Integrating residential energy efficiency measures into optimizing urban energy system models

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Abstract
Due to the complexity and importance of energy-political decisions, optimization models, which are able to capture the many interactions between different energy carriers and technologies, have become common tools for decision support.

Especially for regional energy systems, i.e. for the scope of single municipalities, demand side residential efficiency measures, like domestic retrofitting or the installation of efficient lighting and white goods, are vital tools for reducing and shaping the future energy demand.

These measures, however, are commonly not integrated well in optimization models – or not at all. This paper proposes a new method for the integration of residential efficiency measures in optimizing urban energy system models, which seeks to remedy with these issues. Efficiency measures are modelled as technologies which are able to convert energy between carriers with given conversion rates, e.g. in the case of LEDs from electricity to luminous energy and heat. In order to achieve this, demand is fed into the model as an energy services demand. This allows the model to choose from a range of available technologies which are able to satisfy this demand.

The model results for a German municipality show that the techno-economic incentives for investing in more efficient demand- and supply-side technologies are not sufficient: while a slow shift to more efficient building insulations and appliances can be observed, it is not enough in order to reach the German government's greenhouse gas reduction plans. If these plans are enforced in the model, however, more efficient technologies are employed on the supply side as well as on the demand side. These findings can be used by policymakers in the form of local energy efficiency roadmaps, which are tailored to the specific setting of municipalities.

Introduction

MOTIVATION
In Germany as well as in other European countries, the residential sector accounts for a large share of energy use and thus also a large share of energy-related greenhouse gas emissions. More specifically, about 35 % of the total German end energy demand is caused by the provision of space heating and warm water (BMWi 2014).

The German government is aware of the importance of the heat and building sector and has thus declared the objectives of a reduction of the heat demand in buildings by 20 % until 2020 as well as a reduction of the building sector primary energy demand of 80 % until 2050 (Nitsch et al. 2012, p. 46).

These ambitious objectives can only be reached by a massive increase of energy efficiency in these sectors. The potential savings of energy efficiency measures such as energy-efficient retrofitting measures for buildings and more efficient lighting and household appliance technologies are reported to be substantial.

These demand-side measures, however, also have to be accompanied by the right choice of supply-side measures. All energy related technologies in the scope of buildings and entire cities together form a complex energy system with various interdependencies and dynamic effects. In order to correctly analyse this system and to evaluate the effect of demand- and supply-side measures, a model which correctly captures all these relations is required.

COMMON APPROACHES TO URBAN ENERGY SYSTEMS MODELLING

A lot of studies can be found which focus on evaluating a single heat supply technology. These studies can provide detailed technological assessments but by neglecting interdependencies with other technologies they might miss some of the dynamic effects which occur in complex energy systems.

A large number of models for energy system analysis have been developed to date, most of them focusing on a national level (Jebaraj, Iniyan 2006). These are useful for determining optimal investments in large scale (>100 MW) power plants, but tend to simplify the demand side as well as decentralized energy conversion technologies.

Due to the fact that the most important (measured by total energy use as well as savings potential) end energy carrier heat cannot be transported efficiently over large distances, most of it is usually provided decentralized by local heat generators. National models which explicitly capture the demand side (e.g. Johnston et al. 2005, Merkel et al. 2014) lack the spatial resolution which is required to consider local renewable energy potentials. For these reasons, it seems worthwhile to analyse the spatial structure of local energy systems in more detail.

There are fewer models which focus on the investigation of regional energy systems and specifically on the provision of heat supply (Keirstead et al. 2012). However, most of these models focus on modelling the supply-side and neglect demand side measures. Building retrofit measures have been explicitly considered in (Jennings et al. 2014), but in this study, the geographical structure was simplified and only one generic residence type was modelled per spatial node (district).

OBJECTIVES AND OVERVIEW

It is therefore the objective of this study to present a new optimising energy system model that deals with these issues by explicitly considering the residential sectors' electricity and heat demands with a focus on the correct representation of different energy efficiency measures.

The next chapter presents the methodology of this model in detail, while the following chapter describes which data was fed into the model for this case study and how this data was put together. The subsequent chapter presents some of the results while the last chapter provides a conclusion and outlook.

Methodology

In order to determine the optimal investments in energy conversion technologies and energy efficiency measures, a model in the class of energy and material flow tools with detailed techno-economical technology properties has been developed. In the following sections, the model structure as well as the chosen geographical and temporal structure is discussed.

MODEL STRUCTURE

The energy system of an entire city is modelled as a linear optimization problem. The key driver of the model is residential energy service demand, which has to be satisfied by importing, converting and transporting energy carriers. In order to satisfy the demands, the model can decide to employ technologies, which are able to convert energy carriers with distinct conversion rates. This has to be done in a way that fulfils all constraints and minimizes the total system cost. As a result, all required investments and the optimal dispatch planning for all employed energy conversion technologies are computed.

The objective function states that the overall decision-relevant system expenditures, discounted to the base year 2015, must be minimized. It comprises a macroeconomic perspective, which means that taxes, subsidies etc. are not considered. The cost function is composed of several cost factors:

- *Import flow costs* are associated with the import and export of energy carriers. These flows are valued by wholesale market prices.
- *Transmission grid costs* represent the costs that arise from using the national transmission grid for these imports and exports.
- *Intermediary flow costs* arise from the utilization of the local transport grids.
- *Investment annuities* for installed units represent the share of investment costs that are allocated to each year the technology is in use.
- *Fixed* and *variable costs* arise from the ownership and utilization of technologies.
- *Emission costs* are caused by applying a CO_2-emission penalty on the utilization of technologies.

