AGENT-BASED MODELING OF URBAN ENERGY SUPPLY SYSTEMS FACING CLIMATE PROTECTION CONSTRAINTS

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Summary: The paper presents a novel agent-based modeling approach that is especially designed to investigate the future development of urban energy supply systems embedded in liberalized markets. Private energy investment decisions are modeled using representative agents exhibiting bounded rationality. The bounded rational decision model is parameterized by socio-demographic surveys eliciting the relationship between lifestyles and energy investment decisions. In a further step, a highly resolved energy system optimization model is combined with the agent model and applied to investigate the overall influence of the different investment decisions on the performance of the urban energy supply system. Within a proof of concept application, diffusion curves are derived that describe the time-dependent market penetration of competing energy saving and low carbon energy conversion technologies that are supported by special climate protection incentive schemes.

Key Words: Agent-based Model, Energy Supply Systems, Bounded Rationality, Technology Diffusion

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I. INTRODUCTION

Many industrialized countries support the application of low carbon technologies, for instance, distributed cogeneration units or those using renewable energy sources. A crucial question in this context is whether or not the provided incentives are sufficient to promote a rapid diffusion of these technologies, e.g., one that is compatible with national greenhouse gas emission reduction commitments. Unfortunately, some of the supported technologies (for instance, improved insulation of buildings and cogeneration units) counteract once they are applied within the same urban energy system. In addition to commercial competition, technical counteraction effects therefore must be taken into account. As a consequence, a combined modeling of technical infrastructure and interacting agents is highly recommended.

II. FUNDAMENTAL APPROACH

The paper presents a novel agent-based modeling approach (Wittmann et al. 2006, Wittmann, 2007) that is especially designed to investigate the future development of urban energy supply systems embedded in liberalized markets. Private energy investment decisions are modeled using representative agents exhibiting bounded rationality. The bounded rational decision model is parameterized by socio-demographic surveys eliciting the relationship between lifestyles and energy investment decisions. In a further step, a highly resolved energy system optimization model is combined with the agent model and applied to investigate the overall influence of the different investment decisions on the performance of the urban energy supply system (see Fig.1).

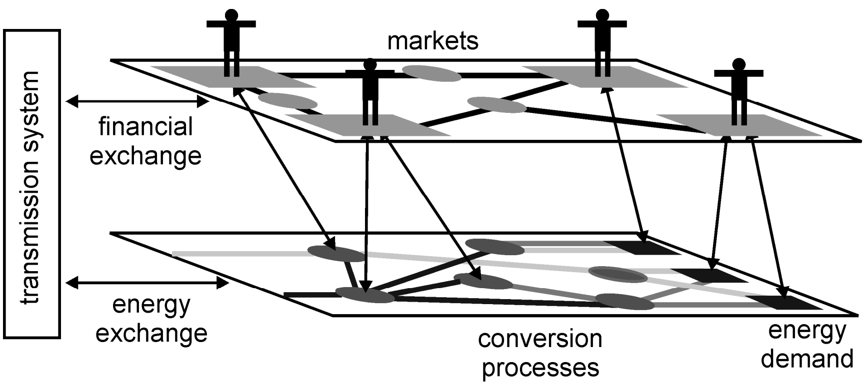

Figure 1: Technological (infrastructure, lower layer) and socio-economic (interacting actors, upper layer) layers of the model

Technological and infrastructural information related to the energy system in question are aggregated based on building-type (Hake et al. 1999) and district-type (Roth et al. 1980) in order to reduce data needs and improve computability. The energy supply network and the conversion technologies are modeled by using a temporally and spatially highly resolved energy system model. For the illustrative application of the approach presented here, the dynamic energy emissions and cost optimization software tool deeco (Bruckner et al. 1997) has been used. The modeling of the behavior of actors is strongly influenced by the doctrine of actor rationality — be it either bounded or unbounded. Bounded rationality forgoes assumptions regarding perfect foresight and optimal behavior in both the short and long term (Simon 1957).

