A BOUNDED RATIONALITY MODEL OF PRIVATE ENERGY INVESTMENT DECISIONS

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Abstract:
The future evolution of energy demand in cities has a major influence on energy market size, pricing, competition level, consumer relations, overall CO_2 emissions, and supply security. This paper presents a bounded rational decision model which can be used to estimate this evolution. It starts with an overview over barriers to energy efficiency investment followed by an introduction to bounded rationality decision models. It further presents a concept which can be used to parameterize this model by introducing a typology of representative actors who face representative decision tasks. The decision outcomes are determined and discussed.

1 Introduction

The economic liberalization of energy systems has made the task of developing suitable public energy policy more challenging. Classical issues like financial cost, environmental protection, and supply security are now accompanied by market issues like effective regulation and network access, the invention and diffusion of new technologies, and the recognition and emergence of decentralized structures. The development of a consistent public energy policy framework requires that one accounts for the various complexities involved. Energy companies also face the challenge of developing long term strategies to enable them to stay relevant and to grow.

In this context, a good understanding as to how the private demand for various energy carriers (electricity, oil, gas, district heating, wood pellets etc.) and technologies will change over time is essential for stakeholders. For instance, residential heat demand is dependant on the insulation standard of the building and the consumption behavior of the occupants. Heat can be supplied by a range of conventional (e.g. gas and oil boilers) and new (e.g. micro-cogeneration, pellet boilers, solar thermal installations) technologies. Electricity demand is likewise dependant on the available technologies and utilization patterns. The thermal performance of buildings, the installed conversion technologies, and the consumption profiles can therefore have a major influence on competition level, market size, pricing, consumer relations, overall CO_2 emissions, and supply security.

This paper describes a model for the private energy investment decisions of building owners. Other evolutionary problems which are similar to the one we investigate include the change of the social structures of neighborhoods, the fuel usage of the national passenger car fleet, and trends in domestic water demand. These evolutions typically involve high capital investment and are therefore infrequently undertaken by individuals. Among the methods applied in these contexts are the Technology Acceptance Model (Davis 1989), the Theory of Planned

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Behavior (Ajzen 1991), together with its application to innovation diffusion (see Venkatesh et. al. 2003 for an overview), and various optimizing and rational choice models.

In contrast to these approaches, we have elected to use a bounded rationality decision model — which ideally would be parameterized using socio-demographic surveys — to gain a more detailed insight into these evolutions. The bounded rationality approach recognizes that individuals have incomplete knowledge and limited information gathering and processing abilities. Furthermore, they may take decisions after traversing only a subset of the information they hold. Modeling proceeds by distilling the large number of individual decision problems into a number of representative decision problems by aggregating the technological and infrastructural data. This technological aggregation is complemented by socio-economic clustering which allows the replacement of the large number of individual decision makers by stereotyped decision makers that are representative of the class to which they belong. This paper (i) presents a bounded rational decision model that enables one to estimate the development of energy demand within the residential building sector in light of individual investments, (ii) indicates how the model parameters might be derived from socio-demographic surveys, and (iii) offers some illustrative results.

2 Private Energy Investment Decisions

There is evidence from numerous engineering/economic studies that many potential investments in energy efficiency, which appear to be cost-effective, remain unexploited (Interlaboratory Working Group 2000, Productivity Commission 2005, Jakob 2005).

Researchers have sought to understand why this should be the case and how best to overcome the apparent barriers to energy efficiency investment. The existence of barriers can be explained by applying different frameworks. The three most important are: (i) neoclassical economics, (ii) behavioral economics, and (iii) institutional economics (Sorrell et al. 2000, Jaffe et al. 1994). These frameworks enable barriers to be studied from three different perspectives, each of which highlights particular aspects of a complex situation. Table 1 introduces each perspective. This classification is not exclusive; each barrier will have economic, behavioral and institutional aspects (Weber 1997).

Perspective	Issues	Actors
Neoclassical	imperfect information, asymmetric information, hidden cost and risk, heterogeneity	individuals and organizations conceived as rational and utility maximizing
Behavioral	inability to gather and process information, format of information, trust, *status quo* bias	individuals conceived as boundedly rational, who apply identifiable rules and heuristics to decision making
Institutional	organizational culture, management time and attention	organizations conceived of as social systems influenced by goals, routines, internal culture, power structures, etc.

Table 1: Barriers to energy efficiency investment.

These different views on barriers offer a starting point for the study of the structure of the socio-economic environment and the decision maker. This paper focuses on investment decisions related to retrofitted energy efficiency measures and energy conversion technologies in the residential sector. These decisions are mostly undertaken by individual households, private building owners, and property management companies. Despite the institutional character of property management companies, this perspective is not particularly relevant for the chosen topic and therefore not applied nor discussed in the reminder of the paper.

2.1 Neoclassical Perspective

The neoclassical perspective ascribes barriers to imperfect and asymmetric information problems, to the heterogeneity of actors, and to the possible presence of hidden costs.

Imperfect information in the energy services market: When considering energy efficiency upgrades, building owners are confronted with a wide range of complex products offered by an equally wide range of firms. Retrofitting houses and choosing among different energy supply technologies is a decision task undertaken infrequently by investors and most technologies will have changed substantially since the previous purchase. Investors also have difficulties evaluating the performance of those technologies because of the complexity of the technologies, a lack of detailed energy consumption data, and a lack of detailed feedback on current performance (Hewett 1998). In contrast, energy (in the form of fuel, heat and electricity) is a simple, uniform and easy to understand product supplied from a manageable number of large, well-established and normally trusted firms. Viewing the purchase of energy efficiency and energy supply as different means to deliver energy services (heat, light, mobility, etc.) people tend to over-consume energy supply and under-consume energy efficiency (Sorrell et al. 2000).

