BEHAVIORAL STUDIES IN ENERGY ECONOMICS: A REVIEW AND RESEARCH FRAMEWORK

Staudt, Philipp, Karlsruhe Institute of Technology, Germany, philipp.staudt@kit.edu

Golla, Armin, Karlsruhe Institute of Technology, Germany, armin.golla@kit.edu

Richter, Bent, Karlsruhe Institute of Technology, Germany, bent.richter@kit.edu

Schmidt, Marc, Karlsruhe Institute of Technology, Germany, marc.schmidt@kit.edu

vom Scheidt, Frederik, Karlsruhe Institute of Technology, Germany, frederik.scheidt@kit.edu

Weinhardt, Christof, Karlsruhe Institute of Technology, Germany, christof.weinhardt@kit.edu

Abstract

The worldwide transition to renewable wind and solar electricity generation leads to more complex and decentralized energy systems. It is no longer sufficient to centrally optimize large controllable units. As electricity systems cannot be controlled from a top-down perspective anymore, the consumer behavior moves into focus and it is becoming an increasingly important factor as individual choices have a growing impact. However, behavioral studies in power systems have traditionally been limited to very few research streams. In this paper we propose a framework for behavioral studies in electricity systems and suggest an according research process. We classify existing literature along the framework and provide four case studies to illustrate the intended process. In doing so we aim to motivate and formulate behavioral studies within the energy domain.

Keywords: energy economics, behavioral economics, experimental design, analytics, market engineering

1 Introduction

Electricity systems are changing worldwide towards a more sustainable use of resources. This entails the use of intermittent generation technology such as wind and solar power. The associated intermittency leads to a re-consideration of the former paradigm that electricity supply follows demand (Palensky and Dietrich, 2011). Furthermore, technological advances in electrical storage technology foster the adoption of residential battery storage and electric vehicles (Brahman, Honarmand, and Jadid, 2015). The charging behavior of consumers can potentially have a large impact on the stability of the energy system (Flath et al., 2013). Furthermore, the digitalization of the energy sector and the resulting smart grid make it easier to communicate with and control a variety of actors in the energy system (Blumsack and Fernandez, 2012). Finally, the intermittent supply and the regional clusters of renewable generation force system operators to re-think their grid structure and often cause the need for grid expansion. However, such expansions are unpopular among the affected local population and can face strong public opposition. All of these developments move consumers into the centre of the future energy system. Individual behavior has a stronger influence on the overall system and consumption flexibility is becoming more important in order to use the energy system efficiently and to reduce the need for infrastructure expansion (Asensio, Munoz-Delgado, and Contreras, 2017). However, the energy system is traditionally often operated centrally even after the liberalization. Recently, more decentralized approaches are being discussed (Schäfer et al., 2015). These approaches often rely on simulations or they are based on assumptions regarding the individual behavior (Mengelkamp, Staudt, et al., 2017). It is therefore crucial to learn more about the individual consumption behavior, the competency of individual consumers with regards to their energy use and the investment behavior regarding individual energy infrastructure such as residential storage. For example, consumer behavior has been examined in the light of a growing problem regarding electricity system cost allocation. As many default tariffs recover grid costs and other sunk costs through volumetric charges they incentivize an optimization of self-consumption from residential solar photovoltaics. This creates problems of cost recovery for utilities, commonly known as the *utility death spiral* (Costello and Hemphill, 2014) and undesired distributional effects (Burger et al., 2019; Huber, Richter, and Weinhardt, 2018). Another recent concept relating to individual behavior is the optimal joint use of distribution infrastructure with the goal to decrease the necessity of grid expansion (Flath et al., 2013). These examples emphasize how individual behavior has consequences for the overall system. To motivate and guide future research in this research direction, this paper provides a framework that is intended to support the design of behavioral research projects in the energy domain. We describe how experimental design can be combined with a traditional market engineering perspective and data analytics approaches to deduct knowledge on individual consumer behavior. The approach is not necessarily limited to consumers but can be used for the evaluation of supplier behavior as well. However, as consumer behavior is less predictable and has not been investigated to the same extent, we focus on this aspect. We also provide a research process for the proposed framework that is based on the design science research cycle (Alan R. Hevner et al., 2004). In this paper we make three main contributions:

1. Presentation of a research framework for the behavioral analysis of electricity related research questions

2. Description of a research process embedding the proposed research framework

3. Discussion of four case studies using the proposed framework

The main objective of this paper is the motivation and formalization of behavioral research in the energy domain. In the following section we begin by reviewing literature on behavioral economics in electricity research. We classify the identified literature along the dimensions of experimental design, market engineering and energy analytics. Next, the research framework and process are introduced and discussed. Finally, we illustrate the framework and the research process by applying them to four exemplary case studies.

