Simulating energy demand and emissions of the residential building stock in Germany by taking occupant characteristics into account

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Summary

A dynamic simulation model of the German residential building stock has been developed. It allows assessing eco-political instruments to reduce final energy demand in buildings and to quantify the corresponding emissions of CO_2, NO_x, SO_2, CH_4, NMVOC, and particulate matter (PM). The model simulates the implementation of energy efficiency measures and heating systems based on renewable energy. Socio-economic attributes of building owners and occupants, such as household income, age structure and household size, are accounted for in the investment behaviour of building owners. Results show that the effects of regulatory instruments alone are limited. Ecological awareness-raising and information strategies targeting profit maker behaviour look promising for substantial reductions of final energy demand in the residential building sector. Assuming constant prospective energy prices, when a refurbishment takes place, the economic potential of final energy demand reduction of refurbishment is limited to a 32% reduction from 2007 to 2030. Decreasing non-renewable energy demand by increasing biomass combustion may result in a strong increase in PM emissions. Future work aims at improving the quality and availability of data concerning the investment behaviour of households as well as analysing the social impacts of energetic modernisation activity regarding residential buildings.

Keywords: Residential buildings, energy efficiency, simulation model

1. Introduction

Due to their importance with respect to final energy and raw material demand, but also air pollutant and greenhouse gas (GHG) emissions, as well as land use, residential buildings play an important role in environmental terms and are therefore in the focus of political decision makers. A plethora of models want to quantify and forecast the energy consumption in the residential sector on a regional or national level. Kavgic et al. [1] and Swan et al. [2] classify the underlying approaches into top-down (econometric, technological) and bottom-up (statistical, building physics based, hybrid).

In an aggregated model for UK for 2000 and 2050, Lowe [3] highlights the carbon intensity of electricity supply as determinant for the decarbonization potential of electrical heat pumps and CHP. He concludes that large CO_2-emissions reductions can be achieved without high demolition rates. Sartori et al. [4] perform a dynamic material flow analysis of the Norwegian building stock from 1900 till 2100. The long-term evolution of demolition, construction and renovation activities is analysed. The methodology can be transferred to the analysis of energy flows. Aydinalp et al. [5, 6] use neural networks in order to predict the energy consumption of residential buildings in Canada.

They distinguish energy demand for appliances, lighting and space-cooling [5] as well as for space and for domestic hot-water heating [6].

Bottom-up models require numerous assumptions to fill in lacking data and generalize small data samples. Swan et al. [2] explain the lack of data for the residential sector in comparison to other sectors by the uniqueness of buildings, privacy issues, the high influence of occupant behaviour, and high costs of “sub-metering”. Typical data sources encompass surveys, individual billing data, “sub-metering”, and estimated total sector energy. Top-down models use typically aggregated data as macroeconomic indicators, number of dwellings incl. construction and demolition rates, climatic conditions, and diffusion of appliances. Thus, a strength and a drawback of these models is the good availability of and reliance on historical aggregated data. Typical data of bottom-up models encompass dwelling and climate properties, indoor temperatures and occupancy schedules [2]. The majority of bottom-up models focus on technical potentials of energy efficiency measures [4], whereas some address also techno-economic potentials [7]. Whilst most models assume general implementation rates of predefined energy efficiency measures [8], Sopha et al. [9] account for the real investment behaviour of building owners at a national scale because of its importance regarding the effects of eco-political instruments. However, the work is limited to heating systems. Wittmann [10] analyses the energy investment decisions of building owners regarding building envelope insulation and the replacement of heating systems for a prototype city.

Especially with a view to energy efficiency measures and heating systems based on renewable energy at a national scale, the investment behaviour and the socio-economic characteristics of building owners and occupants have to a large extent been neglected by modellers so far.

Therefore, in this paper, a dynamic simulation model of the German residential building stock has been developed in order to simulate the implementation rates of energy efficiency measures and heating systems based on renewable energy. Thus, effects of eco-political instruments concerning final energy demand and the corresponding emissions of CO_2, NO_x, SO_2, CH_4, NMVOC, and PM can be quantified. The model is mainly driven by the investment decision of building owners. Special emphasis has been put on the refurbishment of existing buildings because of their importance for emissions. The residential building stock model is described in chapter 2. Underlying data is presented in chapter 3. Selected results are discussed in chapter 4. Finally, limitations and results are discussed and an outlook is given.