The *operational decisions* of local utilities and large independent energy producers are assumed close to individually fully rational, because of the sophisticated software tools already used to support these decisions. Within the approach presented here, operational decisions therefore are made using an optimization model similar to the model applied by utilities. For that purpose, various instances of the deeco model has been applied in order to optimize the operation of those parts of the energy system that are under the supervision of the energy supplier considered.

The *structural decisions* faced by local utilities, independent energy producers, and house owners exhibit increasing levels of ambiguity and mathematical intractability. The orthodox assumptions of unbounded rationality and perfect foresight reduce the set of potential behaviors that require investigation to those that are defined as optimal in some sense. Bounded rationality, on the other hand, introduces the challenge of extracting realistic behavior patterns from an almost unlimited set of possible alternatives (Epstein et al. 1996, Gigerenzer et al. 1999b).

1. Representation of building owners

Decision-making for home and residential building owners is confined to investment decisions. Building owners might consider investment decisions in relation to replacement of energy conversion plants and/or retrofitted energy efficiency measures. The previously mentioned aggregation of technological and infrastructural data transforms the large number of individual decision problems that would otherwise have to be modeled and traversed, into a number of representative decision situations. As proposed in Gigerenzer et al. (1999a) a set of search and stop rules is used to reduce the general decision matrix to an actor specific decision matrix. An evaluation tool is provided for each decision goal, which allows the actor to assess the degree of goal fulfillment for each alternative under consideration. Finally a set of selection rules allows the actor to choose among alternatives. This decision process needs to be adapted to a population of actors which is heterogeneous. In other words, the search and stop rules, the evaluation tools, and the selection rules may be qualitatively different. The outcome of the decision process for any given actor can vary, even if an identical decision task is faced. In order to derive a consistent set of rules to model these investment decisions and thereby describe the evolution of the residential sector consumer energy demand, one has to analyze both the decision problem under consideration and the type of actor who faces the problem (Bettman et al., 1998).

Decisions are assumed to be made with regard to the following meta-goals: (a) maximizing accuracy, (b) minimizing effort, (c) maximizing ease of justification, and (d) minimizing negative emotions (Bettman et al. 1998). In different decision contexts, one or more of these meta-goals predominates. Domestic energy-related investment decisions are major decisions that are typically undertaken infrequently — say every 25–50 years. The predominant meta goals for this kind of technical decision are maximized accuracy and minimized effort, which thereby suggests a more complex and alternative-based decision algorithm (Bettman et al. 1998).

In order to achieve their meta-goals, actors (1) search for goals and alternatives, (2) collect and analyze information about the alternatives under consideration, and (3) evaluate this information in accordance with their goals. Goals can include minimization of cost, maximization of comfort, and minimization of environmental impact. Given these various goals, a range of evaluation techniques are available that can be used to represents different information levels and search (time) budgets (and, in a broader sense, differing levels of rationality). For example, cost minimization can be evaluated using either investment cost, pay back period, or discounted cash flow. The minimization of the environmental impacts of a heating system can be evaluated either qualitatively, by calculating the heat demand, by estimating the resulting primary energy consumption, or by determining the CO_2-eq emissions. As will be discussed in the following, which of these indicators is used to evaluate different alternatives depends on the specific actor that is considered (i.e., on his life-style type and rationality type).

1.1. Search rules

Search rules determine which alternatives are found by describing the different information gathering habits and abilities of decision makers. Naturally, search rules require additional parameters to be set. This section defines a set of search rules SR = {`find_all`, `find_by_aspects`, `find_common`, `find_next`} and briefly indicates these new parameters. It should be noted that some search rules can be used in combination.
The `find_all` rule finds all available alternatives. It is especially useful in cases where the decision maker is likely to behave with high rationality. The `find_all` rule does not require additional parameters to be specified. `find_by_aspects` acts as a filter. This search rule finds all alternatives which satisfy preset aspiration levels regarding each goal. Aspiration levels can be set by the internal constraints or requirements of the decision makers themselves, by legislation, or by referring to common practice within society or the decision makers' reference group. Moreover this rule requires having access to an inventory which stores the values taken to be common practice by society at large or by reference groups. `find_by_aspects` allows the search process to be restricted by defining upper and lower bounds for each goal. It also allows to include budget constraints, soft and hard standards, and similar aspects. `find_common` locates only those alternatives which are defined to be popular in relation to a given decision maker. To apply this rule, the notion of "common" needs some further investigation. Firstly, common alternatives can be those alternatives which have been widely selected by society, by the subset of the society the decision makers refer to, or by the decision makers themselves. Secondly, common alternatives can be those alternatives which are topical, that is mostly offered, sold, or advertised recently. On this account, a set of search domains SD = {`peer_group`, `status_quo`, `topical`} is introduced.

