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Heating and cooling energy demand and related emissions of the German residential building stock under climate change

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Abstract

The housing sector is a major consumer of energy. Studies on the future energy demand under climate change which also take into account future changes of the building stock, renovation measures and heating systems are still lacking. We provide the first analysis of the combined effect of these four influencing factors on the future energy demand for room conditioning of residential buildings and resulting greenhouse gas (GHG) emissions in Germany until 2060. We show that the heating energy demand will decrease substantially in the future. This shift will mainly depend on the number of renovated buildings and climate change scenarios and only slightly on demographic changes. The future cooling energy demand will remain low in the future unless the amount of air conditioners strongly increases. As a strong change in the German energy mix is not expected, the future GHG emissions caused by heating will mainly depend on the energy demand for future heating.

Keywords: global warming, degree days, CO_2 equivalent emission factor

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1. Introduction

The provision of energy, which globally still relies predominantly on non-renewable energy sources, leads to an increasing concentration of greenhouse gases (GHG) in the atmosphere and thus contributes to climate change. To develop readjustment and mitigation strategies, estimates regarding future energy consumption and resulting GHG emissions will be essential. In this regard, particular attention should be given to the household sector as a major consumer of energy. In 2007, the residential building sector accounted for 12 % of world energy consumption (EIA, 2010). In Germany households account for 15 % of total energy consumption, of which about three quarters stem from heating (FMET, 2009). In 2009, heating of German residential buildings caused 121 million tons CO_2 emissions (DESTATIS, 2011).

The energy consumption patterns of households can be determined by a combination of climatic, demographic, economic and lifestyle factors. Commonly the effect of temperature is considered (Amato et al., 2005; Cartalis et al., 2001; Eskeland and Mideksa, 2009; Howden and Crimp, 2001), whereas some studies include other meteorological parameters like humidity or specific enthalpy (Gertis and Steimle, 1989; Howden and Crimp, 2001; Sailor, 2001). Yet Scott et al. (1994) found that even a 20 % change in solar insolation, wind speed, or humidity alters overall building energy demand only slightly.

A number of recent studies show that large energy reductions can be achieved by renovation. By means of a building simulation model Scott et al. (1994) show that independent of climate change, an improvement in the building design could substantially reduce heating energy consumption of U.S. commercial buildings. Yet analysing the same sector in the U.S. Belzer et al. (1996) conclude that even with substantial improvements in building energy performance climate change will lead to an increase in cooling energy consumption that is nearly as large as the decrease in heating energy consumption in the same period. In the U.S. energy saved by efficiency programmes more than offsets the increase in energy consumption for room conditioning due

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to climate change and growth in building stock (Scott et al., 2007). Under warmer conditions, residential air conditioning market saturation generally increases. Analysing 12 cities in four states in the U.S., Sailor and Pavlova (2003) estimate that increases in cooling energy demand due to a warmer climate could be outbalanced by long-term adaptive behavioural responses. The disproportional growth of air conditioner use might lead to an even higher cooling energy consumption. For Germany, Diekmann et al. (2005) examine heating energy demand and CO_2 reduction strategies using a space heating model which accounts for different insulation measures and heating installation improvements. For the heating energy demand of households they estimate an increase of 5 % or an decrease of 29 % by 2030 compared to 1990. The total CO_2 emissions of households will decrease between 8 % and 38 %. Using the same approach Kleemann et al. (2000) calculate a considerable reduction potential for a single-family building by implementing heat insulation measures. However, the model does not account for climate change effects. Loga et al. (2007) investigate energy efficiency measures for the German building stock and find reduction potentials of 0.7 % and 1.7 %/yr for a renovation rate of 0.75 % and 2.5 %/yr, respectively, and insulation standards according to the German Energy Saving Regulation 2007. The corresponding reduction in CO_2 equivalent emissions will be 1.2 % and 3.0 %/yr. Buchert (2009) concludes that the German residential heating and water heating sector offer large CO_2 reduction potential in the next decades.

Nevertheless there is still a lack of studies analysing the impact of a changing climate on the heating and cooling energy demand and resulting GHG emissions considering changes in the residential building stock, renovation measures and market penetration of conditioning systems. Thus, we developed a model based approach simulating the energy demand of German households for room conditioning including the influence of warming, upcoming renovation regulations, demographic changes and different heating systems until 2060. In particular we will answer the question of how the heating and cooling energy demand of German households for room conditioning will change in the future. Moreover we also show which additional factors - beside rising temperatures - will have an influence on this demand. Finally, we calculate the resulting GHG emissions.

In the following (Section 2), we introduce the analysed building data and the method to include the effect of retrofit measures. Moreover, we detail the concept of heating and cooling degree days and the formulae used to calculate the useful energy demand of residential buildings. Taking into consideration different heating systems, we compute the end energy demand and resulting GHG emissions. In Section 3 the results are presented and compared to previous studies. Thereafter follows a discussion of the results (Section 4). A summary concludes our findings (Section 5).

2. Data and methods

2.1. Data

The German building stock comprises about 18 million residential buildings with approximately 40 million dwellings (FMTBUD, 2009). For the analysis we use data from the German Building Typology "Taxonomy and data sets" and "Occurrence of building types with different age of structure" of the Institute for Building and Environment (IWU) for the period 1954-2006. This classification comprises 43 building types by year of construction, number of dwellings in one building of each type and per building type, the volume and the size and insulation standard of the main building components. The insulation standard is expressed by heat transmission values (U-values) which indicate the thermal balance of a building component in W/m^2 component surface and per degree Kelvin temperature difference between indoor and outdoor temperature (Laustsen, 2008).

The climate data were obtained from two different model approaches. We use projections of the regional statistical climate model STAR II (Orlowsky et al., 2008). It is based on observed meteorological data from 2 335 meteorological stations of the German Weather Service (DWD) and covers a time horizon from 1951-2006. This data is re-sampled using cluster-analysis to provide scenario data up to 2060. Thereby, seven different temperature trends were imposed assuming warming of 0.0 °C to 3.0 °C. For our analysis we use projections representing a 1 °C, 2 °C and 3 °C warming trend for Germany. Out of 100 random realisations of this statistical model we selected those with the median of the climatic water balance (Werner and Gerstengarbe, 1997). Further, we use data from the regional dynamic model CCLM under scenario A1B covering the period of 1960-2100 (Lautenschlager et al., 2009). This is a non-hydrostatic model which is forced by the global coupled atmosphere-ocean-model ECHAM5/MPI-OM (GKSS, 2010). For comparison of both models we restrict the time horizon to 101 years, 1960-2060, and average model runs.

2.2. Methodological concept

2.2.1. Projection of future building stock

As the building typology does not contain annual data about the age of a building, but only building classes with different bins of years, we assumed an equal distribution for every class. The annual total sum of the residential building stock calculated according to the building typology slightly deviates from the official statistics of the Federal Statistical Office (DESTATIS, 2010). Thus, we applied the annual number of residential buildings according to the Federal Statistics while assuming the share of building types according to the IWU data. For missing years between 1954 and 1993, we linearly interpolated data on the stock of residential buildings in the former German Democratic Republic (calculated on basis of DESTATIS 2010).