Asymmetric information in the energy service market: A well known example of asymmetric information is the split incentives problem between landlords and tenants. A landlord might not be willing to retrofit a house to reduce the energy demand because she would not be able to recapitalize her investment by increasing the rent. Adverse selection might influence the energy service market when the owner believes that potential future tenants are not able to evaluate the energy efficiency standard of an apartment in comparison to the additional rent burden. This can lead to situations where an investment is not being made or reduced in certain areas because of the perceived or actual inability of future tenants to value this investment appropriately.

Heterogeneity: Building owners might have a range of independent goals when making investment decisions. These goals might include minimization of financial cost, maximization of comfort, or minimization of environmental impact. Decision makers might evaluate and adjust for the risks and inflexibilities associated with investments differently. These risks include technical risks (reliability, technical performance) and external risks (economic trends, energy prices, policy change). Low income households might face severe budget constraints and are not able to access the necessary capital from the market or elsewhere. Or they might face well above average interest rates (Evry 1997).

2.2 Behavioral Perspective

The behavioral perspective offers a different view of the problem. Firstly, decision making is taken to be procedurally rational which implies that individuals are rational in the sense that their decisions are goal directed. Secondly, individuals and firms tend to make satisfactory decisions rather than spending time and effort searching for optimal solutions. Limits on time, knowledge, and ability to gather and process information tend to indicate that decision makers use heuristics, routines, or rules of thumb (Simon 1955).

Gigerenzer et al. (1999a) argue that people adapt their decision behavior to the structure of their socio-economic environment. In situations in which information is scarce or costly and where competitive markets are lacking or absent, individuals tend to rely on heuristics or rules when making decisions. Bettman et al. (1998) point out that decisions tend to be made with regard to the following meta-goals: (i) maximizing accuracy, (ii) minimizing effort, (iii) maximizing ease of justification, and (iv) minimizing negative emotions. In different decision contexts, one or more of these meta-goals predominates. Subject to the particular decision context, people select decision rules or respective heuristics. As stated earlier, domestic energy-related investment decisions are major decisions undertaken infrequently — say once every 20–50 years. The predominant meta-goals for this kind of technical decision are maximized accuracy and minimized effort, which thereby suggests a more complex and alternatives-based decision algorithm relative to more frequently made decisions.

In an industrial context, De Almeida (1998) notes that purchasers of electric motors in France tend to choose heuristics depending on the situation — for example, new equipment purchase, routine replacement or emergency replacement. In each setting, firms used different techniques to evaluate energy related investment decisions. Graham et al (2001) surveyed 392 chief financial officers (CFO) and observed that the methods used for capital budgeting vary depending on the size of the firm and the tenure, education, and age of the CFO. Their "finding that payback period is used by older, longer-tenure CFOs without MBAs … suggests that lack of sophistication is a driving factor behind the popularity of the payback criterion" (Graham et al. 2001, p.200).

Experiments undertaken by Samuelson et al. (1998) and Kahneman et al. (1991) reveal that people prefer to stay with the *status quo* instead of changing. Stern (1986) noted that people respond to average prices or total costs instead of marginal costs, are more sensitive to changes in same, and generally require a higher rate of return for smaller investment.

3 Bounded rationality decision models

The concept of bounded rationality was introduced by H.A. Simon with the aim of developing a descriptive model of human economic decision making (Simon 1956, Simon 1957). Models of bounded rationality attempt to describe how a judgment or decision is reached by referring to the observed procedures that underlie the nonoptimising adaptive behavior of real people. To do so, one has to study both the cognitive abilities of the humans who face the decision task and the structure of the socio-economic environment in which the decision task is carried out. This approach also permits one to uncover how a particular choice mechanism is adapted relative to the properties of the socio-economic environment in which it is made.

Models of bounded rationality typically specify three classes of process: search rules, stopping rules, and decision rules (Gigerenzer et al. 1999b). The search process is modeled as a step-by-step procedure for acquiring pieces of information. The process of searching distinguishes two classes of model — those that search for decision cues and those that search for alternatives. The first class of model is typically better suited to faster and more spontaneous decision processes whereas the latter class can embed a greater level of deliberation (Gigerenzer 1999a, Bettman et al. 1998). The search process is terminated by stopping rules. If two or more alternatives remain under consideration at that point, a decision rule is applied to select among the remaining alternatives.

The decision model developed in this paper will estimate the future insulation performance of residential buildings and the installed energy conversion technologies. The model accounts for a range of the decision characteristics as indicated in section 2. Modelers will have to specify different types of actor who exhibit different distinct behavior patterns as well as an explicit set of technology and energy efficiency options which are potentially available to them. The model cannot be used to predict the outcome of a single decision, but it can be used to estimate the outcome of representative decisions of individuals who belong to the same group. The next sections will introduce the goals, decision rules, and analysis tools which are used within our model.

3.1 Goals

Building owners have a range of independent goals when making investment decisions. They face a multi-criteria decision problem, in which one goal cannot easily be transformed into another goal and thereby extinguished; moreover goals often work in opposition. The set of general goals `G = {cost, environment, comfort}` is introduced.

