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Generic bottom-up building-energy models for developing regional energy transition scenarios

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***Abstract*—Energy demand from buildings has the largest single share of the global final energy demand, but offers massive energy saving potentials through state-of-the-art technologies and behavioural changes. However, the required speed of technology adoption and behavioural changes to achieve such savings are largely uncertain and embedded in complex socio-technical system. Successful examples of achieving such systemic transition in the energy system are mostly found on the regional scale. Therefore a transition from the existing conventional centralized and mainly fossil fuel-based energy infrastructure towards a decentralized and renewable-based energy infrastructure is required. This research presents a generic bottom-up building-energy model for developing regional energy scenarios. Besides the development of regional scenarios, this model allows for analysing various detailed aspects of buildings' energy demand, such as retrofitting behaviour, technology adoption, and occupancy behaviour with agent-based modelling extensions.**

I. Introduction

ENERGY demand from buildings and activities in buildings account for 34% of global final energy demand, of which three-quarters are for thermal purposes [1]. State-of-the-art technologies as well as non-technological options present a major opportunity to reduce energy demand from buildings drastically in the next couple of decades. According to the Global Energy Assessment Report energy demand for heating and cooling could be reduced by about 46% by 2050 compared to the 2005 levels by applying today's best practices while still more than doubling the usable floor space. The long lifetimes of buildings and building technologies require immediate action to reduce energy demand, but also present a significant risk of lock-in. If less than state-of-the-art technologies are promoted global energy demand from buildings will increase by up to 33% [1].

A wide range of policy instruments has been successfully applied to reduce buildings energy demand including control and regulatory mechanism, regulatory informative instruments, economic and market based and fiscal instruments, and support and information programs. However, no one-fits-all solution has previously been found. In addition, the importance of addressing the broad range of co-benefits (i.e. non-energy benefits such as health, ecological, economic, service provision, and social effects) from reduced energy demand in buildings have been highlighted [1].

Energy demand from buildings therefore not only accounts for a significant amount of the final energy use, offers massive savings including a range of co-benefits, but also restricts the speed of change through the long lifetime of our build environment. In addition, buildings are strongly interlinked with the energy supply infrastructure such as electricity and gas distribution networks, or in some cases district heating networks. Changes in either, the buildings' energy demand or the supplying infrastructure, affect and are constrained by the state of the other. Therefore, a transition from the existing conventional centralized and mainly fossil fuel-based energy infrastructure towards a decentralized and renewable-based energy infrastructure is required. Examples for such transitions are so called energy regions, which show possible transition pathways towards a functional sustainable energy infrastructure at regional scale. Energy regions are regional initiatives which usually envision energy self-sufficiency by using regional energy sources and building a decentralized energy infrastructure [2].

Reducing energy demand in buildings is not just a matter of having the right technological kit in place. End-use technologies hold the greatest potential for climate mitigation [3, 4], but there are challenges in terms of sufficient research and development, widespread adoption, as well as appropriate maintenance and usage of these technologies. The total energy consumption of buildings is determined by demand levels, the efficiency of the

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conversion technologies, their operation and maintenance, and the efficiency of supply and distribution networks [5]. All of these require more or less active involvement of supply network actors, home owners, and occupiers; offer a variety of efficiency options over different lifetimes; and are heavily interlinked and influenced by a variety of policies [6].

Agent-based modelling (ABM) is able to capture such complex interactions between policy interventions, social and technical structure, and individual behaviour [7, 8]. Whilst agent-based models of social systems abound, only recently, work has emerged to simulate the long-term development of energy infrastructure and other socio-technical systems [9-14].

This research presents a generic bottom-up building-energy model for developing regional energy transition scenarios, accounting for the complex socio-technical interrelations typically found in contemporary energy systems. We further present a range of potential behavioural extensions to the model addressing individual aspects of the energy demand from buildings, and discuss further research.

II. Case Study Regions

We analysed energy transitions in two Austrian energy regions: oekoEnergieland in the district Güssing, and Energieregion Weiz-Gleisdorf. These were selected because they show significant differences in their initial conditions, applied strategies and transition processes. Furthermore, in both regions efforts to foster a transition towards a sustainable energy region started in the 90s, providing a wealth of data as well as committed stakeholders for collaboration. For both regions detailed data about the regional energy resources, energy infrastructure and energy demand, in particular the building stock, its' size, technical standard, and development were collected.