2 Related Work and Literature Classification

A variety of papers already covers the topic of behavioral studies in energy economics. However, these are often limited to a one-dimensional approach to the problem and do not include a necessary research cycle. In this section we classify existing research according to the pillars of the developed research framework that is presented in the next section: Experimental design (ED), market engineering (ME) and energy analytics (EA). For the literature review, papers are classified within the proposed framework if they include at least two of the three presented pillars. In the review process, 29 journal and conference papers are identified that fit these requirements. They are classified along two dimensions: The three pillars of the behavioral research framework on one hand and the field of contribution on the other hand. In the latter dimension the four categories are 'Field Experiment', 'Laboratory Experiment', 'Simulation' and 'Survey'. An overview of the paper classification is given in Table 1. Note that some papers cover aspects of more than one pillar and are therefore counted in multiple categories.

Classification n=29	Experimental Design	Market Engineering	Energy Analytics
Field Experiment	16	1	17
Laboratory Experiment	3	0	3
Simulation	3	4	3
Survey	5	0	5
Total	27	5	28

Table 1: Literature classification.

Field Experiment. More than half of all papers conduct a field experiment. Of those, 17 combine ED and DA in one research project. Allcott, 2011 and Ayres, Raseman, and Shih, 2013 investigate the effects of social and individual feedback to customers on their energy use. To supply evidence of moral licensing in energy conservation campaigns, Tiefenbeck et al., 2013 conduct a field experiment with 154 apartments at a multi family residence. G. Wood and Newborough, 2003 conduct a field experiment with households providing electronic feedback on energy use. Their findings show a 15% decrease in energy consumption for households receiving energy feedback. A comparison of the effects of self and social interests on user behavior with regard to energy consumption is performed by Ohler and Billger, 2014. To investigate the general willingness to save energy based on feedback and nudging, Goldstein, Cialdini, and Griskevicius, 2008 evaluate the reuse rate of hotel towels. Psychological and socio-demographic variables and their influence on household energy consumption and changes in energy use are subject to a five-month study of 189 Dutch households. Direct and indirect energy use and savings are monitored (Abrahamse and Steg, 2009). To compare environmentally significant measures of household consumer behavior to common social science measures of pro-environmental behavior, Gatersleben, Steg, and Vlek, 2002 conduct two large-scale field studies. Kotchen and Moore, 2008 conduct and analyze an empirical study that compares electricity usage before and after the introduction of a green-electricity program. Their aim is to investigate the willingness to pay a price premium for renewable energies. Bager and Mundaca, 2017 and Bager and Mundaca, 2015 explore consumer reactions on the installation of smart meters in households. Another research focus is user behavior in the context of the rising popularity of electric vehicles, with special focus on charging behavior and range anxiety (Franke and Krems, 2013; Rauh, Franke, and Krems, 2015). Whether general driving behavior can be influenced towards more ecological driving is subject of a six-month field experiment by Schall and Mohnen, 2017. Drivers are given monetary and non-monetary rewards for ecological driving of commercial vehicles. Only one paper covers a field experiment including the pillar of market engineering. Di Cosmo and O'Hora, 2017 investigate nudging based on time of use tariffs and different forms of financial feedback. Note that tariff literature that lacks the focus on behavioral aspects is outside the scope of this work.

Laboratory Experiment. Laboratory experiments with a focus on behavioral studies in the energy sector consider the ED and EA pillars of the proposed framework. One example is a paper by Batley et al., 2001 who investigate the willingness of individuals to pay for renewable energy. Their findings suggest that the willingness to pay a premium for renewable energy depends on social status and income. Two questionnaires are used to examine responsive energy behavior. Consumer reactions to completely furnished and equipped smart homes are analyzed by Paetz, Dütschke, and Fichtner, 2012. Four focus groups with a total of 29 participants were examined. Differences between institutional investors and electric utilities regarding the overall willingness to invest in the German renewable energy market are explored by Salm, 2018.