When applying find_common, the search domain needs to be set. If the search domain peer_group is chosen, the minimum market share a technology has to achieve to be perceived as common by a group of decision makers needs to be specified. This minimum market share can be different with regard to the peers and the location of the decision makers. The search domain status_quo includes all technologies used in the present state and topical refers to technologies perceived to be new. The rule find_common, also requires an inventory which stores information about the past decisions of society at large, of the relevant peer group, past decisions of each decision maker as well as the alternatives which have recently been mostly offered, advertised or sold. Applied in such a way, find_common allows a range of different information gathering habits of decision makers to be accommodated.

The find_next rule finds one alternative which has a particular place in a hierarchy over the available alternatives, starting with the first alternative. The find_next rule requires an order among alternatives to be set. The order of searching can be defined as related to deviations from the status quo of the decision maker or related to the commonness of the alternatives. If it is not possible to define a distinct order over all alternatives available, the respective alternatives will be clustered in such a way that an order over clusters can be defined. The find_next rule will randomly select among the alternatives from the first cluster and then move to the next cluster. Hence, find_next allows the alternatives to be traversed in a preset order.

1.2. Analysis tools

The general goal of minimum cost is determined using three different analysis tools. The investment costs and operational costs can be understood intuitively by recognizing that additional insulation increases investment costs but saves energy and therefore operational costs. The calculation of the payback period and the net present value is done with reference to the present state of the building. The payback period of the present state is set to the aspiration level of the agent who carries out the analysis. A negative net present value indicates that the regarded option is not profitable in reference to the present state option; a positive value represents the present cash-flow, when selecting that option in relation to the status quo option.

The general goal of minimum environmental impact is assessed using three different analysis tools. The qualitative tool reflects a perceived hierarchy, the consumer energy indicates how much energy will be consumed, and the CO_2 emissions reflect the total emissions of an option. Note that the CO_2 emissions from wood pellets were set to zero and that the resulting emissions for those options derive from grid electricity consumption.

The general goal of maximum comfort is only expressed qualitatively. Options that do not allow for grid connected supply of the energy carriers have lower values than those that do. An increase of insulation is regarded as an increase in comfort. Further, the cogeneration plant has shorter maintenance intervals and emits noise so that the comfort is lower than with simpler technologies.

1.3. Decision strategies

In order to specify the different parameters of the decision rules, one has to introduce heterogeneity among actors. This permits the categorization of actors through lifestyle categories which distinguish homogeneous groups of individuals who share the same aspirations in life, the same value systems, and similar lifestyles (Weber et al. 2000). The combination of these categories with different rationality-categories allows the modeler to specify via socio-demographic interviews actor preferences, information levels, and financial budget restrictions as well as the ability of the individual to achieve, through the choice of decision evaluation tools, their relevant meta goals. Using this approach, a large number of individual decision makers can be aggregated and modeled by using representative actors. The aggregation relies on two concepts, which help to select the appropriate goals, search rules, analysis tools, and decision strategies used to reproduce realistic behavior patterns.

The first concept is that of *social milieus* (Bourdieu 1987). It is concerned with distinguishing different homogeneous groups of individuals who share similar aspirations in life, similar value systems, and similar lifestyles. Milieus enable one to perceive people in the richness of their life context and their attitudes towards society, work, family, leisure, money, consumption, and the environment. Therefore, milieus help determine the available income, the decision goals and their relative importance, and the appropriate reference group.