3.2 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 `S = {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 deemed 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 maker herself, by legislation, or by referring to common practice within her society or reference group. Therefore the set of reference domains `RD = {internal, legislation, society, peer_group}` and the set of aspiration levels $AL = \{a_g \mid g \in G\}$ is introduced. Moreover this rule requires having access to an inventory which stores the values taken to be common practice by society at large or the various reference groups. Find_by_aspects allows the search process to be restricted by defining upper and lower bounds for each goal. It also allows budget constraints, soft and hard standards, and similar to be included.

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 further investigation. Firstly, common alternatives can be those alternatives which have been widely selected by society, by the subset of the society the decision maker refers to, or by the decision maker herself. 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 = {society, peer_group, past_decisions, topical}` is introduced. When applying find_common, the search domain needs to be set. As with find_by_aspects, this rule also requires an inventory which stores information about the past decisions of society at large, the relevant peer group, the 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 certain 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, one has to cluster alternatives in such a way that an order over clusters can be defined. The *find_next* rule will then randomly select among the alternatives from the first cluster and then move to the next cluster. Therefore an ordering of clusters needs to be set. Hence, *find_next* allows the alternatives to be traversed in an identified order.

3.3 Analysis Tools

The general goals of the decision task in question may include the minimizing of costs, minimizing of environmental impact, and maximizing of comfort. Analysis tools determine how a particular set of goals will be assessed by an actor. Given the above mentioned general goals, a range of metrics are available, to measure the goal fulfillment of a specific alternative. Imagine the decision maker wants to select an alternative that minimizes cost. She might refer to different analysis tools to explore the costs associated with the alternatives under consideration, thus `AT_cost = {investment, payback, npv}`.

Her decision can be based on investment cost information only. This information is mostly available when selecting among alternatives. No extended search effort or knowledge is needed to locate or process this information.

More detailed information can be obtained if she calculates the pay-back period which includes operational and maintenance cost in her analysis. To conduct this calculation, she could either refer to historical payments or calculate the operational costs from usage projections. The payback period in years τ is given by the following equation, where I and I_{ref} are the investment costs of the regarded and reference options, respectively, and C and C_{ref} are the likewise annual operational costs:

$$\tau = \frac{I - I_{ref}}{C_{ref} - C}$$

Using the net present value, she not only includes investment, and operational and maintenance costs associated with the alternatives, but she compares those costs at their net present value. To apply this method, she needs to select a personal discount factor i, time horizon T, and an estimate of the development of future costs. The net present value npv can thus be calculated by the following equation, where $t = \{0, \ldots, T\}$ is the time interval index and C_t the cash flow at that point in time:

$$npv = \sum_{t=o}^{T} \frac{C_t}{(1+i)^t} - I$$

Normally, the net present value is reported relative to the *status quo*:

$$\Delta npv = npv - npv_{\mathrm{ref}}$$

Similarly, the general goal minimizing of environmental impact offers different approaches to be calculated, `AT_environment = {qualitative, consumer_energy, cotwo}`. Again each approach is able to assess the alternatives to different depth.

The environmental impact of an alternative can be determined qualitatively using simple heuristics. This approach broadly ranks alternatives. We propose five categories ranging from 1 (low) to 5 (high) and assign each alternative to one category. For instance, the alternatives related to the energy source which was used (e.g. oil < district heating < gas < solar < wood pellets). The calculation of consumer energy demand (oil, electricity, gas, etc.) offers a quantitative approach. This metric indicates how much energy enters the building, but it does not include the different impacts of each energy carrier. The calculation of the overall CO_2

emissions (cotwo) of each alternative differentiates energy carriers and includes the weighted impact of their use.

The general goal of maximizing comfort will only be qualitatively assessed in this work. Hence we rank the alternatives regarding the supply contracts (e.g. oil, pellets < gas, electricity < district heating), the indoor climate (e.g. no insulation < standard insulated < enhanced insulation), and the technologies (cogeneration < gas boiler, oil boiler < district heating). Finally, $\mathtt{AT} = \{\mathtt{AT}_{\mathtt{cost}}, \mathtt{AT}_{\mathtt{environment}}, \mathtt{AT}_{\mathtt{comfort}}\}$.

The choice of analysis tool must align with the information processing abilities of a decision maker. The analysis tools are dependant on the goals under investigation and the tools or methods available to explore the accessible information. Different tools can be assigned to different goals reflecting the time, knowledge and motivations that a decision maker has.

3.4 Decision Strategies

A decision strategy is used to select among the currently identified alternatives by combining one or more search rules and specifying the algorithm which selects alternatives. Note that search rules and decision strategies are linked; some strategies require certain search rules, while others do not. Some strategies may require that a specific search rule is altered and the search process repeated. The set of decisions strategies is given by `DS = {SAT, LEX, WADD}`.

The *satisficing strategy* (SAT) (Simon 1955) considers each alternative sequentially in the order in which it is revealed in the search process. For each goal of the alternative currently under consideration, the respective value is compared to some predefined aspiration level. If any goal of the alternative fails to meet an aspiration level, that alternative is rejected and the next considered. The first alternative which satisfies all aspiration levels is selected. The SAT strategy requires the *find_next* search rule. The SAT strategy bundles different aspects of decision making behavior. It can, for example, be used to model traditional decision behavior by ordering the search in relation to deviations from the *status quo*.