In order to determine the future total living space demand, we combined population forecasts until 2060 of the Federal Statistical Office (DESTATIS, 2009) with extrapolated data on the per capita living space demand in the future. We chose the population forecasts 5-W1 (low), 6-W2 (medium) and 4-W2 (high) since they provide a wide span of possibilities (decline in population until 2060: 20 mio., 12 mio., 5 mio. respectively, from a current population of 82 million). The per capita demand of living space was extrapolated (based on the available data covering 1994-2008) employing a functional form which increases and exponentially approaches a constant value. According to the obtained parameters the per capita demand grows from 36.2 m^2 in 1994 to 47.2 m^2 in 2060. This represents changes in life style. The total living space demand was assigned to the different building types according to their mean share and size in the past. We compared this calculated total number based on living space demand and population with the number of buildings according to the Federal Statistics for 1994-2008. We found a good agreement with a deviation of 10 %, which we applied for the projection of the future building stock.

For determining the number of new residential buildings in the future, we extrapolated the trend of the available data from 1996-2007 assuming a decrease with bases of 94 000, 105 000 and 116 000 buildings. These bases represent the lowest ratio of the number of new residential buildings and the population in this period applied to the population forecasts in 2060. Thereby, we assumed that only single-family houses, row houses and multi-family houses as the main residential building types in the past will be erected in the future. Their share in the stock of new residential buildings as well as their component sizes are obtained by averaging the characteristics of buildings erected between 1984 and 2006 for the respective types.

We assumed that only buildings aged 30 years or older in the considered year are at disposal for demolishing. The number of demolished buildings is derived by subtracting the number of new buildings from the total stock in a respective year. We calculated the number of demolished buildings per type based on the mean share of building types in the total stock. As the share of high-rise buildings in the total stock is very low, the resulting number of demolished residential buildings is always lower than 0.5 and therefore assumed to be zero.

The applied building typology only describes the original state of residential buildings and does not take into consideration later renovation measures (Diefenbach and Born, 2007). Hence, we first updated the typology under the viewpoint of past renovation measures. These are dependent on both the intensity of energetic improvements (U-values of building components) and on the annual share of residential buildings that have been renovated (renovation rate).

For determining the intensity of energetic improvements in the past, we considered U-values for different building components from ordinances in the past and planned regulations in the future (Tab. 1). Under the assumption that all required U-values in the ordinances valid at the respective time were followed, the extent of energetic improvement of residential buildings in the past was determined. Buildings constructed after 2012 are assigned U-values according to energy standards as defined in the Integrated Energy and Climate Program of the Federal Government from 2007 (Jochem et al., 2008). As the European Union instructs clients to design buildings in compliance with passive house standards from 2021 on (EU, 2009), we assumed that single-family houses erected after 2020 meet this standard with regard to their U-values.

Table 1: U-values [in W/m^2K] according to the German heat insulation regulations (Wärmeschutzverordnung, WSch) and energy saving regulations (Energieeinsparverordnung, EnEV) for renovation of residential buildings over time by component (IWU, 2007).

Building component	U-values WSchV 1982	U-values WSchV 1995	U-values EnEV 2002	U-values from 2010 on (EnEV 2009)	Possible U-values from 2013 on	Possible U-values from 2020 on
Roof	0.45	0.3	0.3	0.24	0.17	0.1
Wall	0.6	0.5	0.45	0.24	0.17	0.15
Basement	0.7	0.5	0.5	0.3	0.21	0.12
Window	3.1	1.8	1.7	1.3	0.9	0.8

There is a lack of data regarding annual renovation rates in Germany for the past (Diefenbach and Born, 2007). According to estimates it amounts to around 2.5 % (Jochem et al., 2008). However, as most of these renovations do not incorporate the total renovations in an energetic sense, but often only parts of a building are improved energetically, the quota of energetically renovated residential buildings per year is considered to be much lower (Diefenbach and Born, 2007). Diefenbach et al. (2005) suppose an annual energetic renovation rate of 0.75 % to 1.5 % and use 1 % as a general estimate, which we apply in this study.

Due to a lack of detailed data on the type of residential buildings which have been renovated, we assume that in each considered year only those buildings that are 30 years or older and that are not yet demolished are improved (Boermans and Petersdorff, 2007). In order to obtain the annual number of redeveloped buildings per building type, the share of each type subjected to renovation measures in the overall number of residential buildings subjected to renovation measures was multiplied by 1% (renovation rate) of the total stock of buildings in the considered year. For the future we apply the renovation rates according to the considered scenarios (see Section 2.7). The number of renovated buildings is then cumulatively summed over the years of consideration. The considered time frame of 101 years leads to buildings being renovated more than once after 2014. Thus, after 2014, the renovation rate was split up equally to one-time and second renovations.

If for one building type the number of one-time renovated buildings exceeded the stock of buildings in one year before 2014, we apportioned the surplus to the other building types according to their share in the total stock. If this case occurred for years after 2014 (when second renovations are considered), we set the cumulative number of (one-time) renewed buildings to the total number of that building type.

If the calculated cumulative number of one-time renovated buildings of a type was larger than the actual stock of buildings of that type (as occurs due to an assumed constant yearly retrofit rate), we limited it to the stock of that type in the respective year. Moreover, the total renovation rate was assigned solely to the second renovation.

The cumulative number of second-time renovated buildings per type can neither exceed the existing total building stock of that type nor exceed the total number of improvable buildings of that type in a considered year. If the smaller value limits the cumulative number of buildings to be renovated a second time, an apportionment to other building types is carried out until the cumulative number of buildings to be renovated a second time is equivalent to the minimum and therefore set to the minimum. Thus, the cumulated number of second-time renovated buildings always stays below the cumulated number of renovatable buildings or those to be renovated a second time.

2.3. Calculation of the useful heating and cooling energy demand

To assess the impact of temperature on the heating and cooling energy demand, we applied the common concept of heating and cooling degree days (Amato et al., 2005; Cartalis et al., 2001; Eskeland and Mideksa, 2009; Howden and Crimp, 2001; Prettenthaler and Gobiet, 2008).

A degree day is defined as the °C difference between an indoor comfort temperature and the mean daily outdoor temperature, if the latter does not exceed a certain threshold, and is especially dependent on the insulation standard of the considered building. For Germany this comfort temperature is defined in the industrial standard DIN 4108-6 (German Institute for Standardization) as 19 °C (DIN, 2003).

We considered different heating thresholds for different types of insulation. As this differs strongly between building type, we assumed the two thresholds of 10 °C and 12 °C as applied in Christenson et al. (2006) and Prettenthaler and Gobiet (2008). We assigned them to each building type according to its heat loss per volume based on standard DIN V 4108-6 (DIN, 2003) and the German Energy Saving Regulation 2007 (FG, 2007). We found that for residential buildings that are not yet retrofitted, heating thresholds of 10°C and 12 °C are suitable. Newer buildings do have lower, older ones higher thresholds. From 1995 on, when the heat insulation regulation (Wärmeschutzverordnung) came into force, for all building types we use a heating threshold of 10 °C for the determination of heating degree days.

As there is no European Standard for computing cooling degree days, European studies usually apply a common U.S. definition with a comfort temperature of 18.3 °C (65 F) (Aebischer et al., 2007; Christenson et al., 2006; Prettenthaler and Gobiet, 2008). The application of this internationally prevailing base temperature is not plausible in this study as the indoor comfort temperature is assumed to be 19 °C. In this study, we therefore implemented a cooling threshold of 22 °C as a realistic upper limit, which has been used by Benestad (2008) and Matzarakis and Thomsen (2009). Thus, heating degree days (HDD) are calculated by:

$$\text{HDD} = \sum_{i=1}^{n} (19\ ^\circ\text{C} - \theta) \text{ for n = days per year and } \theta \leq 10\ ^\circ\text{C}, \text{or } 12\ ^\circ\text{C} \tag{1}$$

and cooling degree days (CDD) by:

$$\text{CDD} = \sum_{i=1}^{n} (\theta - 19\ ^\circ\text{C}) \text{ for } n = \text{ days per year and } \theta \geq 22\ ^\circ\text{C}. \tag{2}$$

The residential building stock is not equally distributed over Germany. For this reason we weighted heating and cooling degree day data from both models according to spatially distributed population density based on CORINE Land Cover (CLC) data (Gallego and Peedell, 2001). Thereby, we weighted the degree day values by the population in the vicinity of the respective climate station based on Thiessen polygons (for the STAR II model) or by the population within the respective grid cell (for the CCLM model).