The second concept of *rationality type*[1] allows one to distinguish between the different decision making abilities of people. The rationality type focuses on the information gathering and processing abilities of decision makers who faces a specific decision task. It provides insights as to where they search for the relevant information and which techniques they use to assess this information. Further conclusions on how decisions are reached can be drawn.

Hence the combination of social milieus and rationality type should allow decision rules to be specified for a set of actors in a way that the average outcome of a large number of individual decisions can be reproduced.

2. Representation of local utilities and independent energy producers

As indicated earlier, the *operational decisions* of local utilities and independent energy producers are modeled using the temporally and spatially disaggregated energy system model deeco, which is able to determine the hourly share of each conversion technology in order to meet energy demands. This software tool provides information necessary to assess the performance of different technologies and thereby provide support for structural decisions (Groscurth et al. 1995, Bruckner et al. 1997, Bruckner et al. 2003).

Structural decisions are divided into two classes. The first are so called *low stake decisions* that only require limited investment and do not fundamentally change the asset profile of the firm in question. Such decisions include investment in distributed solutions. In contrast, high-stake decisions are undertaken only rarely, have a major impact on the future evolution of the system,

[1] We are grateful to Fritz Reusswig, Potsdam Institute for Climate Impact Research, for suggesting this idea to us.

and demand high capital investment. The *high stake decisions* are addressed in different ways, e.g. by treating each decision option as a new scenario, by invoking third party software to evaluate the alternatives, or by relying on expert elicitation to provide the answer. The many low-stake decisions are modeled endogenously. Firms can be visualized as a bundle of resources which are used to supply one or more markets with one or more products (Wernerfelt 1984, Barney 1991). Strategic managerial decisions are directed towards the goals of ensuring the enhancement of the firm and maximizing future profits. Therefore the resources of a firm need to be developed in such a manner that the firm can meet the needs of possible future markets. Thus, the evaluation of the different investment options includes assumptions about the structure of future markets as well as the role that the firm may want to play in these markets. To construct a consistent quantitative model of the strategic investment decision process, the different investment options are attributed to at least one investment sphere — e.g. central generation, dispersed generation, district heating grid, gas distribution system, consumer relations, etc. This distinction allows the assignment of different shares of capital and venture capital as well as expectations, say, of the rate of return on investment for the different spheres. Each bundle — capital, venture capital, return on investment — per sphere are understood as a single strategy. Investment options are evaluated each year using those different strategies; if an option supported by an evaluation tool is assessed to be appropriate, the investment will be made. Different knowledge levels are modeled by assigning qualitatively different evaluation techniques to the actors. After a period of five years the strategies are evaluated taking the real market development into account, and adjusted as necessary. Using this approach, the competition among different kinds of firms, which have different views on the future development of the market and their own aspirations, is modeled.

III. ILLUSTRATIVE APPLICATION

Within the context of the illustrative application presented in the following, the demand for electricity, hot water, and room heating can be supplied by eight different supply options: energy can enter the considered buildings in the form of electricity, oil, gas, wood pellets or high temperature water by means of a district heating grid (Hea_Grid). Oil can be burnt in a conventional boiler (Oil_BoiConv), gas in a conventional (Gas_BoiConv) or condensing boiler (Gas_BoiCond) or in a reciprocating engine (Gas_CogenConv) providing heat and electricity. The hot water provision of the condensing gas boiler can be supported by a small solar thermal collector (Gas_BoiCondSolar), while the entire heat provision can be supported by a large solar thermal collector (Gas_SolarBoiCond). Wood pellets can be burnt in a conventional boiler (Pel_BoiConv) or the heat provision of the pellet boiler can be supported by a large solar thermal collector (Pel_SolarBoiConv).

The model was applied to a prototype city consisting of nine prototype single family houses which could have one of the nine supply technologies introduced above in their present state. Further, for the proof-of-concept application presented here only the following agents (and associated life-style types) are considered: traditionalist, established agent, technological leader, and real estate manager.