The *lexicographic strategy* (LEX) requires the relative importance of goals to be set. The alternative with the best value on the most important goal is selected. If two or more alternatives are equal, the second most important goal is considered. This algorithm is run until an alternative is selected. The LEX strategy can be used in combination with search rule which provide more then one alternative (e.g. *find_all*, *find_common*, *find_by_aspects*, etc.). The LEX strategy can be relaxed by including the notion of a just-noticeable difference (JND). If several alternatives are within the JND of the best alternative of any goal under investigation, they are considered as equal. The introduction of a JND allows some compensation between goals. Selecting one alternative using the LEX strategy allows one to model decision makers who have very strong preferences over goals. Technology leading behavior can be modeled using the LEX strategy in combination with the *find_common* search rule while defining commonness as those alternatives perceived to be topical.

The *weighted adding strategy* (WADD) requires the decision maker assign a subjective utility u_i for each goal g_i together with a weighting factor w_i to reflect its subjective importance. Thus, for each option:

$$wadd = \sum_i w_i u_i$$

This process is repeated for all alternatives. The decision maker then selects the alternative with the highest overall utility *wadd*. In contrast to the previous strategies, *WADD* is a compensatory strategy. It allows a good value on one goal to compensate for a poor value on another. This trade-off process confronts conflicting goals by introducing weighting factors. The *WADD* strategy can be used in combination with a search rule which provide more than one alternative (e.g. *find_all*, *find_common*, *find_by_aspects*). Combining the *WADD* strategy with the *find_all* search rule will model the greatest degree of rationality.

4 Modeling Private Energy Investment Decisions

The decision model used in this project draws on the ideas in Gigerenzer et al. (1999b). The model combines the decision rules and analysis tools introduced in the previous chapter. Fig. 1 illustrates the modeling process, which is structured as follows:

I. Aggregation of the technology and infrastructural information in such a way that a *general decision matrix* consisting of all alternatives and general goals can be constructed.

II. Aggregation of the socio-economic information in such a way that a *set of representative actors* for distinctive decision maker groupings can be built.

III. Transformation of the *general decision matrix* into an *actor-specific decision matrix* and selection of one option using tailored search rules, analysis tools, and decision strategies.

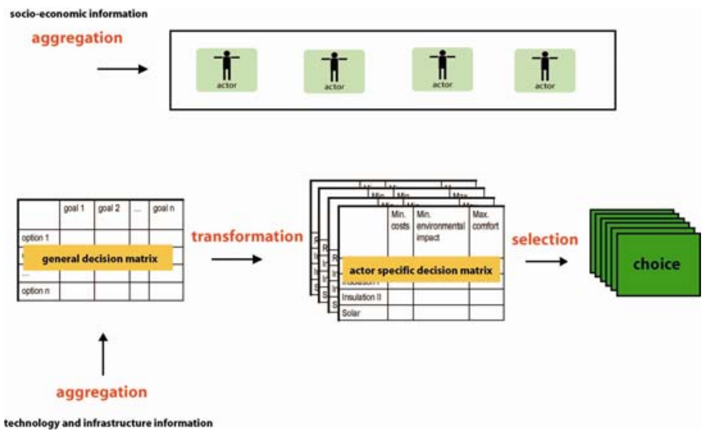

Figure 1 : Modeling process.

4.1 Aggregation of Technology and Infrastructure Information

The model is designed to project the future residential energy demand in cities. We therefore assume that each quarter of a city can be assigned to one of the neighborhood types described in Roth et al. (1980). If a quarter to be studied is composed of different neighborhood types, then further subdivision will be necessary. That typology provides information about the size of and distance between buildings, the availability of different infrastructures (gas grid, district heating grid, electricity grid) and the costs associated with connecting to them.

Each building in a given quarter is then assigned a building type (Hake et al. 1999), which carries information about the annual heat energy demand by introducing a classification of size (single family house, semi-detached building, small residential building, large residential building, multi-story building) and construction period (before 1900, 1901 – 1918, 1919 – 1948, etc.). Each construction period refers to dominating construction material and the technical regulations in place. The present state of the building is determined by the original building type and construction period, the energy efficiency measures undertaken thus far, and the heating system in place.

Each typical building in each quarter can be retrofitted and its heating system replaced. To capture this evolution, a set of options is constructed which reflects the important distinctive steps in the evolution to be modeled. The selection of options was based on observed retrofit investment behavior and the various technologies and configurations available today (Banfi 2005).

We selected three different retrofit options, *status quo* maintenance (maintenance) — the *status quo* is maintained and only necessary maintenance work is done, standard efficiency measures (standard) — all windows are replaced by state-of-the-art windows and the thermal efficiency of the building shell is improved, and enhanced efficiency measures (enhanced) — all windows are replaced by state-of-the-art windows and the shell is considerably improved.

The demand for electricity, hot water, and room heating can be supplied by eight different supply options: energy can enter the building in form of electricity, oil, gas, wood pellets or high temperature water by means of a district heating grid. Oil can be burned in a conventional boiler (Oil_BoiConv), gas in a conventional (Gas_BoiConv) or condensing boiler (Gas_BoiCond) or in a reciprocating engine (Gas_Cogen) 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 burned in a conventional boiler (Pel_BoiConv) or the heat provision of the pellet boiler could be supported by a large solar thermal collector (Pel_SolarBoiConv).