2. Methodology

2.1 Stock and dynamics of building floor area

Building stock: Scope of the bottom-up model is to simulate the energy demand for space heating and domestic hot water preparation in the German residential building stock. In order to account for significant characteristics influencing energy demand, air pollutant and GHG emissions, as well as refurbishment behaviour, the living space $A_{t,BT,CP,EEC,QHS,ECRH,CHS,FS,CS,OS}$ of year t is differentiated by building type (BT), construction period (CP), energetic envelope class (EEC), quality of the heating system (QHS), energy carrier for room heating (ECRH), centrality of the heating system (CHS), German federal state (FS), community size (CS), and ownership structure (OS).

New construction: The exogenous annual construction rate $CR_{t,BT}$ is differentiated by year t and building type. The construction rate is broken down into the level of detail provided by the living space, i.e. $CR_{t,BT,CP,EEC,QHS,ECRH,CHS,FS,CS,OS}$ using data of the last construction period of $A_{t,BT,CP,EEC,QHS,ECRH,CHS,FS,CS,OS}$ and assumptions concerning the changes in energy carriers. The energetic envelope class and the quality of the heating system are defined by the German national minimum requirements.

Demolition: The exogenous annual demolition rate $DR_{BT,FS}$ is differentiated by building type and German federal state. Some building groups (historic buildings, new buildings and recently refurbished buildings) are excluded from demolition by assumption. The demolition rates of the remaining building stock are increased in equal measure in order to match $DR_{BT,FS}$. Thus, analogously to the new construction rates, the demolition rates are broken down to the level of detail provided by the living space, i.e. $DR_{BT,CP,EEC,QHS,ECRH,CHS,FS,CS,OS}$.

Refurbishment: The annual refurbishment-related input rate $RI_{t,BT,CP,EEC,QHS,ECRH,CHS,FS,CS,OS}$ and output rate $ROR_{t,BT,CP,EEC,QHS,ECRH,CHS,FS,CS,OS}$ are differentiated in correspondence to the living space. These rates are determined based on data concerning building physics, the building envelope, the heating system, and the building occupants. Data concerning building physics $BP_{BT,CP}$ (excluding the energetic properties of the building envelope), e.g. areas of building components, building floor areas etc., is differentiated by building type and construction period. Data concerning the building envelope $BE_{BT,CP,EEC}$, i.e. heat transfer coefficients and investments for insulations etc., is differentiated by the energetic envelope class in addition. Data concerning the heating system $HS_{BT,QHS,ECRH,CHS}$, e.g. annual efficiency, emission factors etc., is differentiated by building type, quality of the heating system, energy carrier for room heating, and centrality of the heating system. Data concerning the building occupants $BO_{BT,CP,FS,OS}$ is differentiated by building type and construction period, German federal state and ownership structure.

Thus, the living space in year t+1 can be determined based on stock and flows of living space in t according to equation (1).

$$(A_{t+1} = A_t + CR_t - DR + RIR_t - ROR_t)_{BT,CP,EEC,QHS,ECRH,CHS,FS,CS,OS} \tag{1}$$

2.2 Energy demand as well as air pollutant and GHG emissions of buildings

Space heating demand: The useful energy demand of each building group is estimated by an energy balance accounting for heat losses by transmission and ventilation as well as heat gains by solar radiation and internal heat sources [11]. The calculation is based on data concerning building physics, the building envelope, and the climatic conditions as well as assumptions concerning the indoor temperature. For vacant buildings, an indoor temperature avoiding structural damages has been assumed.

Domestic hot water demand: The useful energy demand for each building is estimated as product of living space and a constant specific value [kWh/(m²yr)]. For vacant buildings, the demand was set to zero.

Final energy demand: The final energy demand is estimated based on the calculated useful energy demand and data concerning the heating system, i.e. annual efficiencies of the heating system including distribution losses.

Air pollutant and GHG emissions: The direct combustion-related emissions of CO_2, NO_x, SO_2, CH_4, NMVOC, and PM are estimated based on the final energy demand and data concerning the heating system, i.e. the corresponding emission factors.

2.3 Scenarios

A tuple of a storyline and a bundle of eco-political instruments is defined as a scenario. The model encompasses several uncertain parameters, e.g. indoor temperatures and refurbishment cycles. The complete set of one concrete realisation of each uncertain parameter is defined as a storyline. As eco-political instruments regulatory instruments, energy taxes, financial subsidies as well as information campaigns are considered. The former encompass minimum requirements concerning the energetic envelope class and the quality of the heating system. Minimum requirements regarding the energy efficiency of new constructions as well as refurbishments are accounted for. The energy taxes are considered by the prices of the different energy carriers. Financial subsidies are modeled as government grants for heating systems and building envelopes. Finally, the shares of “types of decision makers” (cf. chapter 2.4) can be changed by information campaigns or the like. Each instrument provides different levels of intensities. The intensity can be changed for each simulation period in order to account for gradual tightening of eco-political instruments. The whole instruments and corresponding intensities for every simulation period are defined as bundle of eco-political instruments.