Several constraints provide technological as well as economical bounds to the problem. The most important constraints are:

- *Energy balance* constraints specify that energy has to be balanced at all times and at all locations in the model. This means that all energy demands have to be satisfied, i.e. all of the energy that is used, has to be either produced locally or imported. On the other hand, no excess energy is allowed, e.g. if electricity is produced by PV modules, it either has to be used up regionally or exported. The energy carrier "waste heat" is an exception from this constraint and can be produced in excess. It should be noted, that demand side management and local energy storage is not considered in this model.
- It is possible to formulate *flow restrictions* for the model, e.g. the flow between districts can be restricted (in order to represent transportation bottlenecks) or completely forbidden (if districts are not connected). It is also possible to restrict the flow from district to building level or vice versa.
- The amount of available land, which is essential for some technologies such as PV modules, is given explicitly to the model and its use is therefore restricted by *land use constraints*. For example, there is only a given number of m² of south-facing roof areas in each district. If these areas are covered already, the model can either choose to use west-facing areas instead (at the cost of lower yields, but also with a different generation profile) or use other technologies instead.
- It is also possible to formulate *emission restrictions* to constrain the amount of CO_2 as well as PM10 that is emitted

through the city's energy system during each year. For PM10, it is even possible to formulate explicit constraints for single districts. It should be mentioned here that the transport sector, which is the origin for a large share of emissions, is not considered in this study.

GEOGRAPHICAL STRUCTURE

The model uses two logical layers of resolution, district and building level. This means that the equations and constraints of the model, e.g. the energy balance equations, apply to both layers. Technologies can be installed either on district or on building level. This way, large scale (e.g. biomass plants) as well as small scale (e.g. gas boilers) technologies can be correctly represented and positioned in the model.

The boundaries of the model are equal to the administrative boundaries of the assessed city, which means that not only the densely populated city centre is included, but also the surrounding forest and farmland areas that are within the city's bounds.

The whole city area is further divided in districts. Districts are assumed to be connected (which means that resource transport is allowed between them) if they are adjacent to each other. Additionally to the city districts, a number of exogenous districts are modelled in order to represent a connection to the national transmission grid for electricity as well as transport capacities for other resources (e.g. gas).

In order to represent a finer level of granularity, which is especially important for decentral small scale technologies, the building level is also modelled for each district. As it is not possible to explicitly model each single building in a city (due to drastically increasing complexity and calculation durations), a sample of buildings is randomly drawn. In this case study, the sample size is n=100 buildings, which is a good trade-off between detail and calculation times, but this number is flexible.

The samples are drawn in a way that ensures the representativeness of the sample for the whole building stock of the city. E.g., if 50 % of the buildings in a city are medium-sized buildings, built in the age class 1984–1994, it follows that 50 buildings in the sample are in the same size and age class.

TEMPORAL STRUCTURE

The model analyses the regional energy system between the model years 2015 to 2050. A multi-periodic approach is employed, which models every 5th year in this time period explicitly. The time structure is built in a way to represent "typical" days and consists of a set of 72 different time slices per year: 4 seasons (spring, summer, fall, winter), 2 day types (working day, weekend) and 9 continuous blocks of 5 hours (during the night) and 2 hours length each. This fragmentation was done in order to preserve as much of the variation of the demand as well as the supply structure (from e.g. PV modules) while also keeping the number of time slices (and therefore the calculation complexity) to a manageable amount.

REPRESENTATION OF ENERGY EFFICIENCY MEASURES

Demand side energy efficiency measures are a special focus of this energy system model. They are modelled in the same way as supply side technologies, which means that each technology is characterized by the conversion rate for all energy carriers. The efficiency measures that are currently available in the model are more efficient household appliances (characterized by their energy efficiency class), as well as more efficient lighting technologies (LEDs and CFL in contrast to incandescent and halogen light bulbs which are the prevailing technologies in the European stock) and, most importantly, energy efficiency retrofit measures for residential buildings, which are used in the following sections to illustrate the use of efficiency measures in the model.

Several energy carriers are modelled, of which only few are characterized as energy services. For this example, we consider the energy carriers *heat* (which can be understood as the product of the heating system), *waste heat* (which is a by-product of all processes which are not 100 % efficient) and *room comfort*, of which only room comfort is an energy service (cf. Figure 1). This means that demand, which is the driving force behind all model decisions, exists only for room comfort. In order to generate room comfort, at first the model needs to generate heat, e.g. by employing a gas boiler to convert gas into heat and waste heat. The rate at which heat and waste heat are generated is determined by the techno-economic characteristics of the technology. A more efficient technology (e.g. a gas condensing boiler) might be able to generate more useful heat with the same given amount of gas.

Next, the generated heat has to be converted to room comfort. This can be achieved by using insulation technologies. In this example, the technology *KFW55 insulation* converts heat to room comfort and, again, waste heat. Again, more efficient insulation technologies are able to generate a larger amount of useful room comfort from the same amount of heat and are thus able to ultimately save gas.