Simulation. Naturally, papers that focus on simulation put a lot of focus on ME. Four papers are identified within this cluster. An agent-based simulation of a market with highly variable real time electricity prices is investigated by Alan et al., 2014. The agents' purpose is the effective operation of a washing machine. Ilic et al., 2012 and Lo Prete and Hobbs, 2016 cover all three pillars of the behavioral market framework. The former also conduct an agent based simulation for trading in smart grid neighbourhoods and provide a detailed analysis of the results. The latter uses a game theoretic approach to introduce a microgrid in a regulated electricity network. ME and EA are covered by Schneider and Sunstein, 2017, who conduct a behavioral informed analysis on transaction costs and decision biases with regard to their influence on efficient policies in a market with time varying prices.

Survey. The inclusion of survey studies in the behavioral research framework is a conflicting topic. Numerous surveys exist that cover customer behavior in relation to the energy topic but do not refer especially to energy economics or energy markets. Those are excluded from the literature review. The five studies presented in this paper do either have an especially detailed EA section or adress a specific energy market related topic. All of the included papers cover ED and EA. Poortinga et al., 2003 use a conjoint-analysis to investigate the preferences for different types of energy-saving measures. Likewise, on a household level, Faiers and Neame, 2006 interview customers in central England. Their aim is to investigate attitudes towards characteristics of solar systems and the identification of potential barriers. A national representative study in Germany analyses the public acceptance of energy infrastructure and main drivers on a national and local level (Bertsch et al., 2016). In another study on a national level, M. Nicolson, Huebner, and Shipworth, 2017 investigate the willingness of consumers to switch to smart time of use electricity tariffs. The survey is conducted with a representative sample of 2020 British tax payers. A psychological model based on the theory of planned behavior is designed by Litvine and Wüstenhagen, 2011. The study investigates possibilities of behavioral intervention to nudge people into behaving accordingly to their positive attitude towards renewable energy and contains a survey of 1163 electricity consumers in Switzerland.

Summary. For completeness, several papers exist that provide overviews on existing research on household energy consumption (Baddeley, 2011; Faiers, Cook, and Neame, 2007; Frederiks, Stenner, and Hobman, 2015). Those are not within the scope of this framework, but provide useful insights on the topic. In summary, a majority of papers in the field of behavioral studies in energy economics cover ED and EA methods. ME models have a potential to gain more attention from the community. As shown in the framework, a sustainable energy system benefits from research that is based on all three pillars. The most represented form of study are field experiments. This is probably due to the nature of electricity use being subject to real world applications. Many institutions that focus on energy lack the facilities and equipment to conduct large laboratory studies which leads to a lower number of studies in this field. A potential for more behavioral research lies within the field of computational agent-based economics that can be enriched with empirical, behavioral data.

3 Framework for behavioral Studies in Energy Economics

In this section the proposed research framework and process are introduced. An illustration of the framework is provided in Fig. 1. The analysis of behavior is based on the overall environment that is composed of the regulatory and legal as well as the social environment. The prior includes for example regulation on costs and tariffs, while the latter is the driver of behavior that is influenced by social norms such as abstaining from wasting energy. Within this environment the ultimate behavior is driven by personal preferences. Depending on costs or individual beliefs consumers decide on how to consume electricity. The intention of this research framework is the analysis and the manipulation of preferences using different mechanisms to shape the environment such that a sustainable energy system will ultimately emerge. These mechanisms are based on a design process that includes the design itself, the experimental implementation of the mechanisms and the evaluation of empirical data using data analytics. These three pillars are introduced in the following.

Market Engineering. The mechanisms that shape the system's outcome based on the environment and individual preferences can use financial incentives (e.g., Burger et al., 2019), non-financial incentives (e.g., Huber, Schaule, and Jung, n.d.) or regulatory interventions (e.g., Staudt, Garttner, et al., 2018). The design of such mechanisms is the primary task of a market engineer. A framework on market design itself is provided by Gimpel, Jennings, et al., 2008. They define Market Engineering as "the process of consciously setting up or re-structuring a market in order to make it an effective and efficient means for carrying out exchange transactions". However, the mechanisms considered within this framework pillar are not limited to markets. They can include non-financial nudges or regulatory interventions. However, they are all designed to capture individual preferences and to coordinate decentralized decision into one outcome that optimizes the use of existing resources. This dimension is therefore in the center of the proposed framework. It includes the design of market mechanisms such as auction or bilateral trading mechanisms in local markets, of new tariff structures, of new markets such as for reactive power, of nudges for grid or environmentally friendly behavior or of new regulatory incentive mechanisms, just to name a few. Usually, this pillar is the starting point of a design process in energy markets. However, this does not always have to be the case. Sometimes a mechanism might already be in place and its results are analysed to identify possible improvements. In other cases the design might be triggered through survey results or the general public opinion. In summary, this pillar is concerned with the design of efficient and effective mechanisms to create a sustainable energy system from individual preferences and the social and legal environment.