2.4 Refurbishment decision

A refurbishment is determined by its date and the selected alternative. The latter is determined by the building envelope, i.e. type of window, wall insulation, roof insulation, as well as floor insulation, and the heating system, i.e. engine-power class, energy carrier, centrality, as well as the quality of the heating system.

Date of refurbishment: Potential dates of refurbishments are determined by refurbishment cycles. Starting from the year of construction, it is assumed, that for example the heating system is replaced every 20 years and the building envelope is refurbished every 40 years. “Potential” means that such measures are neither always accomplished nor always energetic measures. This matter of fact is accounted for by the choice of the refurbishment alternative, which is performed by decision makers.

Profitability of refurbishment alternatives: Based on socio-economic and demographic characteristics of owner-occupants and tenants, the decision makers are grouped to “types of decision makers”. For some “types” solely the profitability of a refurbishment alternative is decisive. In order to assess the profitability of a refurbishment alternative, the annuity for the supply with space heating and domestic hot water from the perspective of an owner-occupant is used. It is assumed, that decision makers use current energy prices in order to assess the profitability of a refurbishment alternative. The assumption of increasing energy prices tends to decide for thicker insulations and heating systems with lower energy costs. The latter can be achieved by higher annual efficiencies or by changing to less expensive energy carriers.

Practical relevance and legality of refurbishment alternatives: Independent on the regulatory framework and the profitability of an alternative, certain changes of the heating system are not observed in reality to a noteworthy degree in Germany, e.g. the change from fuel oil to coal. This could be partially explained by comfort issues. Therefore, only the changes shown in Figure 1 are allowed in the model. This is accounted for by constraining the refurbishment alternatives. Furthermore, the legality of refurbishment alternatives that is determined by the regulatory instruments is modeled by constraining the alternatives as well.

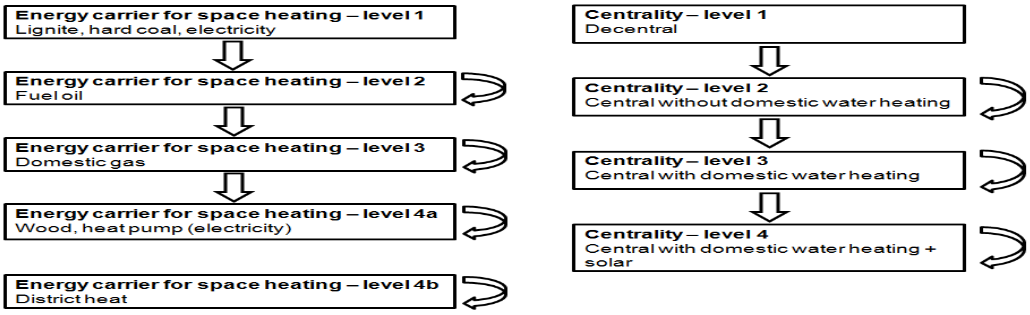

Figure 1: Allowed changes of energy carriers (left) and the centrality of the heating system (right)

Types of decision makers: The decision makers are distinguished into owner-occupants and landlords. These two groups are subdivided into five subgroups each. In the case of owner-occupants, types of decision makers, namely non-energetic renovator, law-abiding decision maker, profit maker requiring a high rate of return, profit maker requiring a low rate of return, and greenie, are distinguished. In the case of landlords, management strategies, namely demolition strategy, maintenance strategy, modernization strategy with high and low required rate of return, and eco-modernization strategy, are distinguished. Non-energetic renovators and landlords with demolition strategies do not invest in energy efficiency measures, as the regulatory policy-instruments concerning the building envelope and the heating system are by-passed legally or illegally, e.g. by patching. Law-abiding decision makers and landlords with maintenance strategy invest in building envelopes and heating systems corresponding to the national minimum requirements. Furthermore, they invest at least in level 2 concerning centrality and level 2 or 4b concerning the energy carrier (cf. Figure 1). They are sluggish and thus stay on their level, if no change is required by rules explained above. Profit makers and landlords with modernization strategy choose the alternative with optimum annuity. At least, the national minimum requirements have to be met. If only the heating system is replaced, the type greenie and landlords with eco-modernization strategy invest in the heating system with optimum annuity from a set of supposedly eco-friendly heating systems, i.e. level 4a and 4b with respect to the energy carrier and level 3 and 4 with respect to the centrality (cf. Figure 1). If, in addition, the building envelope is refurbished, the best insulation is chosen.