This method also provides the advantage that the demand for room comfort can be calculated independent from the building envelope. The demand for room comfort is only dependent on the living area and the outside temperature.

Another example illustrating this logic can be seen in Figure 2: in order to generate the energy carrier *light*, the model employs the *Halogen light* technology, which produces *heat* as a by-product. But as this heat is produced inside the building, it is not lost as waste heat, but can instead be used to replace a (however small) amount of heat that otherwise the heating system would have to provide.

Data for the case study

The aggregation and pre-processing of the required input data for energy system models is a very challenging task which cannot be described in detail here. However, this chapter intends to shortly describe which data was employed for the case study.

This case study analyses the energy system of Landau, a small German town with about 43,000 inhabitants. The town constitutes an area of about 83 km² and consists of 9 districts. The geographical extent of the city's boundaries as well as the districts are imported from OpenStreetMap data and depicted in Figure 3.

BUILDINGS

The numbers and sizes of buildings in each of Landau's districts have been analysed using OpenStreetMap data, this data was further combined with information on the distribution of building ages and types in the German building stock (Statistisches Bundesamt 2010).

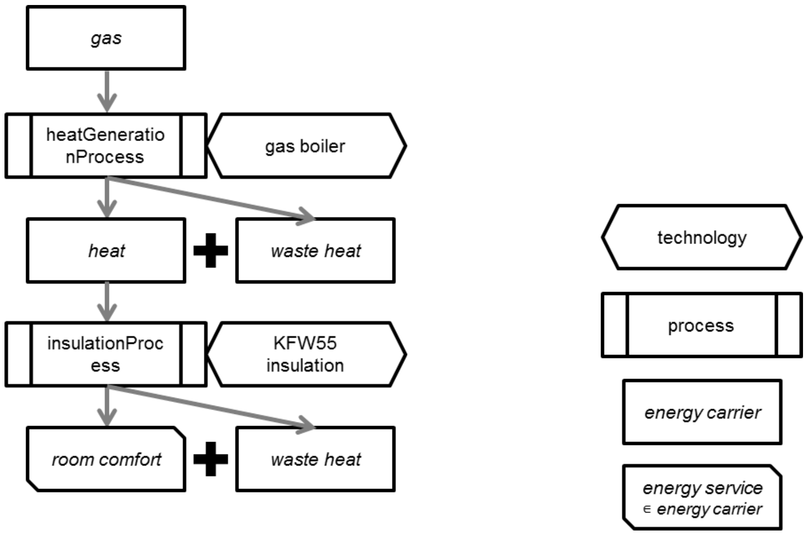

Figure 1. Energy flow example for the conversion of gas to room comfort.

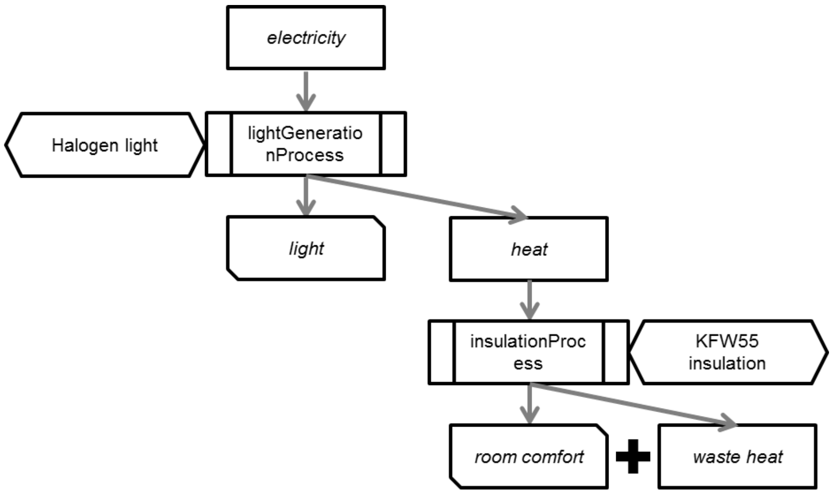

Figure 2. Energy flow example for the conversion of electricity to light.

Figure 3. Landau's administrative boundaries and the city districts, as well as available farmland, meadows and buildings (own depiction based on OpenStreetMap data).

Based on the resulting distribution of building ages, sizes and types, a representative sample of 100 buildings from the city's building stock has been drawn. Each building in this sample is attached with a scale factor, which indicates the number of actual buildings that are represented by this building.

For each building in this sample, it was determined which technologies are already in stock and also in which year they have been installed (which determines when the technology reaches the end of its technical lifetime). This was done by analysing data on the frequency distributions of the actual share of insulation, heating, lighting and appliance technologies in stock (Statistisches Bundesamt 2010), (Noster Juni 2013).

AVAILABLE ROOF AREAS

In order to assess the potential for electricity generation by photovoltaics, the available roof areas have been calculated based on building footprints which were retrieved from OpenStreetMap. The exact building orientation given by this data also allowed for the calculation of each building's, and thus, each roof area's orientation angle. The roof inclination was estimated as having a normal distribution around an average of 40.5 degrees with a standard deviation of 5 degrees.