III. Methods

1. *The need for generic building models*

Put simply, the energy demand from an individual building depends on its size, the installed building envelope insulation, the efficiency of the heating system, and the behaviours of occupants (i.e. room temperature, hot water and electricity demand). On a regional scale those already numerous aspects are multiplied by the number of building, and the heterogeneity of their attributes. Any individual aspect of energy demand from buildings (e.g. heating technology adoption or end-user energy saving behaviour) is therefore embedded and co-evolves in the broader context of the build environment and its interrelation with the energy infrastructure. Consequently any research addressing these aspects relies on some kind of energy demand model from buildings. In this research we present a generic bottom-up building-energy model, which can be applied to different regions. It is intended to present the backbone for a range of behavioural models addressing individual aspects of buildings' energy demand.

2. *Model overview*

In the following we present an overview of the model structure and background data used following the (ODD) protocol to describe agent and individual-based models [7, 8].

Purpose: The model aims to portray the building stock's energy demand and heating systems transition in the energy regions. Furthermore, it is designed to test the effectiveness of different policy measures on overall energy demand, cumulative energy savings and energy source used. It is based on data from the statistical office in Austria and a literature review of buildings' and heating systems' efficiencies, renovation rates and cycles, and stock change.

Entities, state variables and scales: Buildings and a system level policy entity are the two entities modelled. Buildings are categorized by type of building (i.e. single family house (SFH), multifamily house (MFH), non-residential building (NRB)), construction period and type of heating system. Buildings' end-use energy demand is the sum of their heating, hot water and electricity demand [kWh/m^2] multiplied by the energy reference area (ERA) (i.e. useful dwelling floor area (UFA) times a reference factor for residential buildings). Heating demand is determined by the building's envelope standard, which itself depends on type, age and renovation of the building. For hot water and electricity fixed reference values from literature were used. End-use energy is provided through main heating systems and, in about 50% of the buildings, through additional secondary or supporting heating systems, primarily for water heating. Main heating systems are differentiated by type of centrality (i.e. district heating, central building heating, or room or flat heating systems) and energy source used (i.e. oil, wood, wood-chips, coal, power, gas, solar or heat pump, others, waste-heat), defining their conversion efficiency. In addition to main and secondary heating systems some of the buildings are equipped with photovoltaic systems (PV), generating a certain amount of the locally demanded electricity or feeding in any surplus.

The system level policy entity sets measures to influence the general building stock fluctuation (i.e. new construction and demolition rates), buildings' envelope renovation rates and standards, and renovation rates, standards and types of heating systems.

The model has a one-to-one scale for the two energy regions meaning each building is represented. An artificial space representation, based on housing density distributions, is used for demonstrative purposes. Each time step represents one year and the model is run for 50 years (i.e. 2000-2050).

Potential behavioural extensions, such as an analysis of occupancy behaviour, or retrofitting would then include appropriate agents (i.e. occupants, owners, contractors, advisors, etc.).

Process overview: In the following we elaborate on the main execution routine represented in the model. For each year the following six key processes are modelled:

(i) Setting the political (i.e. regulation or incentives) framework conditions according to the scenario modelled, which are based on literature and expert interviews in the regions.

(ii) Stock fluctuation including two sub-procedures; demolitions and new buildings. Only buildings of a certain age and which haven't been recently retrofitted are worth demolishing. The number of buildings demolished is determined based on a demolition rate. New buildings are constructed based on a construction rate. Both rates can be fixed throughout the simulation run or dynamically changing depending on the scenario. Empirical data from the regions are used to run the reference scenario. The attributes of the new buildings (except the heating system which is set new) are inherited from a randomly selected building from the stock in the generic model.

(iii) Envelop renovations are either determined through a fixed rate or by the time past since the last renovation and the performance of the building. In both cases only buildings above the energy demand standard (i.e. buildings with higher energy demand) are refurbished. They get a new heating demand, which is drawn from a distribution below the regulatory standard. Renovation rate is set to currently observed values (i.e. 0.8%) in the reference scenario.

(iv) Heating systems are replaced once they reach their end of life. The type of new heating system is determined from a frequency table according to regional scenarios. The efficiencies of the installed systems increase with the expected technology trajectories, which are derived from literature.

(v) New photovoltaic systems are installed or old once are replaced based on the regional adoption projections based on empirical data.

(vi) Finally, buildings' main attributes such as energy demand per area and overall energy demand per year are updated.

3. Details

Initialisation: The model is initialized with buildings stock and technology data from 2002. Since this data is only partially available on the regional scale several buildings' and technologies' attributes have been calculated referring to data sources on national or district level. Four chunks of data have been collected to initialize the model: (i) building stock data including number of buildings of a certain type, construction period, and energy carrier in the two study regions, (ii) average energy reference area per building type and construction period, (iii) heating, hot water, and electricity demand data, and (iv) heating technology specific data such as current efficiencies and expected efficiency increases.