Transformation matrix: The share of types of decision makers and the management strategy is estimated by expert judgement based on socio-economic and demographic characteristics of owner-occupant or tenant in Germany. The characteristics considered encompass the age of the main-salary earner, the net household income, and the household size in the case of owner-occupants, as well as the rent without utilities, the net household income and utility costs in the case of rented dwellings. The characteristics are summarized in classes. With a given probability, a transformation matrix assigns every combination of classes to a type of decision maker and management strategy respectively. Uncertainties in the transformation matrix could be accounted for in scenarios.

Basic ideas concerning the transformation matrices are summarized in the following. Owner-occupants with low income are not able to invest into the building envelope or ambitious heating systems because of lacking financial resources. Medium income households generally have funds at their disposal for investments. However, as resources are, especially at increasing household size, still limited, required rates of return are high and the majority of the refurbishments performed correspond to the national minimum requirements. In high income households, the willingness and ability to invest in more environmentally friendly alternatives is supposedly higher. Overall, in the class with highest ages, the share of greenies decreases and the share of non-energetic renovators increases because of shorter planning horizons. As data concerning landlords is lacking, conclusions have to be drawn based on the characteristics of tenants. Compared to owner-occupants, eco-modernizations are accomplished less frequently. The household income coincides with the financial capacity of tenants to accept rent increases. Furthermore, such households are supposed to live in neighbourhoods, where refurbished dwellings can achieve adequate rents. Finally, high utility costs are supposed to increase the necessity and the acceptance of energy efficiency measures.

Even though the limited data availability causes high uncertainties in the proposed approach, it enables the integration of qualitative expert statements, i.e. about relations between different uncertain figures. At least aggregated implementation rates can be used in order to determine plausible transformation matrices that reflect the relations mentioned. Subsequently, different plausible transformation matrices can be analyzed in scenarios.

2.5 Spatial and temporal resolution

The spatial resolution corresponds to German federal states and community size. The results are simulated for every year and then broken down to community level by the combination with community data that is given for only one year [12]. This community data encompasses the German federal state, the community size and the share of residential buildings per building type as well as complementary data for every German community. Thus, the model output can be simulated directly at federal state for the different community sizes and indirectly for every single community.

3. Data

The differentiation of the indices concerning equation (1) is provided in Table 1. The main data sources are provided in Table 2. A schematic description of the seven scenarios regarded within this paper is provided in Table 3.

Table 1: Classes for the indices BT, CP, EEC, QHS, ECRH, CHS, FS, CS, CO; EnEV is the German Energy Savings Regulation

Index	Name	Regarded classes	Note
BT	Building type	Terrace house, single family detached house, multi-family house (MFH), MFH in New Laender, large MFH, large MFH in New Laender, high rise building, high rise building in New Laender	-
CP	Construction Period	<1919 (timber frame), <1919 (massive), 1919-1948, 1949-1957, 1958-1968, 1969-1978, 1979-1983, 1984-1994, 1995-2001, 2002-2006, >2006	Variations in dependence on BT
EEC	Energetic envelope class	<1968, 1968-1977, 1978-1981, 1982-1994, 1995-2001, 2002-2003, 2004-2006, 2007-2008 (EnEV07), EnEV09, EnEV09-30%, EnEV-50%	Variations in dependence on BT and CP
QHS	Quality of the heating system	Existing (average), low temperature boiler and the like, condensing boiler and the like	-
ECRH	Energy carrier for room heating	Fuel oil, domestic gas, solid biomass, lignite, hard coal, district heat and electricity	-
CHS	Centrality of the heating system	Decentral, central without domestic hot water (DHW), central with DHW, central with DHW and solar thermal	-
FS	Federal state	16 states of Germany	-
CS	Community size	<5,000 [inhabitants], 5,000-19,999, 20,000-99,999, 100,000-499,999, >=500,000	Variations in dependence on FS
OS	Ownership structure	Building/dwelling owner, principal tenant	-

Table 2: Main data sources concerning building envelope, heating system, building occupants