In total, there are 1.8 km² of usable roof areas available, of which about 9 % are already occupied by PV modules. The largest potential of 980,000 m² remains in the city's largest district, Landau-Kernstadt, where only 7 % of the potential is already exploited. The mean specific yield of PV modules in stock in Landau is at 838 kWh/kW_p (numbers and yields from PV modules in stock have been taken from DGS 2012).

These potential calculations allow the model to exactly match each area's possible electricity production profile to the regional demand. This way, the model is able to balance electricity production and demand (at least partly) by combining differently oriented PV modules' electricity production profiles.

DEMAND

The demand for energy services is the key driver of all model decisions. As the models finest geographical detail is a single building, the associated demand curves had to be provided on building level as well. For data protection and privacy reasons, it is impossible to get measured data for all or even a large number of buildings in a town. On the other hand, very exact demand curves (especially for electricity demand) are required to correctly depict the fluctuations and peaks that occur in measured demand.

For these reasons, an activity-based electricity demand generation methodology, described in (Richardson et al. 2010), was employed for this case study. This was done by automatically generating and subsequently aggregating the demand curves for all apartments (if more than one) in each building that was modelled. This method ensures that e.g. the electricity demand curve for a single family building with 5 inhabitants has a lot more fluctuations than e.g. a multi-family building with 20 different apartments with several inhabitants each.

The heat demand for buildings was estimated using typical specific demands for each building type, heating degree days for assigning the resulting yearly demand to each day and an hourly distribution of heat use over a typical weekday and workday (Loga et al. 2012, IWU 2015).

TECHNOLOGIES

The model considers a total number of 47 technologies in the categories heating, lighting, appliances, insulation and decentral power generation. For each technology, the following techno-economical parameters are fed into the model:

- consumption and production levels for each energy carrier (and thus a measure for efficiency)
- emissions during operation
- investments
- fixed costs [€/a] and variable costs [€/kWh]
- technical lifetime.

Results

For the calculation of the results, two different scenarios have been considered:

1. **Reference scenario.** In this scenario, no restrictions other than the technical ones are imposed on the model. It can choose freely from the complete range of technologies in order to minimize the total system costs.
2. **Emission reduction scenario.** In this scenario, we impose the German government's emission reduction targets (Bundesregierung 2010) on the model. These targets constitute a reduction of greenhouse gas emissions of 40 % until 2020, 55 % until 2030, 70 % until 2040 and 80 % until 2050 (all relating to 1990 emission levels).

REFERENCE SCENARIO

In the reference scenario, we can observe that the model relies heavily on gas condensing boilers as well as heat pumps. Other types of heating technologies are replaced as soon as they reach the end of their technical lifetimes (cf. Figure 4). This strategy is caused by the rather low specific investments accompanied by low energy costs for gas.

It can also be observed that insulation of residential houses is being slowly improved by replacing old insulation types by newer (but not the most efficient) insulations over the model period (cf. Figure 5). However, this is only caused by building envelopes reaching the end of their technical lifetimes. There are not sufficient incentives for the model to actively renew building insulations that are still usable.

Similarly, we can see an improvement of electrical appliance technologies in stock (cf. Figure 6). The replacement of old efficiency classes by newer ones progresses faster in this case, which is caused by the shorter lifetimes of electrical appliances (when compared to heating or insulation technologies). It seems, though, that the price-performance-ratio of A+++ appliances is not attractive enough, since most of the employed appliances are still in the A++ efficiency class.

The results from the reference scenario indicate that there are no significant incentives for investments in renewable energies and energy efficiency measures: although a reduction of greenhouse gas emissions can be observed over the modelled time period, it is not sufficient to meet the German emission reduction targets (Bundesregierung 2010) (cf. Figure 7). This means that the financial incentives (caused by reduced energy demand