(i) Building stock data (i.e. number of buildings) of the two energy regions was collected regarding the following four parameters; construction period, type of building, type of heating system, and the corresponding energy carrier.

(ii) Using the Usable Floor Area (UFA) to calculate the heating demand for each building would neglect large parts of buildings, which are usually heated but not accounted for in the UFA. Therefore, the energy reference area (ERA) is calculated as suggested in the Austrian building standards [15], by multiplying the UFA by a reference factor. Data on UFA was derived from the apartment and flat census 2001 [16] on the district level. The reference factor depends on the type of building. A value of 70% for SFH, 60% for MFH, and 65% for residential community houses was derived [17]. For non-residential building average energy reference areas were derived from the ZEUS database [18].

(iii) Heating, hot water and electricity demand values per square meter of ERA were derived from literature. The heating demand was derived for each building type by investigating a broad range of literature. Depending on the scope of the studies heating demand values for different building categories vary quite drastically (Figure 1). Based on these literature values heating demands distributions could be estimated per building type and construction period. This basically indicated the buildings envelope insulation rate. For hot water and power reference values per square meter and year from literature were used. The hot water demand is based on reference values from institute for housing & environment (IWU) [19] and Energy Saving Regulation of Germany (EnEV) [20] for residential buildings, and on the ZEUS database [18] for non-residential buildings. Power demand for residential buildings were based on provincial data from the statistical office in Austria [21], and again on the ZEUS database [18] for non-residential buildings.

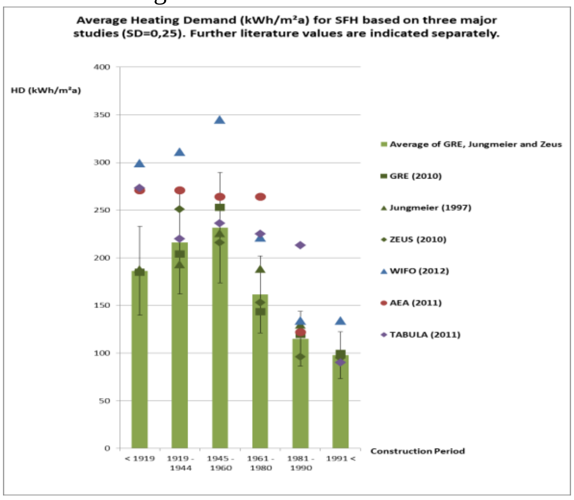

Figure 1: Comparison of heating demand per construction period for SFH

(vi) Based on a broad literature review data for the energy efficiencies of different heating system technologies was collected [22-28]. Heating system technology efficiency indicates how efficient the respective energy carrier is converted into heat, for room heating and hot water. Based on average heating system age of about 15 years in the 2000 stock average heating efficiencies from 1990 were used to initialize the model. State-of-the-art heating efficiencies for 2000 as well as expected efficiency improvements, and the resulting efficiencies, for 2020 and 2050 were derived form a range of studies looking at different heating technology development pathways (Figure 1).

In addition data for secondary hot water systems and photovoltaic (PV) systems have been collected. *Secondary hot water systems* can provide a significant amount of the total energy consumption of a building especially if the building has already a high energy efficiency standard (i.e. low heating energy demand). In the study regions more than 50% of all residential buildings have secondary hot water systems [24, 25, 29]. In most of the cases these are electric or gas based systems, with a minority of solar thermic and hot water heat pumps. *Secondary power systems* on a domestic scale are mainly linked to photovoltaic systems (PV), micro wind and micro-CHP systems might be potential future technologies, but are not considered in this model. Annual PV installation in Austria showed a step change between 2008 and 2012, as installation doubled in each of these years [30]. At the same time the mean module installation price dropped by almost 50% [30]. The provinces where the two case studies regions are located show particularly different pictures regarding installed PV capacity. The province of Styria (Weiz-Gleisdorf) is the leading province in Austria for PV installation, with a total of almost 54 MWpeak installed. On the other end of the scale, the province of Burgenland (Oekoenergieland) has the smallest installed capacity with 3.5 MWpeak [30]. The most installed systems in Austria have a size of 5 kWpeak [30] which is equal to about 40 m^2 of installed panels [31], and provides about 950 kWh per year and kWpeak installed [30]. For the base model (i.e. without behavioural extensions) logistic growth rates are assumed mirroring the two regions different PV adoption patterns.