Experimental Design. When a mechanism is designed, it needs to be carefully evaluated. Numerous examples of poor market design have led to undesired outcomes both in the electricity market and in other domains. The most prominent case of a failed market design is the Californian electricity market (Borenstein, 2002). Therefore, after the initial mechanism design, it needs to be tested in its intended environment through experiments. This relates to the research fields of behavioral economics that combines psychological insights and economic observations and experimental economics that tries to capture economic outcomes through experiments (Loewenstein, 1999). Experiments can be conducted in the field, in a laboratory or using a simulative approach. There are examples and pros and cons for each design. While laboratory experiments provide internal validity, they lack external validity. The opposite is true for field experiments. Simulation results are largely based on assumptions and empirical behavior can only be reproduced to some extent. However, sometimes the environment is too complex to be integrated into an experiment or the necessary infrastructure is not available and simulations are the only viable

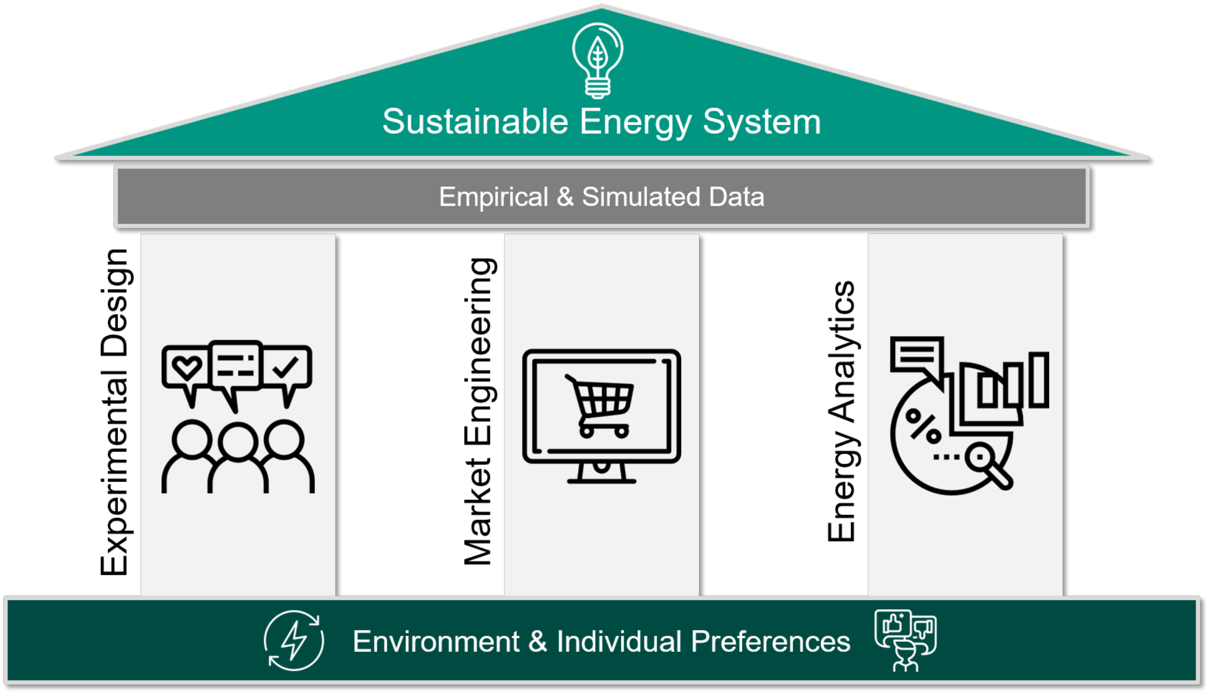

Figure 1: Research Framework for Behavioral Studies in Energy Economics

option. A combination of all three approaches is desirable. A simulation using self-learning computational agents (Weidlich and Veit, 2008) can help to understand dynamic results that arise from the interaction of agents. A lab experiment can show whether the mechanism's complexity is too high and finally a field experiment provides insights into the implementability of the mechanism. In any case, the experiments need to be carefully designed and the necessary stakeholders need to be identified and consulted. The experimental design should be developed in coordination with experts and is intended to find weaknesses of the developed approach. The most important aspect of this step is the collection of empirical data even if it is based on simulation results or interviews.