Category of data	Main data sources
Building physics $BP_{BT,CP}$	[13]
Building envelope $BE_{BT, CP, EEC}$	[13], [14]
Heating system $HS_{BT, QHS, ECRH, CHS}$	[15], [16], [17]
Building occupants $BO_{BT, CP}$	[18]
Other data	[8], [11], [12], [17], [19], [20]

Table 3: Description of the scenarios; other eco-political instruments (energy taxes, subsidies) and storyline parameters are maintained; minimum requirements describe the year of intensification to +/++/+++/++++

Scenario name	Bundle of eco-political instruments			Storyline
	Minimum requirements		Transformation matrix (information campaigns etc.)	Technical lifetime of heating system and building envelope [years]
	Envelope (+/++/+++/++++)	Heating system (+/++)		
Base	(20)07(+), 09(++)	(20)07(+)	Perpetuation	20/40
Strict law	07(+), 09(++++)	07(+), 09(++)	Perpetuation	
Gradual law	07(+), 09(++), 12(+++), 18(++++)	07(+), 18(++)	Perpetuation	
Greenie	07(+), 09(++)	07(+)	Only greenies	
Law-abiding			Only profit makers (low interest rate)	
Profit maker			Only law-abiding decision makers	
Quick greenie			Only greenies	15/30

4. Selected Results

The final energy demand reduction from 2007 to 2030 varies between 16% in the scenario “Base” and 51% in the scenario “Quick greenie” (cf. Figure 2). The scenarios “Gradual law” and “Strict law” show that a sole sharpening of the energetic minimum requirements results in a 24% reduction only, as most building owners do not refurbish. In the scenario “Law-abiding” the effect of enforcing the minimum requirements leads to a 27% reduction. The “Profit maker” scenario shows that the economical potential is about 32% and thus remarkably higher. The extreme scenario “Greenie” appears less economic than the scenario “Profit maker” but causes a 39% reduction. The shortening of the refurbishment cycles enables an additional reduction of 12% which is only caused by an increased refurbishment of building envelopes as all heating systems are replaced already in the “Greenie” scenario.

Overall, the results show that environmental awareness-raising and information campaigns targeting profit maker behaviour seem more promising than regulatory instruments alone in order to achieve a substantial reduction of the final energy demand. A combination of “Strict law” and “Law-abiding” scenarios should cause promising effects as well. Furthermore, if decision makers in the “Profit maker” scenario expect increasing energy prices, reductions in final energy demand are expectedly higher.

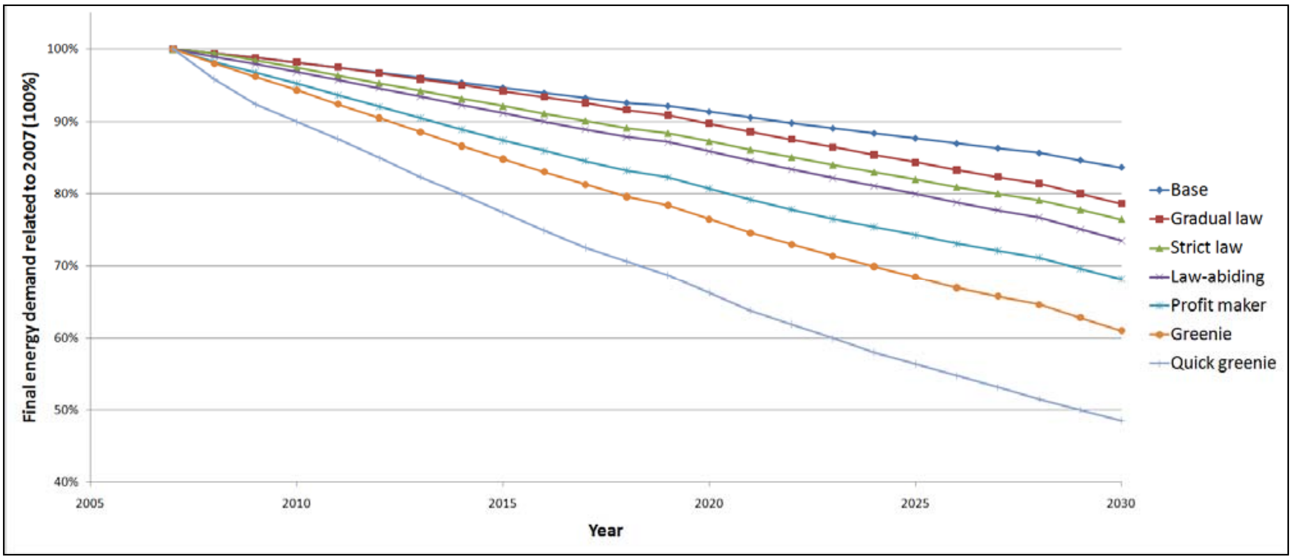

Figure 2: Simulated final energy demand for space heating and hot water preparation in German residential building stock between 2007 and 2030 in the different scenarios