IV. Preliminary Results

In the following, we present a selection of preliminary results from the generic model without behavioural extensions.

1. *Renovation rates vs. legislation standards*

In a first analysis a *reference scenario* with current legislation standards (i.e. 100 for renovation and 80 for new builds [kWh/m^2*a]) and a current renovation rate (i.e. 0.8%) was compared to a *legislation scenario* with tightened standards (i.e. decreasing to 50 and 25 [kWh/m^2*a]), a *renovation scenario* with doubled renovation rate (i.e. 1.6%), and a *combination* of the two. In all cases a static stock (i.e. fixed demolition and construction rates of 1%) was assumed.

On the final energy demand in 2050, tightened legislation clearly has the highest impact reducing the annual regional energy demand between 50% and 60% depending on the renovation rate. However, considering the cumulative savings over 50 years an increased renovation rate is almost three times more effective than the tightened standards. This of course depends on the scope of analysis, running the model for 100 years instead of 50 evens out the difference in cumulative savings.

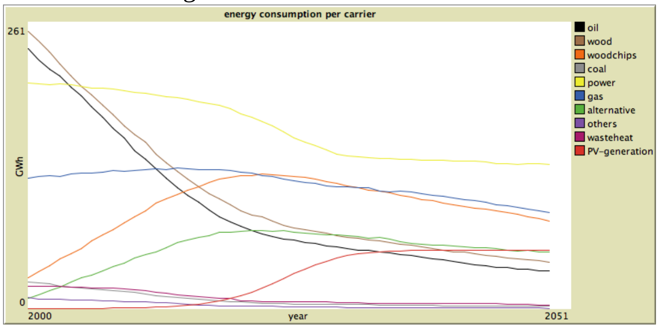

Figure 2: Development of energy consumption per carrier in the energy region Weiz-Gleisdorf

2. *Changing energy carrier mix*

The model allows for tracking the change of energy carriers under different scenarios. In the reference scenarios the frequencies of the installed heating systems observed in the first decade of this century were expected to be static. In such a business-as-usual scenario the initially dominant energy carriers (i.e. oil and wood) quickly drop and are among the least important in 2050. Heating systems based on woodchips, gas, and alternative systems such as heat pumps or solar thermic systems initially see increasing demand. However, the overall energy consumption of these carriers starts to decrease in about 2025 when energy heating demand decreases as more and more buildings are retrofitted. Although no electric main heating systems are installed anymore, electricity consumption only decreases slightly throughout the simulation, as power demand in buildings stays the same. This trend is only mitigated through the increased power generation from PV systems after 2030. Nevertheless electricity demand will become the most important energy carrier in the regions in the future (Figure 2).

V. Discussion

Building stock fluctuations, envelope renovations, heating system replacement and PV installation, are all represented as drastic simplifications of the actual actor interactions and decisions determining these processes. However, this simplification allows for sensitivity analysis of the individual processes and zooming into individual energy demand aspects without overly complex models. In the following we briefly discuss some of these potential extensions.

Building stock fluctuations could be made more elaborate by including population dynamics and service demand per capita (i.e. increasing floor area and room temperature). This route could be particularly interesting if large population fluctuations are expected or changes in the service demand (e.g. rebound effects) are the focus of analysis.

Homeowners' decisions to renovate are influenced by a range of project specific and personal factors and often done in collaboration with construction experts and consultants [32]. Extending the model in this direction would allow addressing the two key parameters discussed above (i.e. renovation rate and building standard). Doing so, the most effective policy levers as well as potential trade-offs (e.g. too tight standards could lead to a reduced renovation rate) could be identified.

Environmental impacts or benefits in the case of a reduction from buildings' energy demand largely depend on the type of heating system installed. Further analysing what determines actors heating replacement and new installation decisions would shed light on what policy instruments could be most effective in reducing environmental impacts caused by buildings' energy demand. Furthermore heating systems are the link to regional energy management as regional energy resources are limited. A sustainable energy management strategy therefore needs to address resource potentials and heating systems altogether.

VI. CONCLUSION

This research introduces a generic bottom-up building model to analyse different regional transition pathways. Input data are gathered from two regions and can be extended to other regions. Besides developing basic scenarios this model can be extended in various directions as exemplified above, which is really the central purpose of the model. The main advantage of such modular setting lies in the possibility of analysing single aspects of buildings' energy demand within their full complexity (i.e. actor interaction, learning, adaptation, etc) without the need for modelling every aspect of the problem, as these are covered by the generic model at first. If individual aspects overlap (e.g. envelope and heating renovations) they can be incrementally included with a clear idea about the impact of each of those aspects.

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