Energy Analytics. In the next step the genrated empirical data needs to be carefully evaluated using the necessary tools. This is done by applying different methods from the data analytics domain. This pillar of behavioural energy research is therefore necessary for two reasons: The evaluation of generated empirical data through experiments and the creation of empirical knowledge that can be used for the design of experiments. The used methodology can be manifold just as the landscape of data analytics is itself. However, non-linear forecasting approaches such as neural networks as well as clustering methods are at the core of this research direction. Energy markets are influenced by a variety of factors such as fuel prices, the weather or current power plant maintenance. Therefore, observed phenomena can be attributed to a variety of independent variables and the ability to anticipate certain situations is an important factor (Hirth, Schlecht, et al., 2019). Furthermore, even if experiments are designed, the uncertainty of electricity markets and the ability to anticipate certain events need to be reflected and therefore need to be initially evaluated through energy analytics. Furthermore, other aspects particular to electricity markets need to be considered such as the repetitiveness of a mechanism or an evaluation of long-term effects. This means that the effect of a repeated mechanism on the behaviour needs to be carefully analyzed using the empirical experiment results and the long-term reactions to short-term behaviour have to be analyzed. The analysis of the empirical data then provides further input for the improvement of the original mechanism.

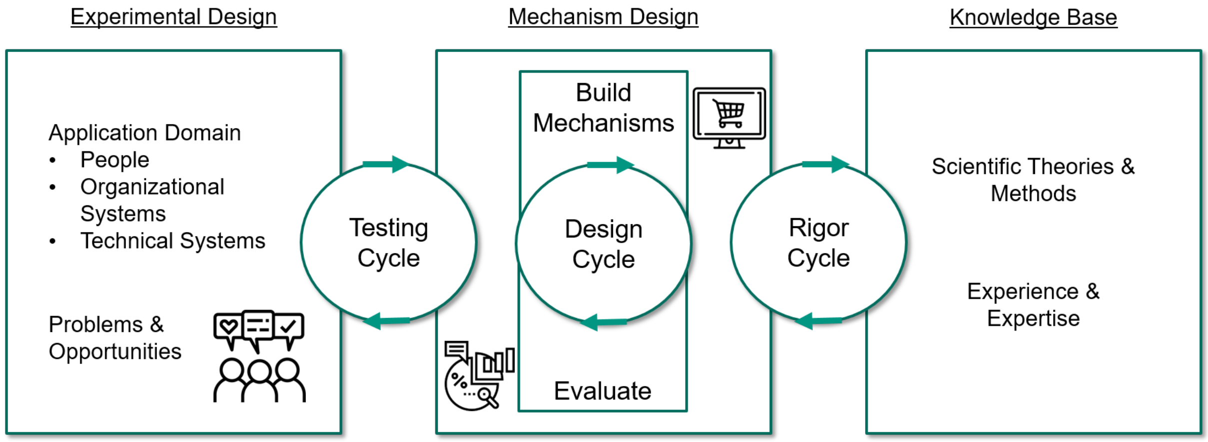

Figure 2: Research process based on the design science research cycle

The Research Process. The description of the research pillars already shows the interlinkage between the different areas. Therefore, we develop a research process that combines the pillars of our framework for behavioural studies in energy economics based on the research cycle developed by Alan R. Hevner et al., 2004. The entire research process is depicted in Fig. 2. The design of a mechanism is a process that needs to go through several iterations. The basis of such a design is both scientific and practical and should therefore be developed by relying on academic and practical experience. Through the iterations, the design needs to be re-evaluated with regards to previous research results and contradictions need to be assessed. The typical initiation of the process is the design of a mechanism that is supposed to achieve a articulated objective. This can be seen in all provided case studies. As described, such a mechanism is then developed based on academic and practical knowledge. The mechanism now needs to be evaluated. As described above, this should ideally be carried out through a combination of simulation, lab experiment and field experiment. Furthermore, it should be accompanied by the consultation of experts in the field. With these steps the research areas of market engineering and experimental design are combined. However, the described process can begin with an existing mechanism. If a mechanism is already implemented the first step might be to analyse the empirical outcomes of the mechanism before it is improved and re-tested. In other cases it might be important to understand the market outcome of other mechanisms or the stakeholder behaviour and abilities, before a new mechanism can be designed that is to be integrated in the existing environment. In this case, the analytics pillar, i.e., the evaluation step of the research process is the first design step. The three pillars are depicted within the process framework in Fig. 2. The described research process is repeated through several iterations until the results conform with the intended outcome. Through these iterations the degree of detail in the experimental design should be increased.