It is assumed that 30 % of the population are technology leaders (7.5 % with high rationality and 22.5 % with medium rationality), 40 % are established agents, 15 % are traditionalists (10 % with medium rationality and 5 % with low rationality) and 15 % are real estate managers. The maximal possible connection rate of buildings to the electricity grid was set to 100 %, to the gas grid to 90 % and to the district heating grid to 30 %. Further, it is assumed that the prices for electricity, heat, oil and gas will increase at a constant rate of 2 % per year, wood pellet prices will raise at 1.5 % per year. The average lifetime of technologies was set to 15 years, the renovation cycles of the building shell to 25 years. The model was executed over a 25 year period. The results are stated and discussed below.

To understand the resulting diffusion curves given in Fig. 2, a look at search rules might yield some insight. Basically one can distinguish between agents who can make options common – technology leaders are looking for topical options and high rationality agents, e.g. the real estate manager, will find all option. Agents who consider only common options – established agents or traditionalists with medium rationality apply the `find_common` rule referring to their peer group, the society and the location. Therefore, new technologies always start entering the system through the `find_all` and the `find_common` (now based on the `search_domain topical`) rule and only percolate through the system if they become common and agents' valuation favors such new technologies. In the chosen example, new technologies such as solar thermal collectors, cogeneration units, and pellet boilers (e.g. Gas_BoiCondSolar, Gas_CogenConv, Pel_BoiConv) are initially only selected by technology leaders. Further diffusion is only possible if agents who only find technologies which have achieved a specific market share (e.g. 5 % for the established agents and 7.5 % for traditionalists) in a location or among the whole society judge them positively and consequently apply them. The Gas_BoiCondSolar, the Pel_BoiConv, and the Gas_SolarBoiCond options belong to this group. In contrast, the Gas_CogenConv never reaches the commonness threshold and is therefore never evaluated by agents searching with `find_common`.

Having chosen the commonness of technologies as the first rationale to explain the diffusion curves produced by the model, a focus on analysis tools is useful. Agents base their decisions on the evaluation of costs, environmental impact, and comfort of an option. The results from the analysis of the comfort and environmental impact of options differ with respect to the applied analysis tool and the status quo, but do not change over time. Occurrence of the diffusion of renewable technologies such as solar thermal collectors and wood pellet boilers among technology leaders is predominant, because the medium and high rationality types minimize the environmental impact. But simulation outcomes get more complex when energy prices are assumed to rise at different rates over the whole scenario timeframe, increasingly favoring high conversion efficiencies, energy efficiency upgrades, renewable energy input, and low price energy carriers. Further, investment costs for novel technologies are assumed to fall, making novel technologies cheaper. Technologies benefiting from these developments (such as Gas_BoiCond, Gas_BoiCondSolar, Gas_SolarBoiCond, Gas_CogenConv, Pel_BoiConv, and Pel_SolarBoiConv) might be chosen by the established agents, the traditionalists or the real estate managers as soon as they become attractive.