Using the aggregation of infrastructure and buildings previously discussed, a number of neighborhood-specific decision matrixes are constructed, each of which holds the options available for typical building in its quarter. Depending on the infrastructure and the connection rate, for instance, district heating supply might not available in a certain quarter or given, the present state of the building, all standard efficiency measures may have already been realized.

4.2 Aggregation of Socio-economic Information

The aggregation of technical and infrastructural information provides a number of representative decision tasks, each differing with regard to the *status quo* and the set of options on offer, as restricted by technical and infrastructural limitations. Each of these decision tasks, duly merged into a set of representative tasks, is usually undertaken by the individual building owners. In this section, we show how a large number of individual decision makers can be aggregated and modeled as representative actors. The outcome of the decision process for any given actor can vary, even if an identical decision task is faced. 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) and 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*[2] 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. To design, undertake and evaluate the required surveys which would allow the empirical determination of different actor models lies beyond the scope of this work. Instead, the specification of different actors is undertaken intuitively, with each actor being accorded a short biography.

4.2.1 Parameters from Social Milieus

The milieu classification used in this work follows the SINUS-Milieu-Typology[3] which was developed by SINUS-Sociovision. This typology is regularly updated and can be adapted to specific topics as required. To obtain a plausible categorization, some further abstractions and aggregations from the SINUS-Milieus were necessary. A brief illustrative description of the chosen milieus and the assigned parameters are given below.

Technology leader: Susan regards herself as successful in life. Profiting from a higher education, she is creative and inventive and loves to explore new opportunities and technologies. After she finished university, she carefully worked on her career and succeeded. She is around 40 and has a partner Tom. Their household income is high. The couple has a number of friends, who share similar values. Susan and Tom spend their income selectively on high quality products. Their circle of friends are interested in technology and chat about innovations regularly. When purchasing, they look for leading products, which are discussed in the relevant magazines and so forth. When planning a bigger investment they carefully read the relevant publications and consult experts and friends. They are always willing to experiment. Having a professional background, Susan knows how to evaluate investments. She is concerned with cost-effectiveness, but is also willing to spend more than necessary if the product is innovative, has good press, and/or the potential to become a new standard. Susan was attracted to the energy field when she learned about the liberalization of the energy market and the ensuing potential of small companies selling small and innovative technologies. She is also aware of peaking conventional energy sources and the dependency their usage imposes. She understands that climate change is a serious treat and that both society and the individual have different options by which to address it.

Traditionalist: Bill is married and has adult children and perhaps grandchildren. He is close to retirement. He has a secondary education, works as an employee, and has a medium income. He and his wife have always worked hard and cared for the family. They try to secure a reasonable living standard for themselves and their children. They bought a house and saved money at the bank. Bill and his wife are members of local associations and contribute to their community. Bill does not like to spend his money, but if he must, he does so very selectively. He tries to get good quality at low price; being older he is also interested in comfort. Having a long experience in purchasing, he generally knows what he wants. Bigger investments are only undertaken if they are really necessary. Bill then tries to replace the product he had. He is interested in getting well established, but also current technologies. Bill knows what he has to pay for his monthly energy bills. He tries to minimize this expenditure by saving energy daily.

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[2] We are grateful to Fritz Reusswig for suggesting this idea to us.
[3] See http://www.sociovision.com/ → Sinus Milieus for further information.

If Bill has to replace an energy technology he consults manufacturer directly. He is neither willing to spend much of his savings nor to indebt himself.

Established: Roger and his wife Paula have known each other since university. They have good educational backgrounds. After finishing university, Roger worked hard, achieved a good reputation, has responsibilities, is benefiting from an above average income, and has a secure living standard. After they had children, Paula left her job and stayed at home to raise the kids. Roger and Paula spend their income selectively on high quality products. They love good wine and food, meeting friends, enjoying cultural events, and traveling. When purchasing products, they try to improve their level of comfort. When Roger is facing a bigger investment, he evaluates it carefully. He and his wife consult experts and discuss the relevant facts intensively. They purchase well established, state-of-the-art technologies. Roger loves winter Sunday afternoons at home. He knows that he has to pay for his well heated house but he enjoys the comfort. Investment in energy technology or energy efficiency upgrades is not a joyful task for him. He has to spend his time acquiring knowledge in an unattractive domain. He is interested in decreasing his annual energy bill and relying on clean and easy to operate technology.

The social milieus approach enables one to derive some of the required parameters for the decision model. This includes the decision goals and their relative hierarchy (as required), the search domain, the financial, environmental and comfort constraints, as well as the rationality type which is used in combination.

		traditional	**technology leader**	**established**
goals (ordered)		cost, comfort	environment, cost, comfort	comfort, cost, environment
search domain		status_quo	topical	peer_group
constraints	budget	Little	much	some
	debt	No	yes	Yes
	comfort (1-5)	≥ 3	≥ 3	≥ 4
	environment	–	legislation	legislation
rationality types		low, medium	medium, high	medium

Table 2: Milieu dependent parameters of the decision model as assumed.

4.2.2 Parameters from Rationality Types

The rationality type approach draws from Gigerenzer et al. (2001). The underlying idea is to categorize decision makers by their information gathering and processing abilities. The following rationality types `RT = {low, medium, high}` are used.

Low rationality: People exhibiting low rationality face considerable problems gathering the relevant information. When looking for options, they tend to rely on past decisions and are therefore focused on the *status quo*. Their active search for new options and additional information is very costly for them and therefore limited. In addition, those people have problems estimating the future costs related to an option and including them in the decision making process.

