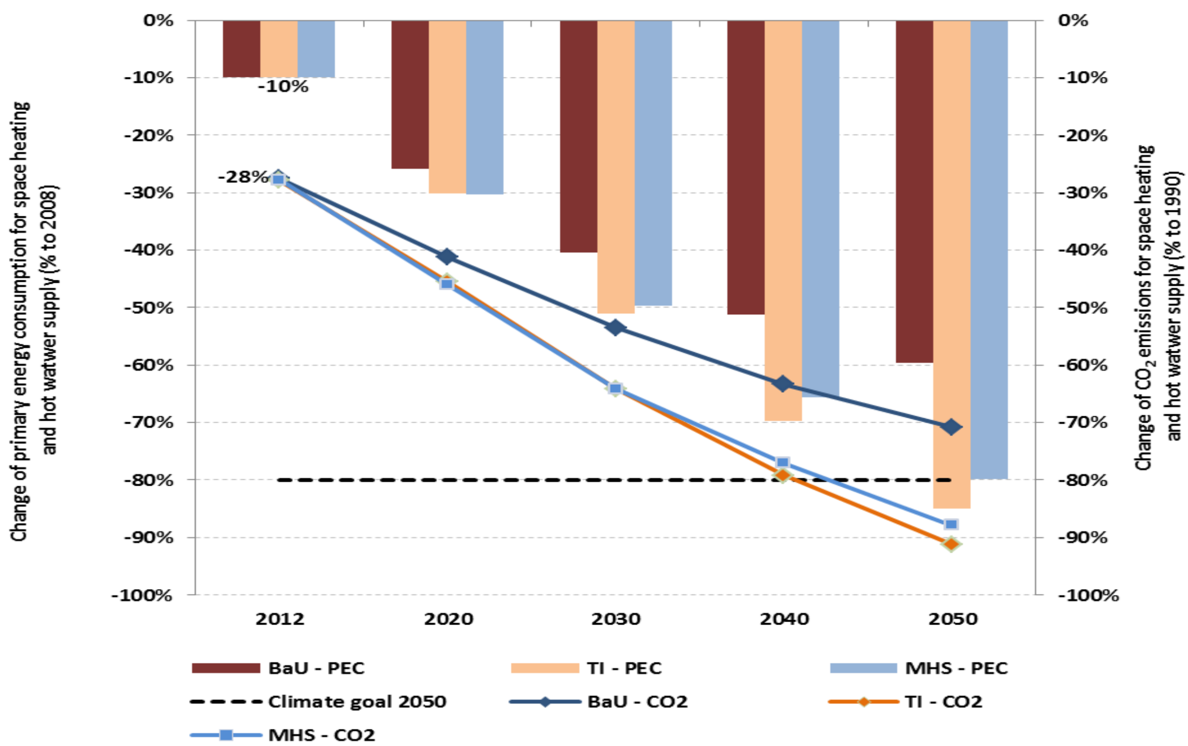

Fig. 4. Primary energy demand and CO_2 emissions.

Table 4. Costs over strategy (present value 2013–2050).

		BaU	TI	Δ to BaU	MHS	Δ to BaU
Investment costs	billion €					
heating systems in existing buildings		443	617	174	515	72
heating systems in new buildings		270	270	0	343	73
		40	39	-1	39	-1
thermal insulation of existing buildings		87	262	175	87	0
thermal insulation of new buildings		46	46	0	46	0
Fuel costs	billion €	802	703	-99	755	-47
Net costs	billion €	1245	1320	75	1270	26
CO_2 emissions	million tCO_2	2364	1889	-475	1919	-445
Specific reduction costs	€/tCO_2			158		58

Table 5. Overview of sensitivity analysis.

	Scenario	Sensitivity
S1	TI	Replacement cycle of heating systems:20 years
S2	TI	Heat insulation measures not outside the technical renovation cycle
S3	TI, MHS	Fuel prices