The heating energy demand corresponds to the heat that the heating system must supply to a building to attain a certain comfort temperature. It is influenced on the one hand by heat losses through outer surfaces and ventilation of a building (both are influenced by the number of degree days) and on the other hand by gains of heat through insolation and waste heat of internal heat sources like electric equipment and residents (Jungmann and Lambrecht, 2008). When outdoor temperatures lie above indoor temperatures, the transmission and ventilation heat fluxes are simply reversed (DIN, 2007). Thus, the heat supplied to the building results in a certain cooling energy demand.

The annual heating energy demand Q_h of each residential building was calculated on the basis of the German DIN standard V 4108-6 (DIN, 2003), given the formula:

$$Q_h = 24 \cdot 10^{-3} \cdot f \cdot \text{HDD} \cdot (H_T + H_V) - \eta \cdot (Q_S + Q_I) \text{ [kWh/a]}, \tag{3}$$

where
f = Factor for inclusion of a night setback of the heating system temperature = 0.95 [kh/d],
H_T = Transmission heat losses,
H_V = Heat ventilation losses,
η = Factor for inclusion of the utilisation factor of internal and solar heat gains,
Q_S = Usable solar heat gains (constant value),
Q_I = Usable internal heat gains (constant value).

Transmission heat losses derive from heat conduction in the building components as well as heat transfer to the outer surfaces of the components. Thus, they are a measure of the heat insulation quality of the building envelope and depend on the U-values of the building components; the smaller the U-values, the better their energetic state (Jungmann and Lambrecht, 2008). Transmission heat losses H_T are calculated with the following equation.

$$H_T = \sum_{i=1}^{4} (F_{xi} \cdot U_i \cdot A_i) + A \cdot \Delta U_{TB} \text{ [W/K]}, \tag{4}$$

where
F_{xi} = Temperature correction factor (depending on the kind of building component),
F_{xi} [wall, window, roof] = 1, F_{xi} [basement] = 0.6,
U_i = Mean U-value of a building component [W/(m$^2\cdot$ K)],
A_i = Surface area of each building component [m^2],
A = Heat transmitting surrounding area [m^2],
ΔU_{TB} = Thermal bridge correction factor = 0.05 [W/(m$^2\cdot$ K)].

The replacement of warm ambient air by cold outdoor air results in heat ventilation losses H_V. For calculation of these losses, differences in the leak tightness of buildings are neglected, thus

$$H_V = 0.19 \, [\text{W/K} \cdot \text{m}^3] \cdot V \, [\text{m}^3], \tag{5}$$

where V = heated building volume (constant per building type).

Usable solar heat gains Q_S are mainly conveyed via windows and other glazings and depend on the total energy transmittance g of the in-built glass, the glass surface, and the intensity of radiation. Assuming buildings are fully exposed to radiation, usable solar heat gains are calculated by

$$Q_S = \sum_{i=1}^{4} 0.567 \cdot I_i \cdot g_i \cdot A_i \text{ [kWh/a]}, \tag{6}$$

where:
I_i = Intensity of radiation (depending on orientation: $I_E = 155$, $I_S = 270$, $I_W = 155$, $I_N = 100$) [kWh/(m$^2\cdot$ a)],
g_i = Total energy transmittance of glazing type in case of vertical insolation [-],
A_i = Area of windows [m^2].

Electrical equipment, lighting, and attendant residents cause internal heat gains depending on the amount, the frequency of use, the efficiency of the devices and the degree of activity of the residents. As these influences cannot be quantified generally the regulation assumes a mean value of internal heat gains Q_I:

$$Q_I = 22 \, [\text{kWh/m}^3\text{a}] \cdot 0.32 \cdot V \, [\text{m}^3] \, . \tag{7}$$

The DIN standard 18599 (DIN, 2007) allows for a complex and detailed determination of the heating and cooling energy demand of buildings. However, for comparability reasons a simplified approach for calculating the heating energy demand in DIN 4108-6 was chosen here and applied to the determination of the cooling energy demand Q_C. Thus the cooling energy demand [in kWh/a] was calculated as follows:

$$Q_C = (1 - \eta_{HP}) \cdot \Bigg(0.024 \cdot \text{CDD} \cdot \big(\sum_{i=1}^{4} F_{xi} \cdot U_i \cdot A_i + 0.05 \cdot A + 0.19 \cdot V\big) + \big(\sum_{i=1}^{4} 0.567 \cdot I_i \cdot g_i \cdot A_i + 22 \cdot 0.32 \cdot V\big)\Bigg) . \tag{8}$$

Due to the fact that the provision of residential buildings with air conditioners is much smaller than the provision with heating systems, we multiplied the calculated annual cooling energy demand by the share of households with air conditioners resulting in the actual cooling energy demand. Further, we assume an equal distribution of these cooling systems over all building types.

Table 2: Annual utilisation rates (Beer et al., 2009) and CO_2 equivalent emission factors (including upstream chains)(Memmler et al., 2009) for different type of heating system according to the respective energy sources .

Type of heating/ energy source	Annual utilisation rate	CO_2 equivalent emission factor
Coal boiler	0.79	0.43
Heat oil boiler	0.75	0.32
Gas boiler	0.79	0.25
Biomass boiler	0.79	0.01
Solar heat and heat pump	2.25	0.14
Electric heating	0.99	0.67
District and local heating	0.98	0.32

Table 3: Heating (left) and cooling energy demand scenarios (right).

	Heating			Cooling		
Assumptions/ Scenario	High	Medium	Low	High	Medium	Low
Future renovation rate	1 %	2 %	3 %	1 %	2 %	3 %
Future building stock	High	Medium	Low	High	Medium	Low
Projected temperature increase until 2060	1 °C	2 °C	3 °C	3 °C	2 °C	1 °C
Market saturation of heating (left) and cooling (right) devices	100 %	100 %	100 %	13 %	2.5 %	1 %

2.4. Calculation of the end energy demand

So far, we have calculated the useful energy demand defined as the energy that a heating or cooling system must theoretically supply to a building. However, it does not consider how efficient this demand is supplied. We therefore further calculate the end energy demand which is the amount of energy necessary to meet the useful energy demand after deducting transport, static, exhaust gas, radiation and transformation losses. These losses are considered by the annual utilisation rate of a certain heating system defined as the ratio between generated heat and necessary input energy. This value indicates the efficiency over a certain time period under practical conditions and thus also considers static and standing losses (FMENCNS, 2005). Thus, the end energy demand is given by:

$$E = Q_h/\varepsilon \text{ [kWh/a]} \tag{9}$$

where:
E = End energy demand [kWh/a],
ε = Annual utilisation rate [-].

The annual utilisation rate differs between energy source and the heating system. We vary energy sources and heating systems over time while assuming constant annual utilisation rates. The annual utilisation rates applied for different types of heating are summarised in Table 2. As no data is available about the share of solar heat or heat pumps in the energy source "solar heat and heat pumps", an equal distribution is assumed.