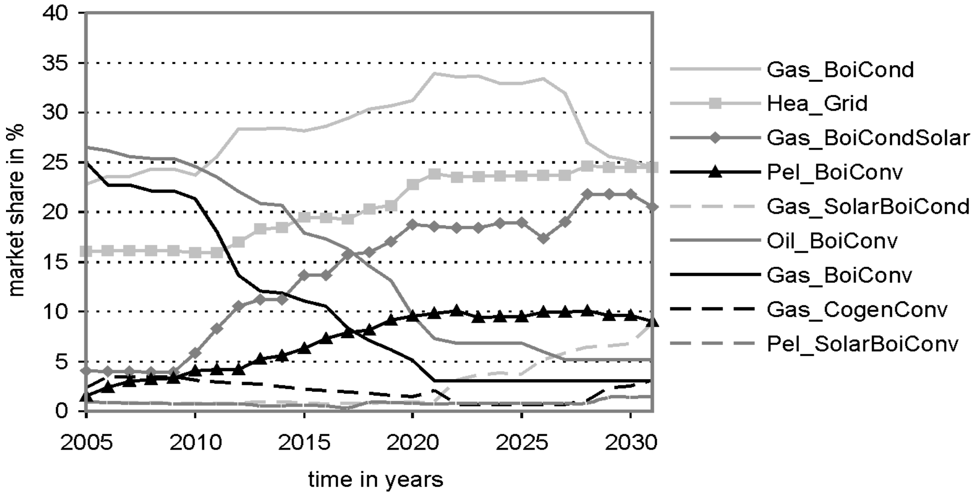

Figure 2: *Diffusion curves obtained by the simulation exercise*

Further, the results in Fig. 2 show two losing options, the conventional oil and gas boiler (Oil_BoiConv and Gas_BoiConv). Initially used by around 50 % of the agents both options drop to 3 % and 5 % respectively over the last time interval. The conventional gas boiler is mostly replaced by a condensing gas boiler and is only kept by some traditional agents with low rationality preferring to maintain the status quo. Likewise, the conventional oil boiler is on its way out. Finally, the Gas_CogenConv option deserves some attention. Over the first five years of the simulation this option is selected by the technology leader with medium rationality just occasionally and therefore takes up slowly. Because of its high cost and its context dependent performance, only some buildings are economically attractive environments for micro-cogeneration. Later, solar options are favored because of their lower consumer energy demands and economic attractiveness. As it is assumed that unit production costs decrease and prices for fuels increase, the micro-cogeneration unit becomes an interesting option to the real estate manager towards the end of the simulation and therefore the market share rises again.

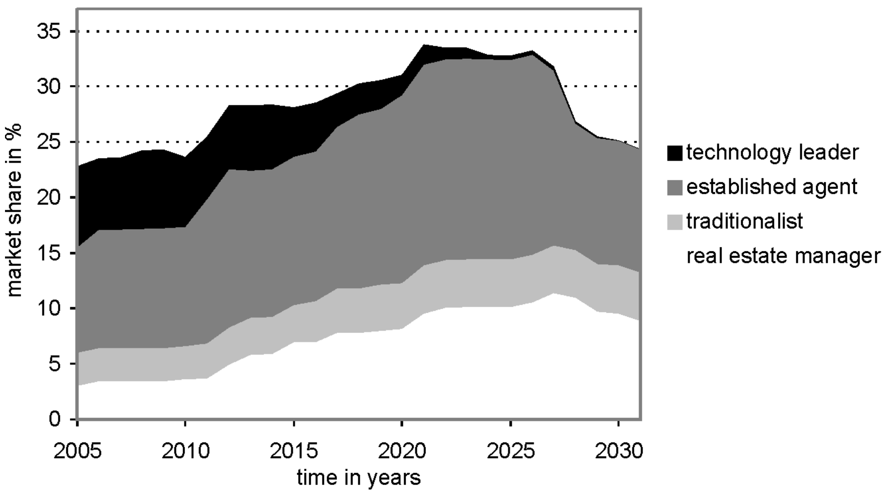

Figure 3: *Looking behind the diffusion curves for gas fired condensing boilers without solar thermal water heating (Gas_BoiCond).*

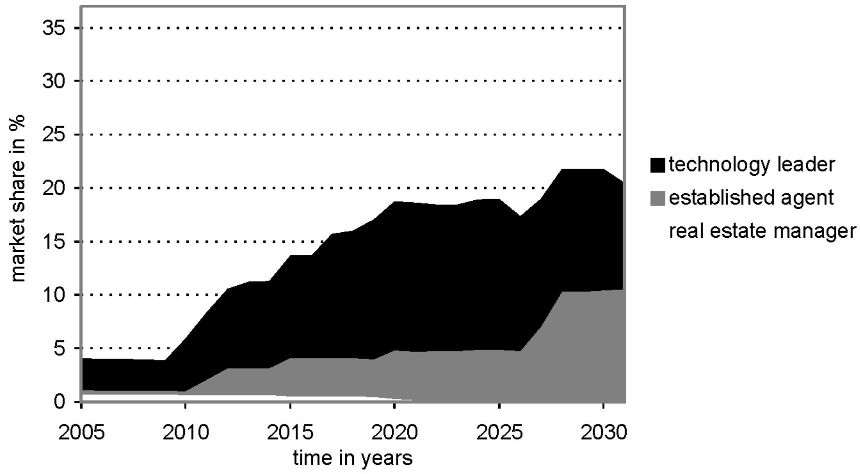

Figure 4: *Looking behind the diffusion curves for gas fired condensing boilers with solar thermal water heating (Gas_BoiCondSolar).*