Medium rationality: The medium rationality type is for people who have some experience in decision making. They gather information by asking friends and consulting recommended experts. In addition, they try to estimate the future costs associated with an option and will incorporate this data in their decision making.

High rationality: Decision making with high rationality is reserved for people who know how to make accurate investment decisions. We assume these people know how to get and assess the relevant information and then evaluate it with respect to their goals. They understand discounted cash flow analysis and are knowledgeable about the likely development of relevant economic factors.

In contrast to the social milieus, the rationality type allows the specifying of search rules, analysis tools and decision strategies. The chosen decision rules are shown below.

		low rationality	medium rationality	high rationality
search rule		find_next	find_common	find_all
analysis tool	cost	investment	payback	npv
	environment	qualitative	consumer_energy	cotwo
	comfort	qualitative	qualitative	qualitative
decision strategy		SAT	LEX	LEX

Table 3: Rationality type dependent parameters of the decision model as assumed.

4.2.3 Specification of Actors

Various combinations of social milieu and rationality type enable and restrict the different bounded rationality decision models available to each representative actor. We distinguish nine types of building owner actors. Five represent building owners who live in the building they own and four represent landlords. One of the four landlord actors represents the real estate management companies, while the other three represent private landlords. The private landlord actors are built by combining the private landlord with the private building owner actors in such a way that all parameters which are not specified in the private landlord column are taken from the respected private building owner column. The three private landlord actors were built by combining the technology leader / medium rationality, the technology leader / high rationality and the established / medium rationality. If a residential building is owned by more then one person, we assume that the type which represents the majority of owners can be used. The types and the related parameters are shown in table 4.

		Private Building Owners					Landlords	
		traditional / low rationality	traditionalist / medium rationality	technology leader / medium rationality	technology leader / high rationality	established / medium rationality	private landlord	real estate management company
search rule	**Rule**	**find next**	**find common**	**find common**	**find all**	**find common**	**type**	**find all**
	search domain	x	peer group	topical	x	peer group	type	x
	search order	status quo	x	x	x	x	type	x
analysis tool	**Cost**	**investment**	**pay-back period**	**pay-back period**	**net present value**	**pay-back period**	**net present value**	**net present value**
	discount factor	x	x	x	3%	x	3%	8%
	time horizon (years)	x	x	x	15	x	15	10
	Environment	**–**	**–**	**consumer energy**	**CO_2-emissions**	**consumer energy**	**type**	**CO_2-emissions**
	Comfort	**qualitative**	**qualitative**	**qualitative**	**qualitative**	**qualitative**	**qualitative**	**qualitative**
decision strategy	**Strategy**	**satisficing**	**lexicographic**	**lexicographic**	**lexicographic**	**lexicographic**	**type**	**lexicographic**
	goal ranking	x	cost, comfort	environment, cost, comfort	environment, cost, comfort	cost, environment, comfort	type	cost, comfort, environment
	JND	x	x	5%	5%	5%	type	5%
	aspiration-cost	–	≤ 10 years	≤ 20 years	≥ - 5000 €	≤ 15 years	type	≥ 0
	aspiration-environment	–	x	x	x	x	type	x
	aspiration-comfort	> 3	≥ 3	≥ 3	≥ 3	≥ 4	type	≥ 3
constraints	Budget	≤ 125 €/m²	≤ 125 €/m²	≤ 250 €/m²	≤ 250 €/m²	≤ 250 €/m²	type	≤ 500 €/m²
	Debt	no	no	yes	yes	yes	type	yes
	Comfort	≥ 3	≥ 3	≥ 3	≥ 3	≥ 4	type	≥ 3
	Environment	–	–	legislation	legislation	legislation	type	legislation

Table 4: Parameters of the building owner decision model as assumed. JND: just noticeable difference; type: the selection is dependent on the actor type (e.g. technology leader / high rationality) of the private landlord.

4.3 Matrix Transformation and Selection

The actor decision model constructs an actor-specific decision matrix by searching the general decision matrix for all admissible alternatives. The actor-specific decision matrix thus holds only the subset of options which can be known to the actor. Each of those options is then evaluated with regard to each goal by applying the analysis tool specified. The completed actor-specific decision matrix holds all alternatives available to an actor as well as the values of each alternative regarding each goal. The actor model finally chooses one alternative from the actor-specific decision matrix by applying a decision strategy. The strategy might require that the search and evaluation process be repeated if no feasible alternative is found on the first iteration.

5 Results

This section discusses the results of the decision model. Subsection 5.1 present the general decision matrix, while subsection 5.2 introduces the results of the decision model for each type of actor.

5.1 General Decision Matrix

The set of technology options consists of nine supply options and three efficiency options, as described in section 4. Each efficiency option can be combined with each supply option, which leads to a set of 27 options in the general decision matrix. The general goals of minimum cost, minimum environmental impact, and maximum comfort are calculated using three analysis tools for the first two goals, and one for the last. Table 5 presents the completed general decision matrix. Each possible analysis tool was applied. The matrix was generated using an energy system optimization software tool called *deeco* (Bruckner et al. 2003) coupled to a decision modeling software tool called *xeona* which was developed by the authors. The matrix is based on demand and cost data for a typical single family building constructed between 1958 and 1968 and located in a quarter where gas and district heating grids are available. The present state supply option is a conventional gas boiler (*Gas_BoiConv*) with no insulation upgrades realized thus far (*maintenance*). Note that an equivalent matrix can be calculated for each building type having access to different local infrastructures.