2.5. Derivation of future scenarios

Since the future energy demand is associated with high uncertainty, we develop scenarios: a medium scenario and two extreme scenarios, thus covering the scope of possible and plausible future developments of the useful energy demand (Tab. 3). Within the scenarios the development of the number of households through the construction activity, the renovation activity, temperature changes and the market saturation of room conditioning devices are considered. Possible future changes of further influencing factors are neglected.

We assume the future renovation rate to range between 1 % (continuation of past development) and 3 %, as agreed in the Integrated Energy and Climate Protection Program (IEKP) of the Federal Government of Germany from 2007 (FMTBUD, 2009). Scenarios for the future stock of buildings are based on the extrapolated living space demand and the three population forecasts. Increases in the projected temperature are assumed to range between 1 °C and 3 °C, which corresponds approximately to the emission scenarios B1, A2 and A1FI, respectively. Temperature data based on the CCLM model correspond to a warming of around 1 °C. Thus, for comparability the high scenario for heating and the low scenario for cooling were calculated on the basis of both climate models. While full market saturation was presumed for heating systems, a lower saturation of 1 % (constant value according to Adnot et al. (2008)), 2.5 % (values estimated by Adnot et al. (2008) for 2030) and 13 % was assumed for cooling systems. The last value is based on the actual number of air conditioners in Italy (Adnot et al., 2008), whose climate is projected for Germany in the future by Kopf et al. (2008) based on heating and cooling degree days.

The total heating and cooling energy demand of residential buildings in Germany was calculated for not yet renovated and one-time and second-time renovated residential buildings with the statistical software R (RDCT, 2009) according to Eqs. (3) and (8) respectively.

For the future trend of different energy sources in all heating systems we apply two existing scenarios for Germany: “business-as-usual” (low sustainability scenario in the original study) and “regionalisation” (high sustainability scenario) to the end energy demand of households in Germany by energy source until 2050 (Beer et al., 2009; Beer, 2011) (Fig. 1). Both scenarios are based on projections. As the scenario expressing medium sustainability only slightly differs from the high sustainability scenario, we only applied the two extreme scenarios. We hold values constant for the period 2050 to 2060 and linearly interpolated missing values between the data given on a 5-year basis.

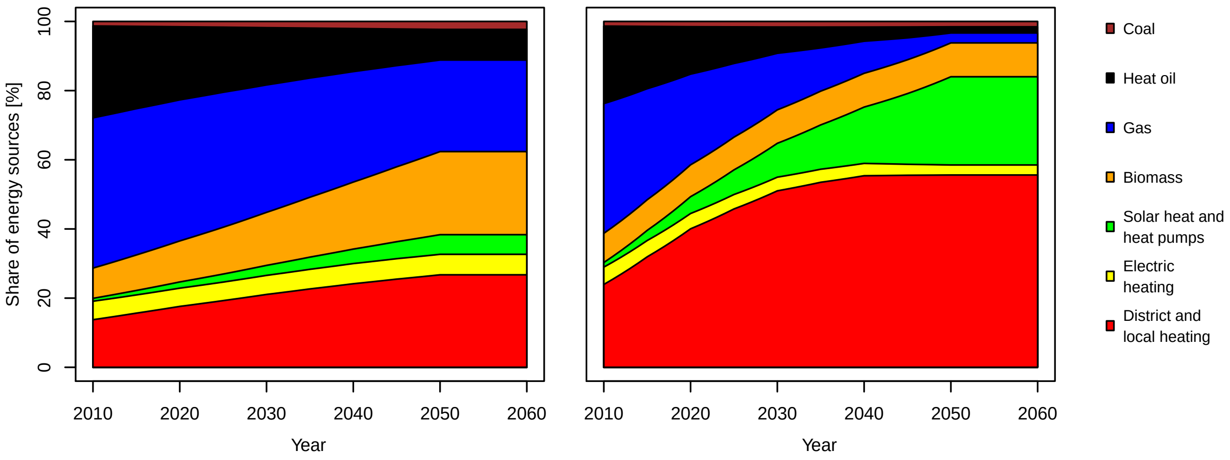

Figure 1: Share of energy sources used for heating of residential buildings in Germany according to scenario “business-as-usual” (left) and “regionalisation” (right) based on Beer et al. (2009).

2.6. Calculation of GHG emissions caused by heating

Multiplying the calculated annual end energy demand of German residential buildings per fuel by the specific CO_2 equivalent emission factor provides the amount of GHG emissions caused by different heating systems. We apply the CO_2 equivalent emission factors of Memmler et al. (2009) that are given in Table 2. Due to the great current uncertainty regarding the energy sources contributing to the future electricity mix, we restrict our analysis to the GHG emissions caused by heating.

2.7. Validation

For validation the calculated useful heating energy demand was compared with the heating energy consumption of German households for room conditioning in the period 1995 to 2008 (Fig. 2). Our calculated theoretical heating energy demand exceeds the real consumption. This is due to various factors, which have not been included in our simulations. First, increasing energy prices normally lead to a reduction in energy consumption. Since energy prices steadily increased in recent years (FMET, 2009), residents reduced their heating activity. Second, it is assumed that all residential buildings are occupied. However, in the past an average of 8 % of the dwellings in Germany were unoccupied (DESTATIS, 2010). Moreover, one million second residences and one million holiday flats are not constantly occupied (Kott and Behrends, 2009) and are therefore heated only part of the time. Yet this temporary occupation is not accounted for and it is assumed that room conditioning applies for the whole building volume. Third, the calculations do not allow for the specific characteristic of the urban building density and the related interaction between buildings and their environment, as the building typology only considers free-standing buildings. Yet in a city considerably less outer surfaces exist than denoted in the building typology due to adjacent buildings. It is therefore plausible that the real energy consumption is lower than the simulated demand, as 88 % of the German population lives in urban areas (OECD, 2007). Finally, in reality, not all rooms of a residential building are continuously heated to the same assumed indoor temperature. This leads to a lower annual heating energy consumption than that theoretically needed.

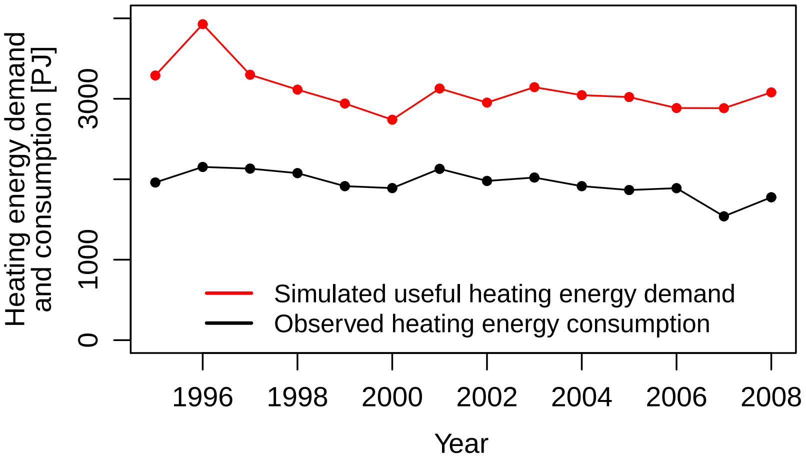

Figure 2: Comparison of calculated useful heating energy demand and observed heating energy consumption according to the Federal Statistical Office.

Bearing these factors in mind, it is plausible that the calculated energy demand exceeds the energy consumption. What is important is that the courses of the curves are quite similar. Due to a lack of data on the cooling energy consumption of German households in the past, it is not possible to validate the results concerning the useful cooling energy demand.