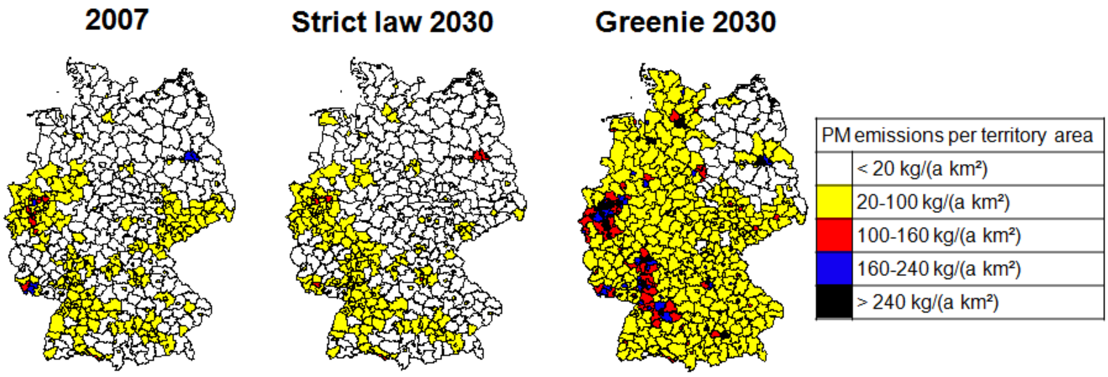

Figure 3: Evolution of the PM emissions per territory area between 2007 and 2030 in the scenarios “Strict law” and “Greenie”

In 2007, PM emissions per territory area are higher in the German federal states Saarland, North Rhine-Westphalia and Berlin (cf. Figure 3). This can be partially explained by the population density and the share of lignite and hard coal in final energy demand for space heating and domestic hot water preparation in the order of 1% to 6%. In the scenario “Strict law”, PM emissions decrease until 2030 about 3%. In the scenario “Greenie”, an increase of 135% is forecasted. Whereas the substitution of lignite and hard coal leads to a reduction of PM emissions, this effect is overcompensated by a drastic increase of biomass combustion in the “Greenie” scenario. In some areas, PM emissions quintuple in the model, but the model accounts only for about 60% of the PM emissions [21] from residential buildings as secondary biomass heating devices are not considered. However, as stationary plants of residential buildings emit about 11% of PM emissions in Germany [21], a potential local aggravation by excessive biomass combustion could be expected.

5. Discussion

5.1 Limitations

The set-up of bottom-up models requires numerous assumptions (cf. chapter 1). Especially the relatively high spatial resolution and the assumptions concerning the building owner behaviour might induce strong uncertainties. The amendment to the First Ordinance on the Implementation of the Federal Immission Control Act (1. BImSchV) of 2010, which is not yet implemented in the model, will considerably reduce the simulated drastic increase in PM emissions from the residential building sector. This ordinance sets not only very strict emission factors for biomass heating systems but enforces these also via stringent controls. Additionally, secondary heating devices that are not yet included in the model are of high importance regarding PM emissions as well. Furthermore, in the scenario “Greenie”, highest PM emissions per territory area occur in areas with high population density. As the availability of biomass is lower than in rural areas, it is not clear whether the simulated high shares of biomass as an energy carrier are possible.

5.2 Conclusions and outlook

The model results show that under the assumptions made the effects of regulatory instruments alone are limited. Ecological awareness-raising and information strategies targeting profit maker behaviour look promising for substantial reductions of final energy demand in the building sector. Assuming constant prospective energy prices, when a refurbishment takes place, the economic potential of final energy demand reduction is limited to 32% in the period 2007 to 2030. Finally, the results highlight that cross-media effects might occur, e.g. reductions in non-renewable final energy demand and thus GHG emissions due to increased biomass combustion may result in a drastic increase of PM emissions.

Overall, this model serves as a basis to identify bottlenecks on the way to sustainable energy-efficient future in the residential buildings sector by accounting for barriers, such as by-passing the Energy Savings Regulation or financial burdens of low income households. Future work aims at improving the quality and availability of data concerning the energy-investment behaviour of households as well as analysing the social impacts of energetic modernisation activity regarding residential buildings.

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