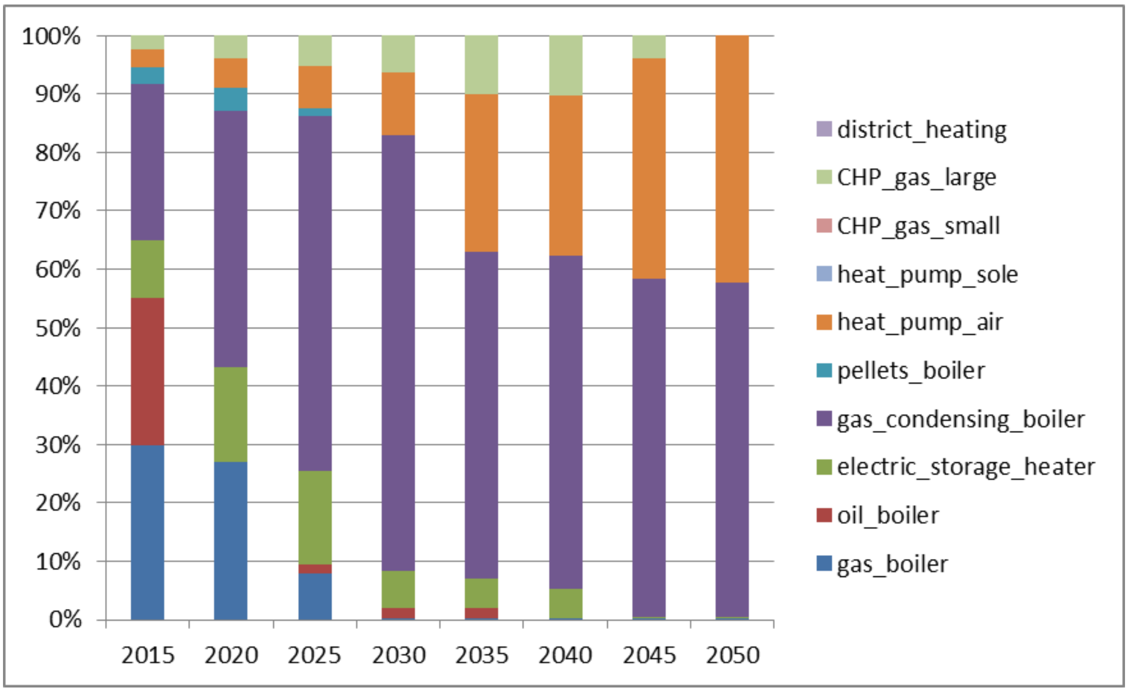

Figure 4. Development of the share of heating technologies in stock in the reference scenario.

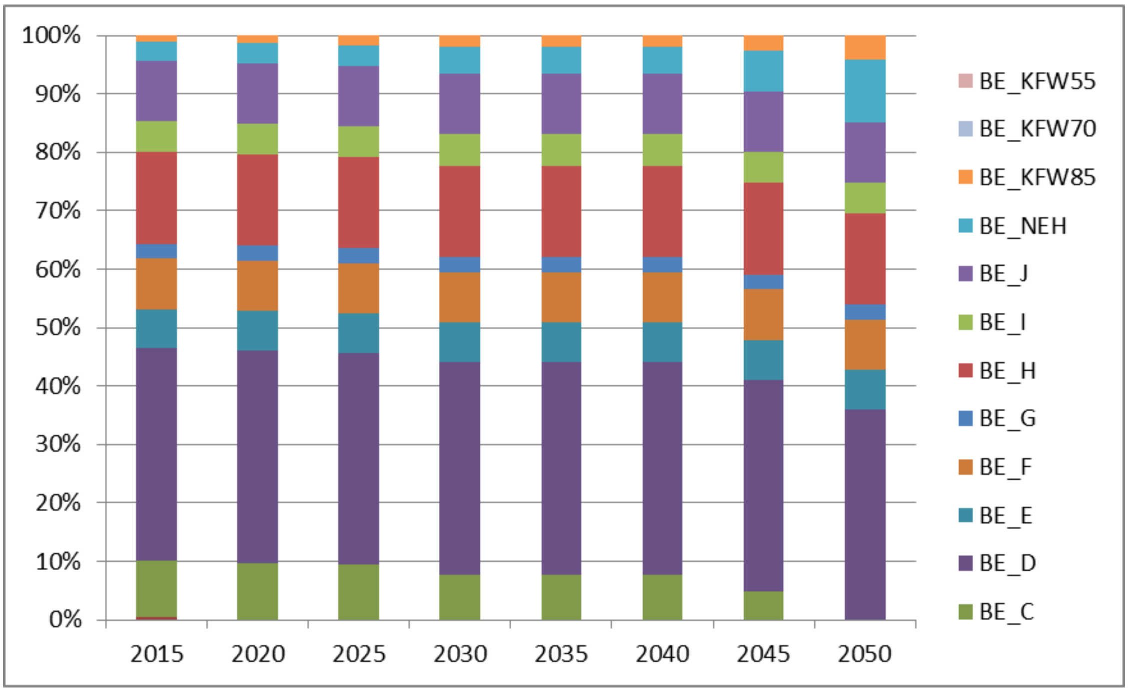

Figure 5. Development of the share of insulation technologies in stock in the reference scenario – the descriptors correspond to insulation standards for typical age classes and subsidization standards and are sorted from BE_C (least efficient) to BE_KFW55 (most efficient).