3. Results

3.1. Estimation of the useful energy demand

The heating energy demand displays a strong inter-annual variability. However, independent of the scenario, a clear downside trend of the heating energy demand is observable in the future with decreases of around 81 % (from 759 TWh to 143 TWh between 2010 and 2060) under the scenario “low energy demand” and around 57 % (from 936 TWh to 400 TWh) under the scenario “High energy demand” (Fig. 3).

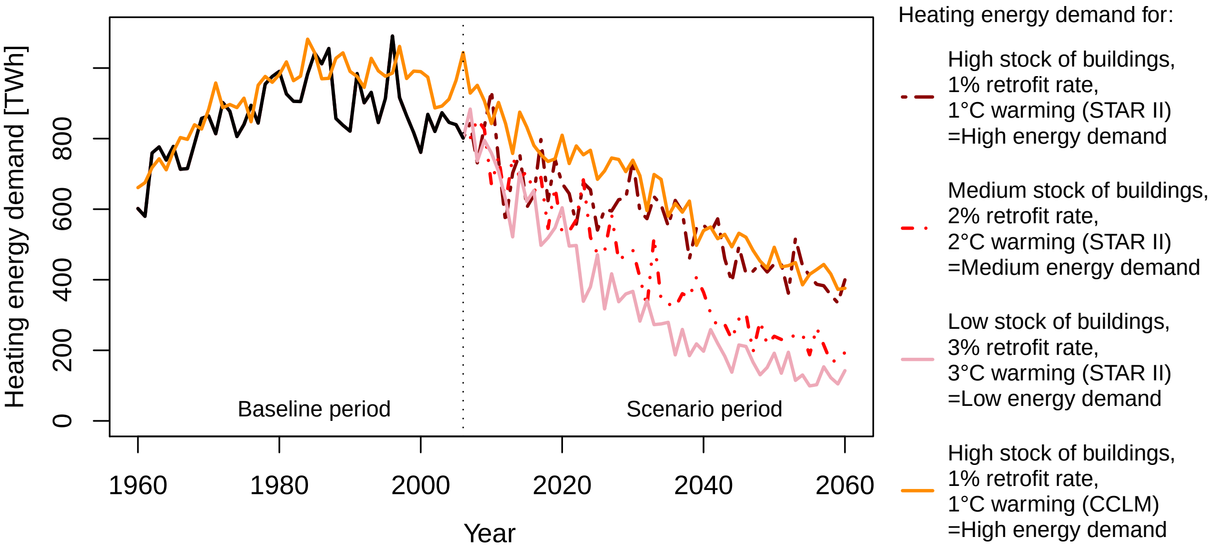

Figure 3: Heating energy demand of German households in the past and according to the four future scenarios based on climate data of the models STAR II and CCLM and observed climate data (solid black).

Calculations based on CCLM data yield a future decrease of the heating energy demand of 55 % from 843 TWh to 376 TWh in the high scenario.

The actual cooling energy demand strongly depends on the assumed share of residential buildings with air conditioners (Fig. 4). Whereas the actual cooling energy demand slightly decreases from 0.07 TWh to 0.05 TWh in scenario “low energy demand” between 2010 and 2060, it increases by 235 % from 0.26 TWh to 0.86 TWh in scenario “High energy demand” based on data from the climate model STAR II. All actual cooling energy demand curves converge in the mid 2030s as the share of households with air conditioners is assumed to stay constant from 2030 and beyond. Assuming that all households have air conditioners, the cooling energy demand roughly remains at the same level under the scenario “High energy demand” and decreases by 27 % (from 7.2 TWh to 5.3 TWh) under the scenario “low energy demand” between 2010 and 2060.

Calculations based on CCLM data yield a future decrease of the cooling energy demand of 23 % from 7.5 TWh to 5.8 TWh in the low scenario.

3.2. Influencing factors on the future useful energy demand

The effect of the considered factors on the useful energy demand is exemplarily shown by the medium scenario for the climate model STAR II (Fig. 5). As the number of air conditioners cancels out the effect of all other factors it is presumed for this comparison that all residential buildings are provided with air conditioning systems. In Fig. 5a and b it is shown that the annual variability of the energy demand depends on the annual fluctuations of the degree days and thus the projected temperature. In order to quantify this relation, we calculate the Pearson correlation coefficient (PCC) between both records. Since the data is dominated by trends, we consider the year-to-year differences and accordingly quantify correlations in the annual variability. These derivatives lead to a correlation coefficient of 0.96 for heating and 0.64 for cooling. The initial increase in the heating energy demand until the end of the 1980s and the later decrease of both the heating and cooling energy demand cannot be explained by this factor alone. The fact that the heating energy demand decreases from the 1980s on despite an initially still increasing stock of residential buildings (Fig. 5c) and that the PCC is only -0.54 reveals that the heating energy demand is superimposed by another factor, renovation. The cooling energy demand resembles the residential building stock (PCC: 0.92).

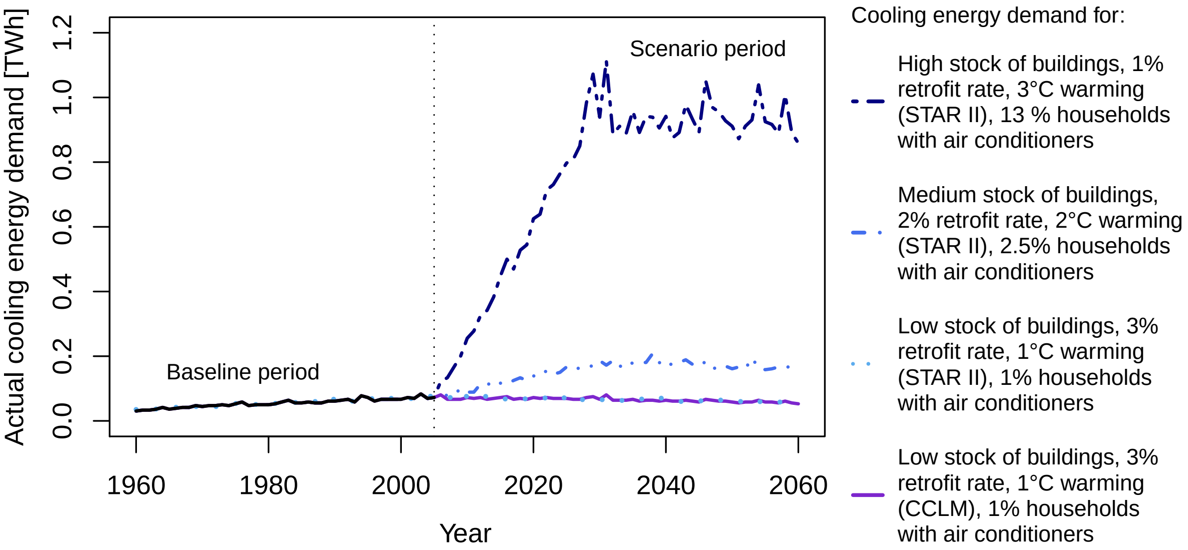

Figure 4: Actual cooling energy demand of German households in the past and according to the four future scenarios, based on climate data of the models STAR II and CCLM and observed climate data (solid black).

However, between the beginning of the millennium and 2038 an initial increase and later decrease in the stock of buildings was accompanied by a rather constant development of the cooling energy demand (Fig. 5d).