In order to better illustrate the proposed framework it is applied to four different use cases in the following section, to provide an understanding of the research process and its components.

4 Case Studies

The following case studies are based on active fields of research in the energy economics community. They are intended to facilitate the understanding and use of the proposed framework. This can help researchers to structure their research projects more clearly and to ensure scientific rigor.

4.1 Local energy markets

Background and motivation. Local energy markets are a widely discussed topic in academia and some designs are already tested in pilot projects. Since 2000, several frameworks, assessments, and architecture analyses have been published (Kamrat, 2001; Mengelkamp, Notheisen, et al., 2018; Richter, Mengelkamp, and Weinhardt, 2017). In its core, it describes an energy market where local energy produced by small power plants like PV panels is sold to local consumers. Traditionally, energy was produced in large controllable power plants and transmitted to the consumer through the transmission grid. A utility as an intermediary organized the distribution of energy to the consumer and the billing. With a rising share of renewable production, this structure cannot be upheld (Wüstenhagen and Bilharz, 2006).

Identifying the underlying problem. Renewable power plants are mostly small and connected to the low voltage distribution grid, near the consumer. In this new situation, local energy markets can be an alternative for local consumers to satisfy their energy demand (Koirala et al., 2016). This would allow the consumer to choose between different local energy sources and to differentiate between local energy and energy from the grid outside the market area. Especially the differentiation between several local energy sources is difficult. Electricity is a homogeneous good and a consumer device, e.g., a refrigerator or dishwasher, does not differentiate between electricity coming from a solar plant or a coal power plant. Yet, with rising awareness of climate change and other environmental issues, the consumer might prefer electricity from renewable energy. Also, some may prefer local energy instead of energy generated outside of their hometown (Tabi, Hille, and Wüstenhagen, 2014). These preferences cause a problem in the design of the local energy market because already established market mechanisms in the energy sector cannot be applied in this setting as they do not allow for a product differentiation.

Designing a market mechanism. The goal is to develop an adequate market mechanism which takes the consumer preferences into account. The starting point is an extensive literature analysis for auction designs with heterogeneous goods. In this step the existing knowledge base of the research community is consolidated. This includes the review of different auction designs like a combinatorial auction or multi-attribute double call auction (Bichler and Kalagnanam, 2005; Gimpel and Mäkiö, 2006). Each of these auction designs has disadvantages (e.g. computational feasible) or is not suitable to solve the preference problem. Therefore, the first result of this research is that each energy origin needs its own market, which allows the application of well-known market mechanisms like the merit-order. Consumers need to communicate redundant bids on each of these markets to satisfy their energy demand. These bids only differ in price, not amount. Thus, the chronological order carrying out the different markets is important. If a consumer demand can be satisfied on one market, the bids on the other markets become obsolete. As a subsequent step, a new literature analysis is conducted to find mechanisms which can determine the chronological order of market clearing that represents the preference distribution over all consumers. Therefore, the literature analysis focuses on voting mechanisms and preference based orders. In the subsequent iterative step, the newly designed market mechanism includes a preference-based voting mechanism to determine the chronological order of the market execution.

Evaluation and Redesign of the market mechanism. This first mechanism design is then reviewed by academic market mechanism experts and experts in practice. The results of these consultations start the next iteration in the research cycle and improves the developed market mechanism. At the end of this cycle, a simulation is conducted to estimate the performance of the mechanism. The next step is to start with the implementation of a first prototype version. In this phase, technical issues can be discovered and may lead to a redesign or adjustment of the market mechanism.

Application in real-world environment. The next step is, the real-world implementation of the mechanism inside a local energy market with different energy production origins and several consumers to conduct an appropriate field experiment. This is the application into an appropriate environment. In this environment, different objectives can be evaluated. For example, trading phases and small changes in the mechanism structure can be tested to collect enough data for subsequent analysis. This analysis is the last step in the research framework. The collected data is evaluated against the simulated data to confirm that the designed market mechanism works properly. This research procedure is currently used in the Landau Microgrid Project (Mengelkamp, Garttner, and Weinhardt, n.d.).