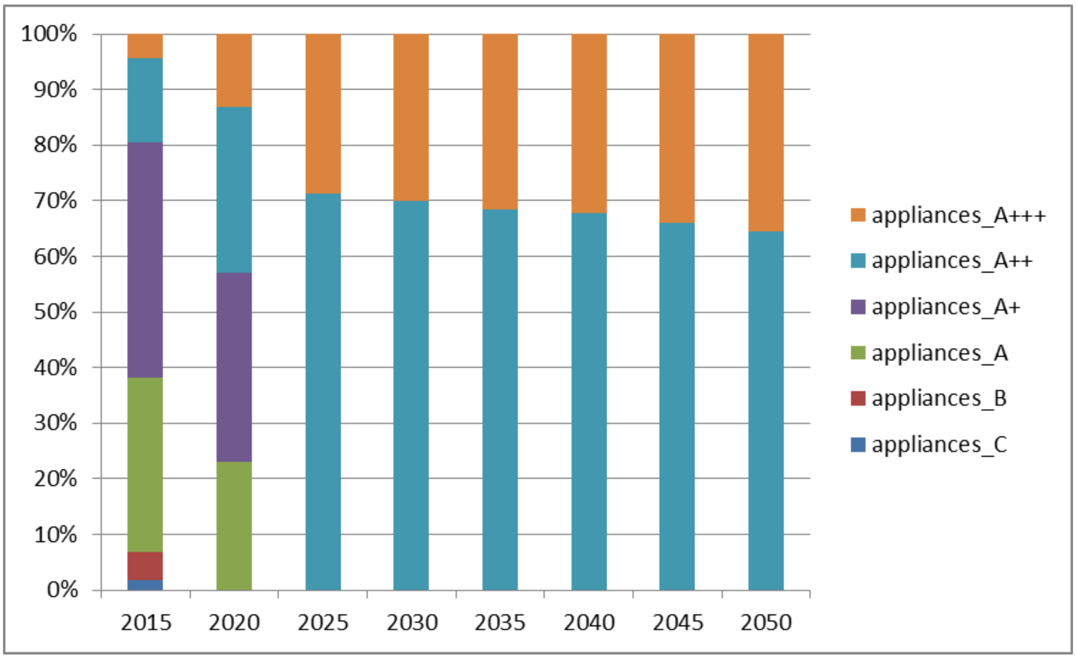

Figure 6. Development of the share of electric appliances technologies in stock in the reference scenario.

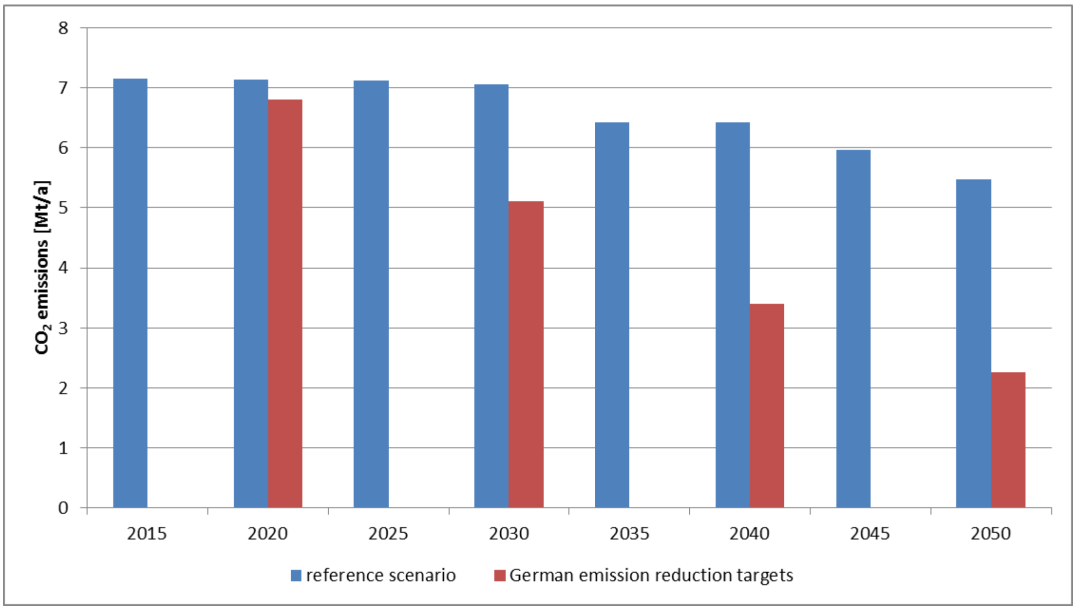

Figure 7. Observed pathway of CO_2-emissions in the reference scenario over the model period, compared to the German government's greenhouse gas reduction targets.

and emission costs) alone are not large enough to sufficiently encourage a shift to more efficient technologies and hence may need to be addressed by new or stricter policy measures.

EMISSION REDUCTION SCENARIO

If the German government's objectives on greenhouse gas emission reduction are imposed as additional constraints to the model[1], an obvious shift of investments to more efficient and less CO_2-intensive technologies takes place: It can be observed that, with increasing constraints on CO_2-emissions, the model reduces the number of gas condensing boilers and replaces them with more efficient heat pumps.

The same applies to building insulation: with stricter emission constraints, the shift to more efficient insulation technologies is accelerated and more efficient insulation types are being installed as a replacement for older insulations. In this scenario, the incentives for emission reduction are large enough so that the model actively replaces older insulation types even before they reach the end of their economical lifetimes.

1. Given the already achieved reduction from 1990–2015 for Germany as a whole, the remaining required reductions are calculated for each target year in relation to the 2015 baseline emissions from the (unrestricted) reference scenario.