From 2010 the gradient of the curve of one-time renovated residential buildings doubles, as the renovation rate increases from 1 % to 2 %. However, from 2014 the quota is reduced to half the initial value as an equal apportionment of the renovation rate is assumed. From the middle of the 2040s the curve of one-time renovated residential buildings converges due to the limited number of renovatable buildings. Thus, the trend of the heating energy demand is mostly influenced by performed one-time renovation measures (PCC of -0.97 for 1984-2060) and to a lesser extent by second-time renovations (PCC of -0.9 for 2014-2060) (Fig. 5e). This is due to the fact that the U-values only slightly differ between one-time and second-time improvements. Thus further renovation measures hardly influence the heating energy demand. Unlike with the development of the heating energy demand, there is no obvious relation between the beginning of renovation measures and changes in cooling energy demand (PCC of 0.2 for one-time renovations in the period 1984-2060 and -0.54 for second-time renovations in the period 2014-2060, Fig. 5f). An increasing number of CDD (causing an increase in the cooling energy demand) interacts with more renovated buildings (causing a decrease in the cooling energy demand). Further, the development of the stock of residential buildings leads to an increase or decrease in the cooling energy demand - depending on the scenario and the period under consideration.

The effect of temperature increase, building stock, and renovation rate on the energy demand is further examined by varying specific factors while all other factors keeping constant (Fig. 6). By this sensitivity analysis it can be shown that the development of the residential building stock has only a slight influence on the energy demand until the beginning of the 2020s, since the building stock changes start to differ clearly from each other only afterwards. Concerning a 1 °C warming and a renovation rate of 1 %, the strongest influence of the residential building stock on both heating and cooling energy demand becomes obvious. With regard to the heating energy demand this difference decreases under the projected increased warming and future renovation rate (Fig. 6a). In contrast, changing other factors hardly reduces the strong influence of the building stock development on the future cooling energy demand (Fig. 6b).

Considering the same renovation rate and the same development of the stock of residential buildings, the heating energy demand is roughly 30 % lower and the cooling energy demand less than 10 % higher at the end of the considered period in the scenario given a warming of 3 °C than for 1 °C. Until the end of the examined period the same temperature and building stock development results in a heating energy

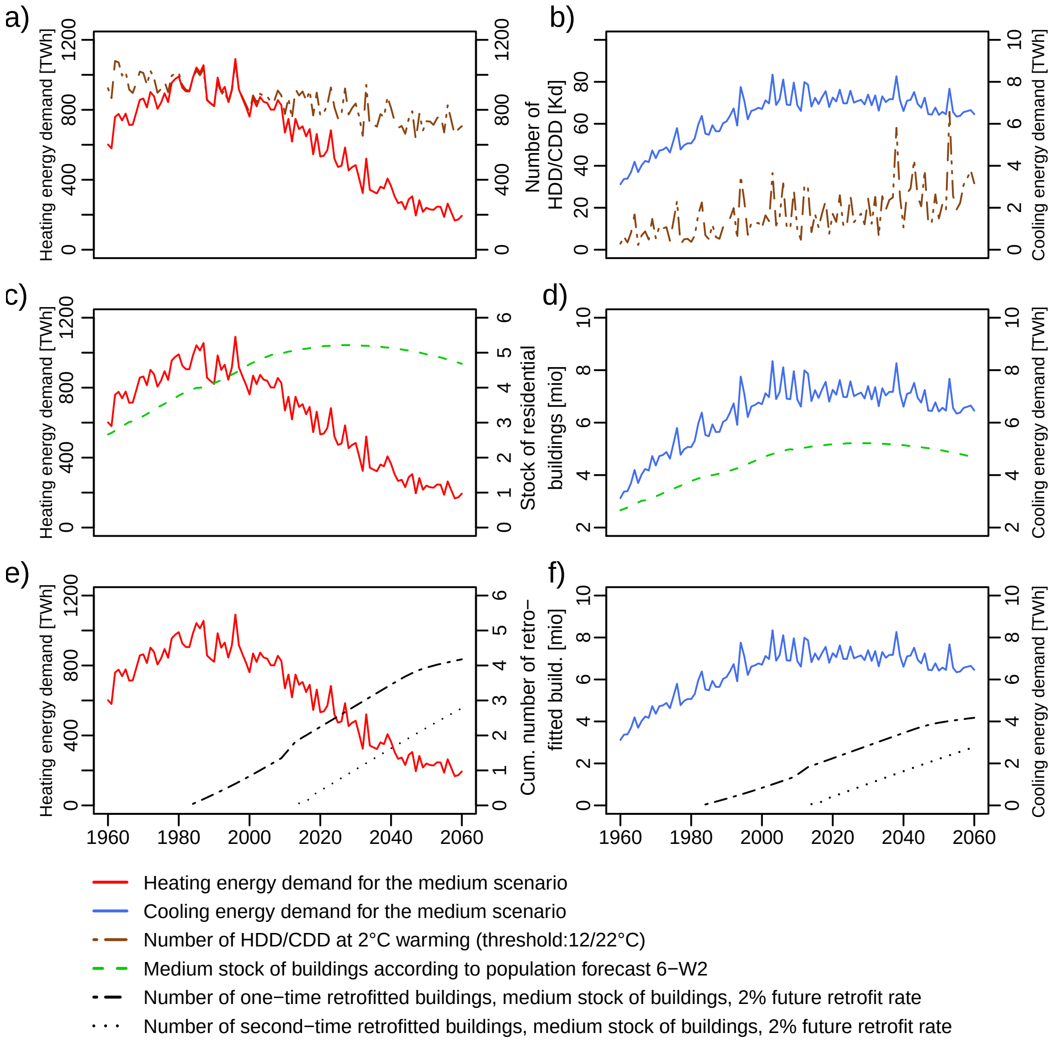

Figure 5: Relation between influencing factors and heating/cooling energy demand of German households based on climate data of the model STAR II.

demand 35 % lower and a cooling energy demand 5 % lower under a 3 % future renovation rate than under a renovation rate of 1 %. Thus, while the heating energy demand is strongly effected by performed renovation measures, the cooling energy demand is mainly influenced by the future stock of buildings.

For the same scenarios the future heating energy demand based on CCLM data is on average higher and the future cooling energy demand is lower than that projected based on STAR data, because the CCLM model projects colder conditions. Nevertheless, the findings regarding the effect of influencing factors on the future energy demand apply analogously for calculations based on CCLM data.

Table 4 summarises the percentage change in heating and cooling energy demand in the different scenarios for 1961-1990 compared to 2031-2060. Heating energy demand declines on average by 44 % in scenario “high energy demand” and by 78 % in scenario “low energy demand” when comparing the period 1961-1990 with 2031-2060. Again, the strong effect of renovation measures becomes obvious. In the same period, the cooling energy demand will increase by 59 % in scenario “high energy demand” and increase by 25 % in scenario “low energy demand”.