4.2 Tariff Design

Background and motivation. Electricity tariffs can be defined as mechanisms that allocate electricity system costs among all its consumers, thus determining how much different customers are charged for their electricity consumption. Past research has demonstrated that a) consumer behavior is influenced by tariffs (Faruqui, Sergici, and Warner, 2017) and b) that in turn human consumption behavior impacts system-wide costs and welfare (Allcott, 2012; Borenstein, 2005; Faruqui, Harris, and Hledik, 2010; Savolainen and Svento, 2012). Hence, in the context of residential electricity use, tariffs are the link between economics and human behavior.
The introduction of time-varying electricity tariffs for residential customers can make a significant contribution to the transformation of the energy system. However, while system benefits of adequate time-varying tariffs are significantly positive, each individual households' individual benefit is hard to foresee as it highly depends on the household's consumption profile and the respective tariff. Quantifying the individual household savings potentials and communicating it in the right way could increase adoption of system-beneficial tariffs. In the following, we outline a study addressing this issue by building on the presented three-pillar framework of market engineering, energy analytics and experimental design.

Design of use-case specific tariff. Tariff design aims at creating a mechanism that yields certain desired market outcome criteria. One well-known outline of relevant tariff criteria is Bonbright's Principles of Public Utility Rates (Bonbright, Danielsen, and Kamerschen, 1961). These criteria include both economic aspects such as economic efficiency, utility revenue adequacy and equity, but also customer oriented aspects such as bill stability, customer acceptability and customer satisfaction. For this case study we e.g. include the aspects of economic efficiency by allocating electricity generation costs with time-varying prices, namely real-time prices (RTP) and time-of-use pricing (TOU). For literature explaining the efficiency-improvements of time-varying prices over flat prices see for example (Schweppe et al., 1988). All other cost components, namely network, policy and administrative costs are designed mimicking the current tariff of the customer. Hence, the only differentiating aspect of the new proposed tariff is its dynamic component.

Analytical evaluation of tariff effects. After designing the tariffs, their impacts are assessed on real world smart meter data, using adequate data analytics methods. Thus it is evaluated on a household-level under which circumstances residential customers could profit if they switch to a new tariff design. For this, we use 30-minute consumption profiles of more than 100,000 households in Illinois, USA, presented in (Burger et al., 2019). In the first step two machine learning methods (artificial neural networks and random forests) are used to predict the optimal future tariff for each household, given the historical data. In a second step, the tariff effects are combined with a simulated adoption of distributed energy resources (DER), namely solar PV and household battery storage. Depending on a customer's load profile, installation of a new DER-technology might render certain new tariffs more financially viable. New total expenditures for electricity and DER-installations are calculated and the most beneficial combination for each individual household is identified.

Experimental validation of applicability. Yet, deriving the optimal tariff analytically does not necessarily mean that people are going to switch accordingly. Evidence exists that private consumers can be unable or unwilling to select the tariff which is most cost-effective for them (Bundesnetzagentur and Bundeskartellamt, 2018; M. L. Nicolson, 2018). Hence, empirical experiments are needed to drive the analytical findings towards applicability. For this, we build on the rich literature on *robo-advisors*, especially (Jung, Dorner, Glaser, et al., 2018; Jung, Dorner, Weinhardt, et al., 2018). Robo-advisors can be described as “digital platforms comprising interactive and intelligent user assistance components that use information technology to guide customers through an automated [. . .] advisory process.” (Jung, Dorner, Glaser, et al., 2018) Based on experiences with robo-advisors in the financial sector we design a *tariff robo-advisor*. We subsequently conduct a controlled lab experiment, with a representative sample panel. Thus we assess if a tariff robo-advisor can support self-selection of people into beneficial time-varying tariffs. Especially, we analyse if there are certain socio-demographic groups of customers more likely to follow suggestions of a robo-advisor than others. Finally, we compare the shares of customers switching their tariff with robo-advisor assistance to the analytically determined potential.

Updating tariff design and analytical evaluation based on experimental findings. Last, findings from the lab experiment can be used to update the tariff design step. For example, results might show that customers prefer TOU tariffs over RTP tariffs, even if that means forgoing additional savings. This can indicate risk-aversion of residential customers. Consequently, tariff designers might choose to offer an RTP tariff with a certain upper price limit to render the RTP tariff more appealing to risk-averse customer groups.