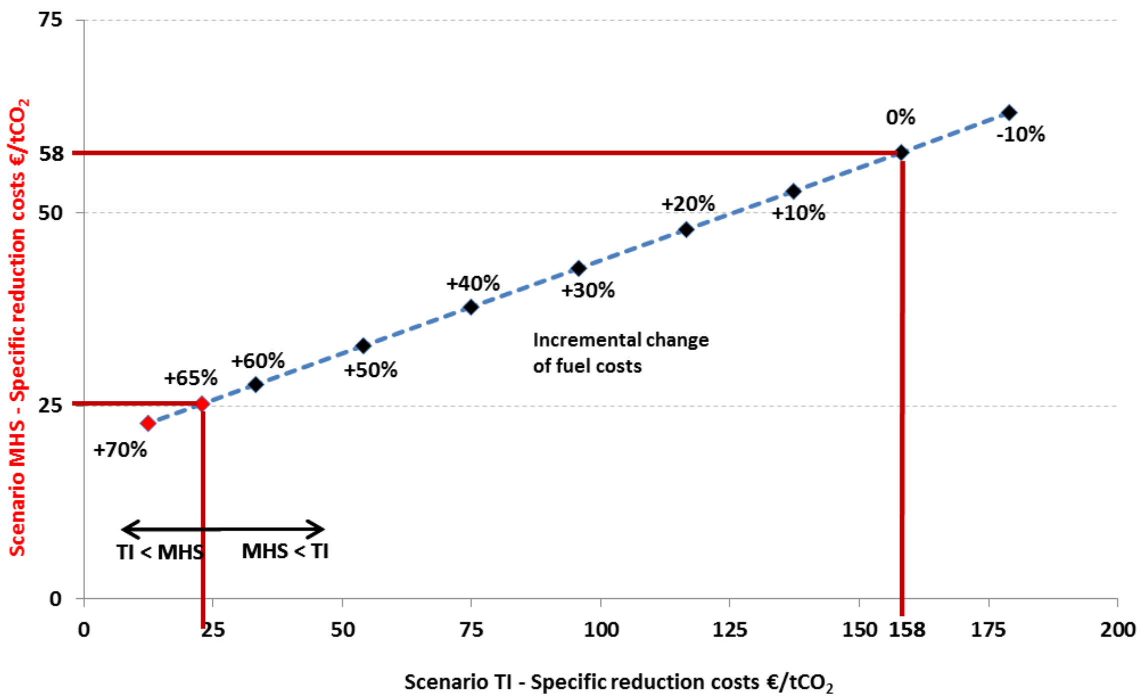

Fig. 5. Incremental change of fuel costs (S3).

S3: Impact of fuel costs. If the end-user prices listed in Table 3 are varied, then also the specific avoidance costs differ. How sensitively the specific avoidance costs react to changes in end-user prices can be seen in Figure 5. If the end-user price of energy carriers is decreased by 10%, then the specific avoidance costs increase in the MHS scenario from € 58/tCO_2 to € 63/tCO_2 and in the TI scenario from € 175/tCO_2 to € 179/tCO_2. Conversely, a 10% increase in energy costs gives rise to a decrease in the specific avoidance costs to € 53/tCO_2 in the MHS scenario and to € 137/tCO_2 in the TI scenario. Only when the end-user price is increased by 65% do the strategy costs in the TI scenario lead to specific avoidance costs of € 23/tCO_2 to € 25/tCO_2, which are lower than in the MHS scenario. For S3, it can therefore be concluded that only if the energy price is increased annually by 3% is the TI scenario more cost-efficient than the MHS scenario.

5. Conclusions

The results clearly show that simply continuing the current measures put in place by the German Federal Government is not enough to achieve a climate-neutral building stock by 2050. Further measures will be necessary, similar to those proposed in the TI and MHS scenarios. The results also show that the currently favoured strategies in the residential building sector, which focus predominantly on energy-efficient measures for the building envelope, are not the only option for achieving climate-neutral residential building stock by 2050 and that interesting alternatives exist which are simultaneously more cost-efficient. Implementing the package of measures in the two scenarios is ambitious. This applies in particular to the demanding renovation road map in the TI scenario but also to the measures in the MHS scenario, which envisage the early replacement of heating systems and a heightened use of innovative heating systems. Both scenarios involve several technical identical measures, but they differ in the capacities of installed heating systems. In all scenarios analysed, improving efficiency through thermal insulation measures represents a central and indispensable field of action. However, the analyses also indicate that by altering the priorities and focusing more on support measures, a climate-neutral building stock can be achieved at much lower costs. Today, incentives in the form of subsidies are already in place to encourage the implementation of existing political measures in the buildings sector (e.g. the KfW programmes). The sensitivity analyses clearly show that the results of the scenarios are robust. Higher energy prices become relevant when they increase by 65% compared to the baseline energy prices.

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