The general goal of *minimum cost* is determined using three different analysis tools. The investment cost and operational cost can be understood intuitively by recognizing that addition insulation increases investment costs but saves energy and therefore operational costs. The calculation of the payback period and the net present value is done in reference to the present state of the building. The payback period of the present state is set to the aspiration level of the actor in question. 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 higher emissions of the *Pel_SolarBoiConv* options are related to the ancillary electricity required to operate the solar collectors.

The general goal of *maximum comfort* is only expressed qualitatively. Options which do not allow for grid connected supply of the energy carriers have lower values than those which do.

And 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 those of simpler technologies.

The decision matrix in Table 5 further shows that the hierarchy of options changes relative to different goals, but also in regard to different analysis tools. For example, option G (*Gas_BoiConv/maintenance*) has the lowest investment cost, but A (*Gas_BoiCond/ maintenance*) wins on payback period and P (*Hea_Grid/maintenance*) has the highest (most attractive) net present value. Regarding environmental impact, option F (*Gas_BoiCondSolar/ enhanced*) outperforms on consumer energy, but X (*Pel_BoiConv/enhanced*) has the lowest emissions. A large set of options is perceived to be leading when the analysis is only qualitative. In terms of comfort, most of the options with grid supply and enhanced insulation offered the highest qualitative comfort. The matrix also shows that not only the best option changes when looking at different goal and applying different analysis tools, but the whole hierarchy of options is normally affected.

The application of different analysis tools enables on to model different levels of sophistication. For instance, in terms of environmental impact, consumer energy metric reflects only the amount of energy which is used and therefore favors technologies with a high efficiency and direct renewables input, whereas the use of CO_2 emissions additionally recognizes the different specific CO_2 content of fuels. A similar effect arises when comparing payback period with net present value. The payback period does not distinguish between present and future payments, whereas the net present value discounts future payments and thereby gives a different picture regarding cash flow.

options			general goals							
no.	supply network	insulation	minimization of cost				minimization of environmental impact			maximization of comfort
			investment cost [€]	operational cost [€/a]	payback period [a]	net present value [€]	environment [ranked]	consumer energy [kWh/a]	CO2 emissions [kg/a]	comfort [ranked]
A	Gas_BoiCond	maintenance	28,113.9	3,458.1	1.1	2,901.8	2.0	48,470.0	11,438.6	4.0
B	Gas_BoiCond	standard	35,901.6	2,690.0	7.8	4,283.9	2.0	35,785.3	8,880.8	4.3
C	Gas_BoiCond	enhanced	55,768.8	2,177.9	18.1	-9,469.9	2.0	27,328.8	7,175.5	4.7
D	Gas_BoiCondSolar	maintenance	33,098.9	3,302.3	12.5	-223.1	3.5	45,633.6	10,917.4	4.0
E	Gas_BoiCondSolar	standard	40,886.7	2,534.1	11.0	1,159.1	3.5	32,948.9	8,359.5	4.3
F	Gas_BoiCondSolar	enhanced	60,753.9	2,022.0	19.3	-12,594.7	3.5	24,492.3	6,654.2	4.7
G	Gas_BoiConv	maintenance	27,824.3	3,725.4	10.0	0.0	2.0	52,778.6	12,327.9	4.0
H	Gas_BoiConv	standard	35,667.8	2,887.3	9.4	2,161.6	2.0	38,966.1	9,537.3	4.3
I	Gas_BoiConv	enhanced	55,572.1	2,328.6	19.9	-11,072.7	2.0	29,758.1	7,676.9	4.7
J	Gas_CogenConv	maintenance	48,696.5	2,142.6	13.2	-1,976.1	3.0	59,581.1	4,813.3	3.8
K	Gas_CogenConv	standard	52,523.1	1,685.6	12.1	-348.0	3.0	44,701.7	3,989.3	4.0
L	Gas_CogenConv	enhanced	69,749.5	1,381.0	17.9	-13,938.0	3.0	34,781.9	3,440.0	4.3
M	Gas_SolarBoiCond	maintenance	58,791.3	3,123.8	51.5	-23,785.2	5.0	42,179.2	10,318.7	4.0
N	Gas_SolarBoiCond	standard	66,579.1	2,387.8	29.0	-22,785.9	5.0	30,034.2	7,867.6	4.3
O	Gas_SolarBoiCond	enhanced	86,446.2	1,903.5	32.2	-36,871.7	5.0	22,047.9	6,255.1	4.7
P	Hea_Grid	maintenance	31,164.7	2,881.6	4.0	6,733.3	3.0	47,500.6	9,356.3	4.0
Q	Hea_Grid	standard	40,289.8	2,240.9	8.4	5,257.1	3.0	35,069.4	7,343.4	4.3
R	Hea_Grid	enhanced	61,048.6	1,820.6	17.4	-10,484.4	3.0	26,782.1	6,001.4	4.7
S	Oil_BoiConv	maintenance	28,534.8	3,372.0	2.0	3,508.3	1.0	52,778.6	15,854.4	3.3
T	Oil_BoiConv	standard	36,434.0	2,626.4	7.8	4,510.2	1.0	38,966.1	12,140.9	3.7
U	Oil_BoiConv	enhanced	56,375.4	2,129.3	17.9	-9,497.2	1.0	29,758.1	9,665.2	4.0
V	Pel_BoiConv	maintenance	34,226.3	2,923.8	8.0	3,167.7	5.0	54,598.3	1,805.8	3.3
W	Pel_BoiConv	standard	40,837.7	2,295.5	9.1	4,056.9	5.0	40,309.7	1,768.9	3.7
X	Pel_BoiConv	enhanced	59,920.6	1,876.6	17.4	-10,025.5	5.0	30,784.2	1,744.2	4.0
Y	Pel_SolarBoiConv	maintenance	64,903.7	2,677.5	35.4	-24,569.8	5.0	47,930.6	1,938.0	3.3
Z	Pel_SolarBoiConv	standard	71,515.1	2,070.0	26.4	-23,928.3	5.0	34,129.7	1,900.0	3.7
AA	Pel_SolarBoiConv	enhanced	90,598.1	1,670.2	30.5	-38,238.8	5.0	25,054.5	1,874.3	4.0