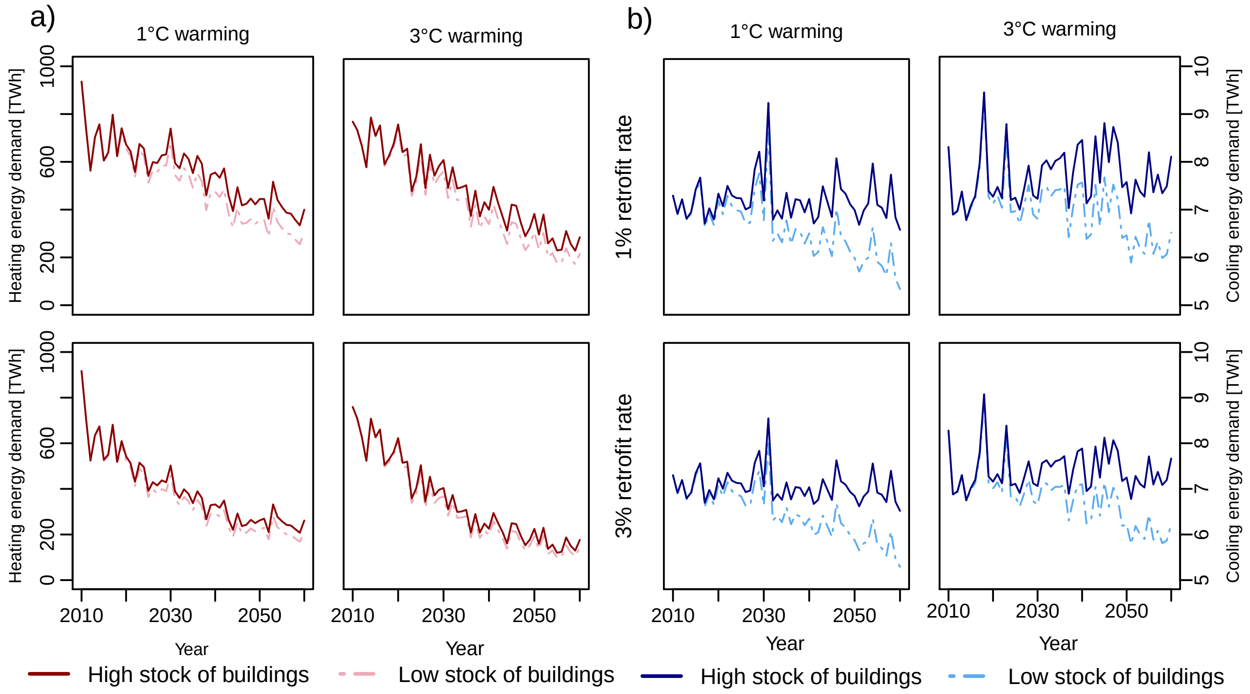

Figure 6: Sensitivity analysis of heating (left) and cooling (right) energy demand based on climate data of the model STAR II.

Table 4: Percentage change in heating (left) and cooling (right) energy demand between 1961-1990 and 2031-2060 under different scenarios with regard to warming, renovation rate and building stock (high/low), based on climate data of the model STAR II.

	Heating			Cooling		
Percentage change in average energy demand	1 °C warming	2 °C warming	3 °C warming	1 °C warming	2 °C warming	3 °C warming
1 % future renovation rate	(-44/-53)	(-51/-59)	(-56/-64)	(46/28)	(53/33)	(59/39)
2 % future renovation rate	(-59/-65)	(-64/-70)	(-69/-74)	(43/26)	(49/30)	(53/34)
3 % future renovation rate	(-66/-72)	(-71/-75)	(-75/-78)	(42/25)	(47/29)	(51/32)

3.3. Estimation of GHG emissions

The future GHG emissions will significantly decrease in all scenarios. The range will be between 86 % (from 255 Mt CO_2 eq. to 35 Mt CO_2 eq.) in scenario “low energy demand”/“regionalisation” and 66 % (from 319 Mt CO_2 eq. to 108 Mt CO_2 eq.) in the scenario “high energy demand”/“business-as-usual”. The development of emissions is strongly influenced by the climate-related inter-annual variability. In order to examine the effect of different scenarios regarding the energy mix, we also combined the scenario “low energy demand” with the energy source scenario “business-as-usual” and the scenario “high energy demand” with the energy source scenario “regionalisation” (Fig. 7). It can be seen that the effect of changing energy sources is small compared to the effect of changing energy demand. This is due to the fact that the energy mix is not expected to drastically change in the future with regard to emissions. Although there will be a shift to more district and local heating (with a higher annual utilisation rate but a CO_2 equivalent emission factor comparable to that of heating with oil), in both energy source scenarios, the share of renewables is expected to be still less than 40 %. Assuming a 100 % share of biomass in 2060, would reduce the emissions caused by heating of residential buildings to a low value of 2.5 Mt CO_2 eq. in scenario “low energy demand” and 7 Mt CO_2 eq. in scenario “high energy demand”. The corresponding values for an assumed share of

100 % solar heat and heat pumps would be 8.9 Mt CO_2 eq. and 25 Mt CO_2 eq., respectively.

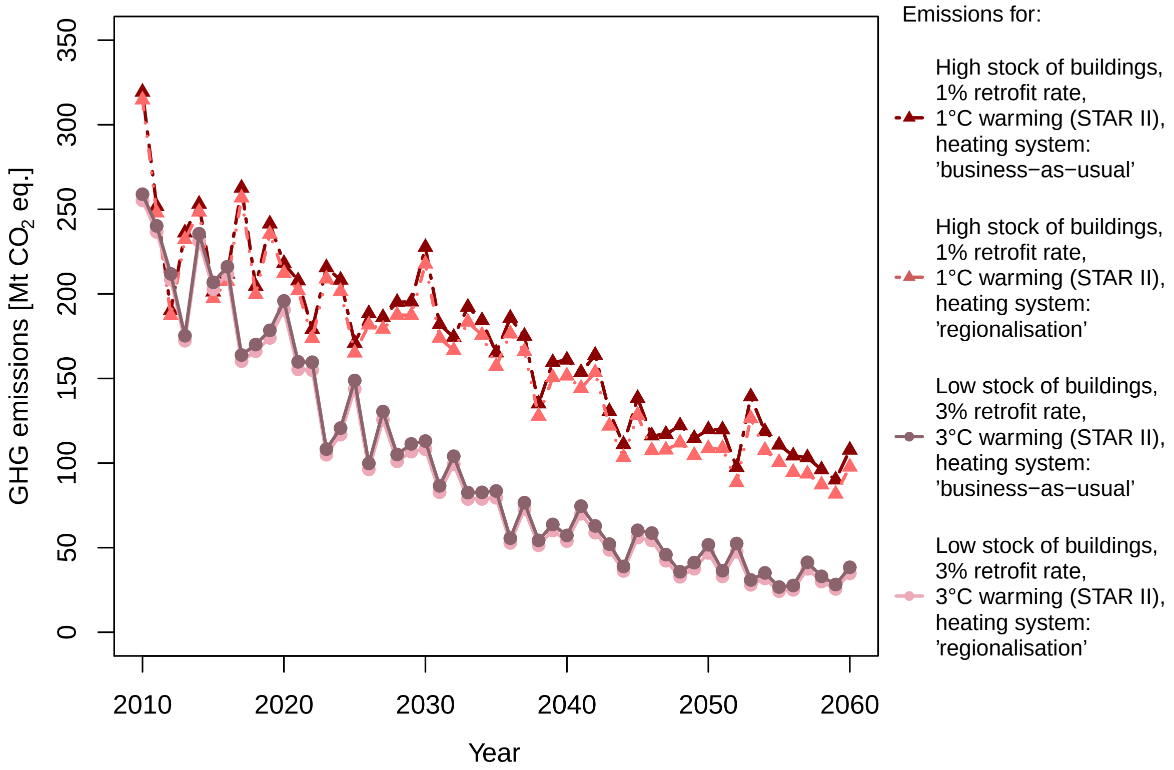

Figure 7: GHG emissions from heating of German households according to the future scenarios, based on climate data of the model STAR II. Results are based on projections.