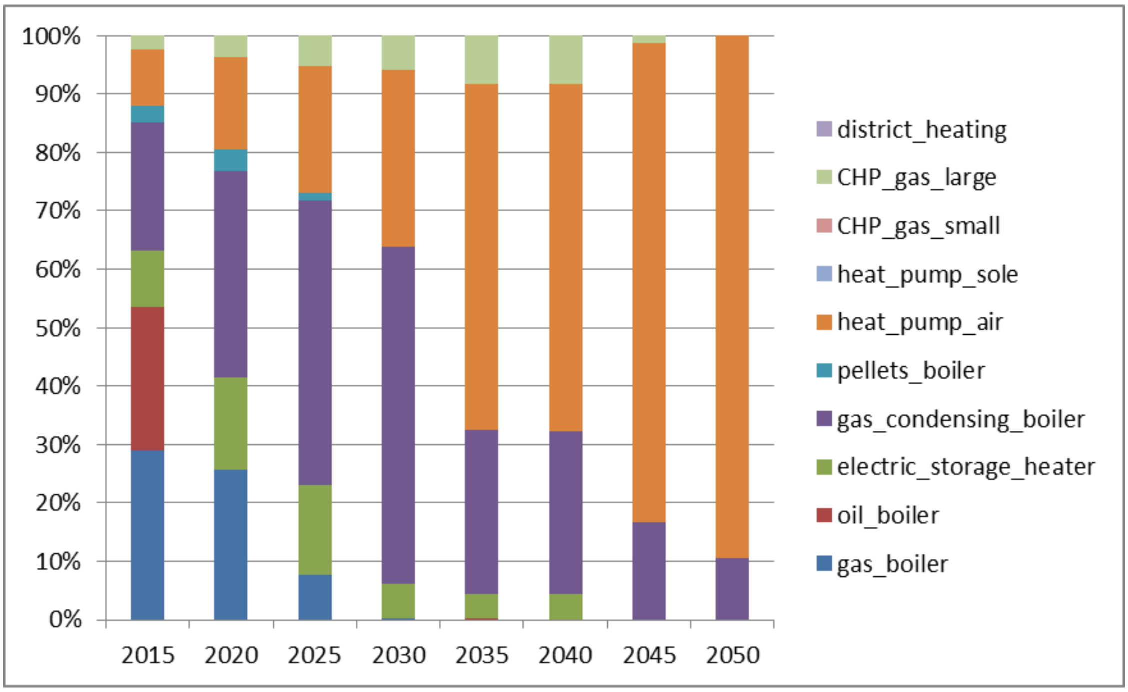

Figure 8. Development of the share of heating technologies in stock in the emission reduction scenario.

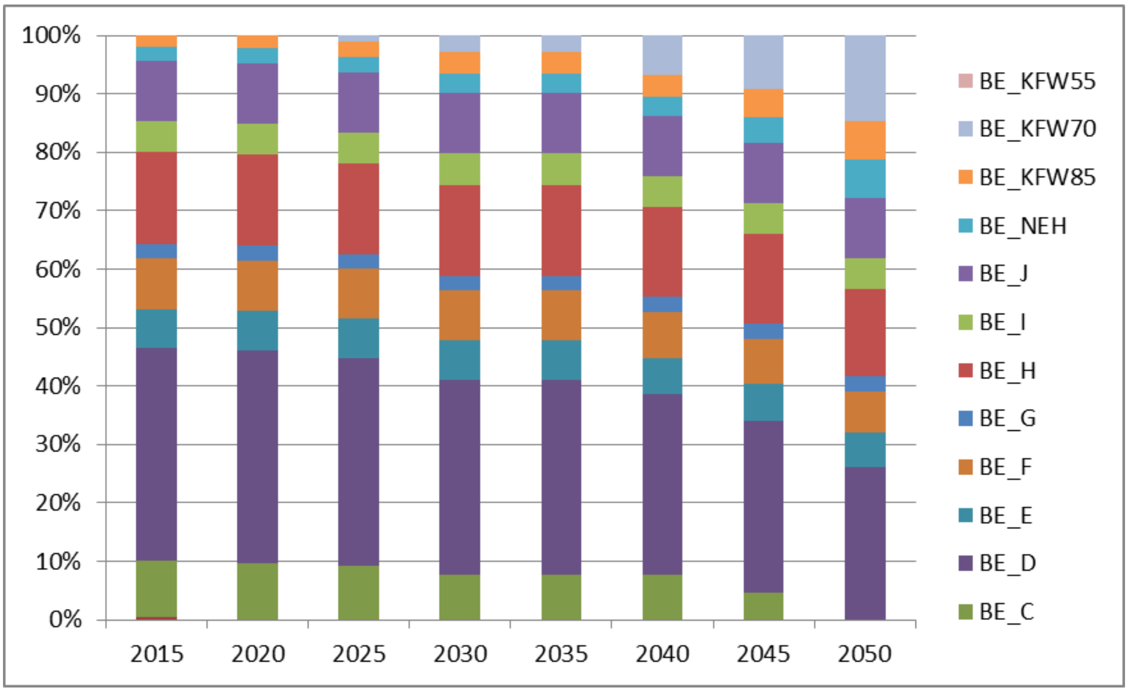

Figure 9. Development of the share of insulation technologies in stock in the emission reduction scenario.

We can also observe that in this scenario, the model relies also on more efficient household appliances, e.g. the share of the most efficient appliance class A+++ in 2050 is increased from 36 % in the reference scenario to 55 % in the emission reduction scenario.

The costs involved with the emission reduction scenario are obviously higher than they are without the additional CO_2-reduction constraints. The difference is not all that significant, however: the total discounted system cost in the emission reduction scenario is only 4.88 % larger than in the reference scenario. The investments in new technologies are substantially larger, but they are at least partly compensated by reduced costs for energy imports, transmission and emission costs, as a larger share of the energy demand is sourced from local renewable resources. Other positive effects such as reduced dependency on foreign fuels are not considered yet, but might also play a role in the decision-making processes.