Table 5: Completed general decision matrix. The present state is given by option G.

5.2 Single Decision Outcomes

The decision outcome for the different actors is determined by the assigned analysis tools and decision rules. Each decision process requires the generation of an actor-specific decision matrix, which can deviate from that shown in Table 5 depending on the selected search rules, aspiration levels, and analysis tools and their related parameters — including discount rate and time horizon. Table 6 shows the decision outcome of the actors specified in section 4. It further shows which parameters of the decision model determined the selection.

actors		**selection**		**result determination**				
Milieu	**rationality**	**supply network**	**insulation**	**sr**	**al**	**JND**	**decisive goal**	**rank**
traditional	low	Gas_BoiConv	maintenance	no	no	no	investment cost	1
traditional	medium	Gas_BoiCond	maintenance	no	no	no	pay-back period	1
establish	medium	Gas_BoiCond	standard	no	cost	yes	pay-back period	2
establish	medium LL	Hea_Grid	standard	no	cost	yes	net present value	2
techleader	medium	Gas_BoiCond	enhanced	no	cost	no	consumer energy	1
techleader	high	Pel_BoiConv	standard	no	cost	yes	net present value	2
techleader	medium LL	Gas_BoiCondSolar	standard	no	cost	no	consumer energy	1
techleader	high LL	Pel_BoiConv	standard	no	cost	yes	net present value	2
real estate manager		Hea_Grid	maintenance	no	no	no	net present value	1

Table 6: Decision outcome. Results were determined by sr: search rule; al: aspiration level; JND: just noticeable difference.

A range of different technologies were selected and some actors undertook efficiency upgrades. Keeping in mind that a conventional gas boiler in a non-insulated building (*Gas_BoiConv/maintenance*) defined the present state, the selection of the traditional with low rationality can be readily understood. The present state option was feasible within the aspiration levels and therefore selected.

Both, the traditional and the established with medium rationality selected the condensing gas boiler. In contrast to the traditional who selected the option with the lowest payback period, the established accounted for comfort in the first place, and this then ruled out low comfort options. The LEX strategy then moved to the second goal and selected the standard insulation option due to its short payback period and high comfort. The highest comfort option has an investment cost above the aspiration levels.

The district heating grid was selected by the establish landlord and the real estate manager. They differ regarding the selected energy efficiency measure. The priority for comfort for the established landlord ruled out low comfort options again, and then selected the option with the highest net present value, while as above the highest comfort options has investment cost above her aspiration level. In contrast, the real estate manager based his decision on net present value. The decision rules for the real estate manager assume that the investment costs cannot be passed on to tenants *via* higher rentals.

The technology leaders all selected the standard insulation, but they differ regarding the technology option. While the technology leader with medium rationality selected the Solar supported water heating, the actor with high rationality selected the wood pellet boiler. This difference is due to the different tools used to evaluate environmental impact.

In this example, none of the determined decision outcomes would change if the search rules are altered, for instance, if find_all was applied throughout. The choice of search rule becomes significant for this example if fuel and technology prices change over time. Assuming a steady rise in gas and oil prices and further technical and cost improvements for the solar collectors and wood pellet boilers, then established and traditional actors might not find these topical, good comfort, low cost options. In other words, they remain late adopters.

A change in adoption behavior can be modeled by making options common which are applied by over 10 % of the actors in the regarded district.

6 Discussion and Outlook

The private energy investment decision model presented in this paper offers a new approach for understanding and estimating energy demand 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 actors, and development of a set of information search, transformation, and selection processes by which the actors can make their investment decisions.

The illustrative application provided demonstrates that a rich set of decision outcomes can result from this form of simulation. And although these outcomes cannot be reliably predicted in advance, once formed they seem to accord well with intuition. Compared to empirical analysis using regression models, the outcomes of the different actor models seem to be reasonable (Lutzenhiser 1993, Schuler 2000). The simulation presented used only one of several categorized building types and only one present state for the supply technology and energy efficiency measures. The next step would be to adopt an ensemble approach by extending the analysis to a large number of representative decision problems and then calculating the aggregate outcome for an e.g. 25 year period.

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 methodology. This methodology was 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 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.[4] More work is also needed to validate the assumed actor 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 on how policy measures are applied with regard to different technical and socio-economical structures of cities or their quarters. 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 is becoming increasingly evident that the energy decisions that investors, households, and end-users make need to be included in energy system models. The proposed model could be coupled with an energy system model with embedded price discovery and which can thereby react sensitively towards energy prices.

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[4] See http://www.sociovision.com/ for additional information on services. Microm GmbH (http://www.microm-online.de/en/) offers spatially resolved data.

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