4. Discussion

We calculated the future heating and cooling energy demand and resulting GHG emissions of households by means of different scenarios concerning warming, renovation, building activity, market penetration of room conditioning systems and energy sources used for heating. This is the first integrated approach to analyse the impact of these factors on the future energy demand and emissions of households for room conditioning in Germany. However, the results of this study agree with a number of international studies showing a reduction of the future heating energy demand and an increase in the future cooling energy demand. We find a reduction of the heating energy demand of 44-78 % when comparing 1961-1990 with 2031-2060, while Aguiar et al. (2002) determine a decline in the future heating energy demand of residential buildings in Portugal of 34-60 % when comparing the period 1958-99 with 2070-99. Although both studies examine a similar decrease, a comparison is only possible in a limited extent due to different considered time periods and geographical regions. Moreover, Aguiar et al. (2002) as well as Amato et al. (2005) and Christenson et al. (2006) assume fixed characteristics of the building stock in Portugal, the U.S. and Switzerland, while we take into account considerable future building stock changes. Prettenthaler and Gobiet (2008) study the influence of climate change on the energy demand for heating and cooling of buildings in Austria and find a climate-induced decrease of the average demand for heating of 20 % until 2050. The lower reduction than that we found for Germany is mainly due to the fact that the authors do not include building stock changes and renovation measures. However, they account for different heating systems on a highly regionalised level.

Examination of all the considered factors shows that renovation measures have the strongest influence on future heating energy demand of buildings. This underlines the role active policy making in this sector can play in regard to an ambitious climate protection policy. Independent of climate change, an increase in the annual renovation rate from 1 % to 3 % could lead to a heating energy demand decline for German households of between 14 % and 22 % (Tab. 4). For U.S. commercial buildings Scott et al. (1994) find an even stronger reduction potential of building efficiency improvements of 30-40 %. Scott et al. (1994) also show that tripling of insulation would allow for a cooling energy demand reduction of 28-60 % but by examining only the effect of increased qualitative renovation. We try to show the influence of better insulation and increased renovation rates, which are increasingly a target of environmentally friendly policy making in the building sector.

Few studies determine the impact of insulation measures on the future energy demand of households in Germany. Kleemann et al. (2000) calculate a reduction potential of 70 % for insulating an un-renovated single-family building according to EnEV 2002 standards. Comparing the years 2000 and 2025 Buchert (2009) concludes that the heating energy demand of residential buildings in Germany will decrease by 8 % without renovation measures and by 35 % with insulation measures, considering future building stock changes but disregarding climate change. Loga et al. (2007) apply the same building typology as we did and find that an increase of the renovation rate to 2.5 % yields an annual reduction potential for energy of 1.7 % and for emissions of 3 %. For Germany we find a mean annual heating energy demand decrease of 0.35 % - 2.0 % and a mean reduction in emissions of 1.5 % - 2.0 % in the period 2010 to 2040. The Energy Concept of the Federal Government (FG, 2010) aims at reducing the heating energy demand of residential buildings by 20 % until 2020. Assuming the year of publication as the reference year, we find a heating energy demand decrease of 22-31 % between 2010 and 2020 depending on the scenario. Whereas this political aim seems within reach, our results for the emission reduction raise doubts about the feasibility of the Federal Government's plan (FG, 2010) to achieve an almost climate neutral residential building stock in Germany in 2050. Based on our scenarios, which include rather ambitious developments regarding the renovation rate, we calculated GHG emissions from heating of 61 to 139 Mt CO_2 eq. by 2050, representing reductions of 60-78 % compared to 2010.

While we neglect the influence of energy prices and income since we focus on energy demand, Eskeland and Mideksa (2009) conclude that the responsiveness of electricity consumption to changes in income is much greater than the effects of climate warming and energy prices in Europe. Doubling prices would only lead to a 20 % reduction in energy consumption. We found that the future development of the cooling energy demand strongly depends on the scenario considered. For the U.S., Scott et al. (2007) determine increases in residential cooling energy demand of 6-27 % between 2005 and 2050. Cartalis et al. (2001) examine an increase in cooling energy demand of 15-28 %. However, in contrast to these studies, we take into consideration changes in the number of air conditioners and come to the conclusion that such future increases will have a strong impact on the actual cooling energy demand. Assuming an increase in the share of households with air conditioners from 1-13 % we obtain a future increase of the actual cooling energy demand of more than 200 %. Aguiar et al. (2002) underline the profound impact of the number of air conditioners and estimated that the cooling energy demand increases in the Portuguese building stock by 130-525 % until the end of the century and if one-third of the residential floor area is air-conditioned 4.5 to 6 hours per day. Sailor and Pavlova (2003) also find that adoption of air conditioners as an adaptive response of households to temperature increase might have a much larger impact on energy consumption than warming itself.

In conclusion, existing studies on the future energy demand of German residential building only account for renovation measures and/ or building stock changes. None of these studies examine the combined influence of a projected temperature increase, renovation measures, and building stock changes on the future energy demand of households for room conditioning. In our study we show how the future energy demand for room conditioning of residential buildings develops in Germany based on various influencing factors. However, there are some limitations:

The applied building typology of the German Institute for Building and Environment (IWU) is only an approximative representation of the German building stock. Moreover, buildings that are used for multiple purposes are classified as residential buildings if they account for more than 50 % of the used area. Especially in cities the share of residential buildings with shops on the ground floor can be large.

In reality there is no linear relationship between the number of degree days and the required energy to overcome a certain temperature difference (Scott et al., 1994). The use of constant threshold temperatures neglects possible differences in the diurnal variation in temperature as well as the fact that a heating system would not be turned on if the temperature falls below the threshold only one day. We presume that residential buildings are heated or cooled 24 hours to the same comfort temperature. However, indoor comfort temperatures vary between 6 °C and 30 °C (Shove, 2003) and are expected to change under changing climatic conditions (Chappells and Shove, 2005). We also assume that both the comfort sensation of residents and the heating and ventilation behaviour only depend on temperature and we thus disregard other factors such as the surface temperature of the components, humidity and different physical activity of people. The resident's possibility of exerting influence on the indoor comfort temperature affects the comfort. The more control they can exercise, the more comfortable the residents feel and the more they are willing to tolerate deviations from the indoor comfort temperature (Roberts, 2008).

We did not consider future changes in the efficiency rate of different heating systems. There is a trend from "constant-temperature" and "low-temperature" boilers to "condensing" boilers both for oil and gas but useful quantitative data are not available.

Our methodology could be applied to a more regional resolution, i.e. in terms of the local characteristics of climate and building stocks depending on data availability.

5. Conclusion

As there is a lack of information on the development of the future heating and cooling energy demand of German households under a changing climate, insulation improvements and population changes, we introduced a modelling approach allowing for the assessment of the combined effect of projected temperature increases, renovation measures and building stock changes. This was a considerable extension of currently existing approaches for Germany. Our analysis allows for cross-checking of policy goals in Germany. As a further benefit the approach could be transferred to other countries.

We showed that a strong future decrease in the heating energy demand of the German residential building stock will be accompanied by an increase in the cooling energy demand. The latter is strongly dependent on the assumed future share of households with air conditioners. Our results indicate significant consequences for energy production and supply systems especially since heating and cooling are provided by different energy sources. We therefore expect a strong future shift of energy demand from primary energy towards electricity.

It was clearly shown that the future heating energy demand is mainly influenced by performed renovation measures which underlines the importance of renovation for reducing the energy demand. Political action regarding the support of renovation measures represents a win-win-strategy regarding climate mitigation and energy saving. For example, the minimisation of cooling requirements can be encouraged by further building regulations and sustainable urban planning. Without drastic changes in the energy mix, a reduction of GHG emissions caused by heating of residential buildings can mainly be achieved by reducing the demand for energy. We feel that our approach can pave the road towards to deeper insights into the internal dynamics of the building sector in regard to its climate relevance.

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