The diagrams in Fig. 3 and 4 show how the diffusion curves for gas-fired condensing boilers (`Gas_BoiCond`, Fig. 3) and gas-fired condensing boilers with solar thermal water heating (`Gas_BoiCondSolar`, Fig. 4) are obtained from the different agent specific diffusion curves. The `Gas_BoiCond` option spreads at a slowly declining rate into the city, leading to a period of saturation before it starts to fade out towards the end of the simulation. One can easily identify that the real estate managers, the traditionalists and the established agents sustain this diffusion while the technology leaders choose different options. The decline at the end is due to the stepping out of the established agents who increasingly select the `Gas_BoiCondSolar` option and the real estate manager who perceives the `Gas_CogenConv` options to be attractive.

Turning to Fig. 4, the technology leader favors the `Gas_BoiCondSolar` option for the first half of the scenario time frame, making it common to the established agents (their threshold for commonness is 5 %). But they would not pick it up until it becomes economically attractive as well. In the second half of the simulation time frame, the further diffusion of solar thermal water heating is driven by established agents, who overcompensate the stepping out of the technology leaders. Similar trajectories are obtained for the diffusion of pellet boilers (`Pel_BoiConv`), which are selected by traditionalists as soon as they are made common by technology leaders and become economically attractive. The established agents never choose pellet boilers because of their low comfort value.

IV. DISCUSSION AND OUTLOOK

The presented decision model offers a new approach for understanding and estimating energy demand and technology diffusion trajectories within the residential housing sector. The modeling concept relies on three steps: the aggregation of technologies and infrastructures to provide representative options, the aggregation of socio-economic data to yield representative agents, and the development of a set of search, analysis, and selection processes by which the agents can make their investment decisions.

The proof-of-concept application provided demonstrates that a rich set of decision outcomes can result from this form of simulation. Both positive and negative diffusion curves, mostly displaying an S-shape, were obtained. In addition, some curves never took up, indicating a non-attractive option. Further, results can be understood referring to the assumptions made and thus are sensible. Compared to empirical analysis relying on regression models, the decision outcomes of the model seem to be reasonable (Lutzenhiser 1993, Schuler 2000). Technology leaders introduce novel technologies referring to two environmental performance measures, their final energy consumption and their CO_2 emissions. This makes it possible to model market entries of high efficiency options, perhaps with additional solar input, and options which use fuels with low CO_2 emissions. The traditional and the established agents are late adopters. Thus, they slow down diffusion rates for novel technologies. Finally, the heterogeneity of agents used for the bounded rational decision model enables us to account for different performance features of the technology and efficiency options in different ways, leading to a rich set of diffusion curves

The combination of sociological and technological dynamics within a single energy system simulation provides some unique benefits. Both aspects are well established in their own right, with the sociological dynamics being based on the social milieu methods. These methods were developed to support applied sociological investigations for direct marketing, product and services design and placement, voter analysis, and related issues. The approach is empirical and can be conducted at a high geographical resolution. Good base data sets exist, although most are proprietary. Further effort would be required to refine and particularize this information for use in energy system investment models. More work is also needed to validate the assumed agent types used in this analysis. This may comprise computer-assisted telephone interviews, focus group discussions and/or questionnaire surveys in order to better understand how house owners and managers make energy investment decisions.

Public interest applications for this model include the assessment of domestic sector policy measures, particularly in terms of effectiveness and robustness. It might further yield insights in how policy measures are applied with regard to different technical and socio-economic structures of cities or single districts. Private applications could include improved insight into existing and new energy technology markets, spatially highly resolved infrastructure and utilities planning, and the identification of robust business strategies. From a research perspective, it becomes increasingly evident that the energy decisions of investors and households need to be included in energy system models. The proposed model can be coupled with an energy system model with embedded price discovery and is therefore sensitive towards energy prices.

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