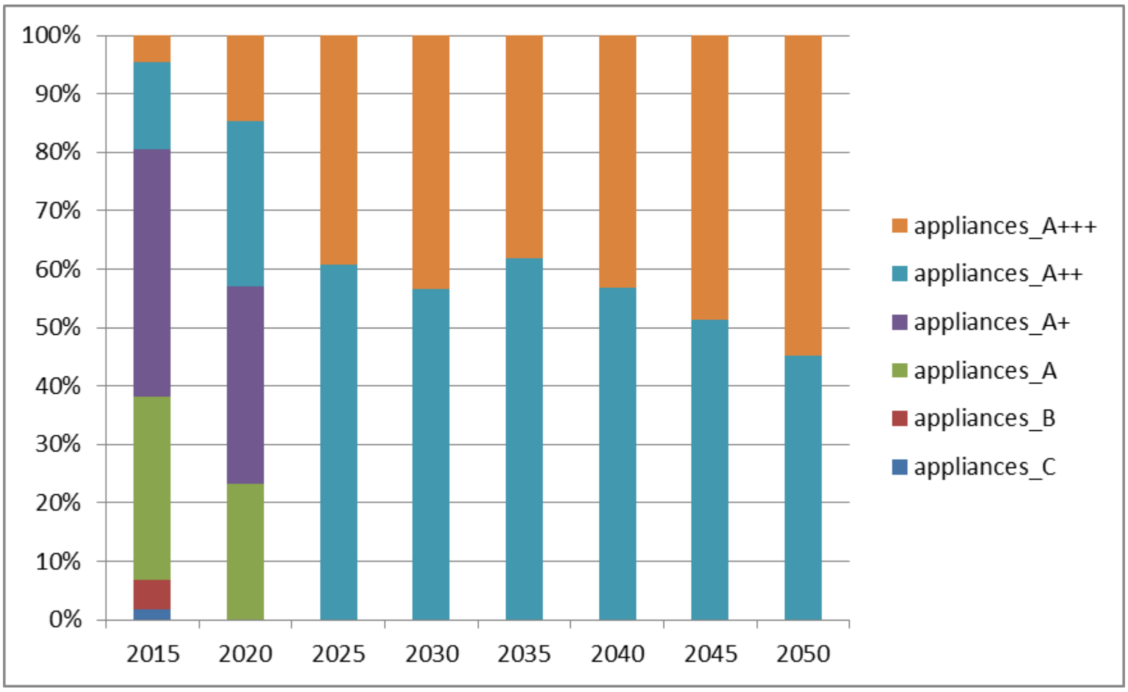

Figure 10. Development of the share of electric appliances technologies in stock in the emission reduction scenario.

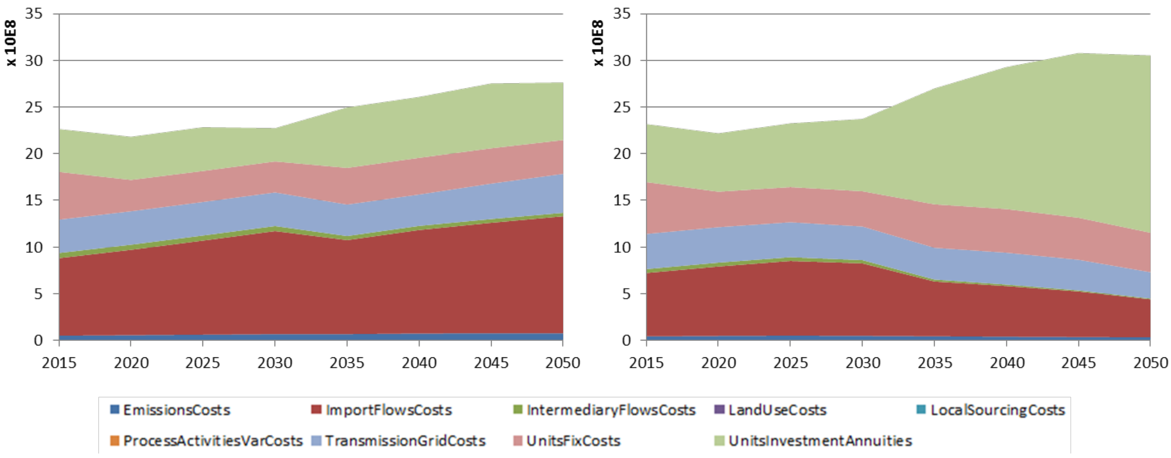

Figure 11. Development of the total system costs (not discounted) in the reference (left) and in the emission reduction (right) scenarios.

Conclusion and Outlook

In this study, a new model for the analysis of regional energy systems has been presented. It focuses on the electricity and heating sectors and on the correct representation of energy efficiency measures. In contrast to previous models, demand side efficiency measures are also represented in detail in this model.

The case study for the German city of Landau implies that a shift to more efficient technologies seems possible over the next decades. However, the techno-economic incentives seem to be insufficient to reach the German government's emission reduction targets.

In Germany, there regulations and subsidization schemes are already in place in order to encourage the use of renewable energies for heating (Bundesgesetz 2008) and to incentivize investments in efficient building insulation (KfW 2015). The model presented in this study could be used to help with the design of such policy measures in order to reach the targets in the most cost-efficient way.

In the further development of this model, besides the continuous improvement of the model data quality, more scenarios will be implemented which analyse the best ways of achieving the emission targets.

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