4.3 Range Anxiety

Background and motivation. Electric vehicles (EVs) have various advantages over vehicles with an internal combustion engine (ICE). From an environmental point of view they help to reduce emissions (Donateo et al., 2015; Falcão, Teixeira, and Sodré, 2017; Ferrero, Alessandrini, and Balanzino, 2016), from a grids perspective they have the potential to reduce redispatch costs (Staudt, Schmidt, et al., 2018) and peak consumption (Taljegard et al., 2019) and due to the efficient drive train the cost for electric driving is lower than with ICE cars (Laurischkat, Viertelhausen, and Jandt, 2016).
Nevertheless EV adoption is still low. Reasons for this are higher investment costs (Laurischkat, Viertelhausen, and Jandt, 2016), increased total cost of ownership (Falcão, Teixeira, and Sodré, 2017) and a limited driving range (Franke, Neumann, et al., 2012; Liao, Molin, and van Wee, 2017). Combined with longer charging time, the latter limits the utility of EVs in everyday use. Drivers experience range anxiety, the fear of fully discharging the battery before reaching the desired destination (Neubauer and E. Wood, 2014), which was shown to have a negative impact on EV adoption (Guo, Yang, and Lu, 2018). Not all users are equally affected by range anxiety (Rauh, Franke, and Krems, 2015) it is possible to influence individual range anxiety through appropriate information systems (Liao, Molin, and van Wee, 2017; Neubauer and E. Wood, 2014).

Design of range anxiety insurance. In this case study we introduce an approach to examine the reduction in range anxiety to improve vehicle-miles of travel (VMT). It is assumed that drivers fear the inconvenience of a breakdown of their EV due to low state of charge (SOC). Therefore we start with the market engineering pillar of our framework and define a mechanism that shifts the cost and inconvenience of a breakdown away from the driver through an insurance mechanism (Doherty and Schlesinger, 1983). This insurance should both cover a convenient way to continue the journey and coverage of all costs linked to the breakdown. Especially in this stage constant feedback of experts in the field of insurances is essential to ensure a viable offer for EV drivers.

Experimental test of user reaction. Following the framework, we continue with an experimental design to validate our predicted outcome. This can be done in two stages. A lab experiment can be conducted to gain feedback on the user interaction with the insurance in case of a breakdown, as reduced

inconvenience is assumed to be essential for a cut down in range anxiety. The lab design allows multiple iterations in the design cycle.
The second stage can be a field experiment where EV drivers are exposed to a driving situation in which the expected range and the distance to the desired destination are identical. Similar field experiment design can be found in literature. Rauh, Franke, and Krems, 2015 measure stress on a cognitive, emotional, behavioral and physiological level of participants in an EV with a reduced SOC to determine range anxiety. The objective of the field experiment is to collect data of the behavior of drivers with and without insurance.

Analytical validation of insurance. This leads to the third and last pillar of our framework. Analytics is applied to determine the change in user behavior in case the driver is offered an insurance against breakdowns and the change in range anxiety.

4.4 Distribution Grid Congestion

Background and motivation. The energy transition causes a variety of challenges for the electricity system. Among those is the grid integration of intermittent renewable generation. This is true for the transmission grid that is faced with more congestion due to the clustered installation of renewable capacity. However, the distribution grid needs to change its entire operation paradigm. As renewable capacity is often installed at the distribution level, the power flows are more and more often reversed such that power is transmitted to the higher voltage levels (Schermeyer, Vergara, and Fichtner, 2018). Furthermore, the expected increased market penetration with electric vehicles might cause congestion in the distribution grid in the other direction if too many charging processes are begun simultaneously. Both difficulties can be overcome by expanding the grid capacities accordingly. However, grid expansions are both unpopular and expensive (Bertsch et al., 2016) and the smart grid allows for less intrusive information system based coordination (Flath et al., 2013). Therefore, a mechanism is developed in combination with an information system that supports a joint optimization of the distribution grid use, reducing the need for grid expansions.

Identifying the underlying problem. First, the underlying problem is identified: Sometimes there is too much energy in the distribution grid and sometimes too little. In the short-run both problems cannot be solved through infrastructure as grid expansions and generation capacity installation take time. This already results in so called feed-in management that describes the down-regulation of renewable generation (Schermeyer, Vergara, and Fichtner, 2018). Therefore, the designed mechanism needs to incentivize two things: An increase in consumption of electricity in times of high renewable infeed and a decrease in consumption in times of high load. Assuming that the latter is a problem caused by electric vehicles, we can assume that there is a considerable number of electric vehicles present in the distribution grid. Therefore, we focus our approach on targeting electric vehicles.

Designing a coordination mechanism. The proposed mechanism uses a financial incentive to convince electric vehicle users to behave grid friendly, using the so-called deadline differentiated pricing (Salah and Flath, 2016). This pricing mechanism requires users to define a period during which their electric vehicle is to be fully charged again. Longer periods provide more flexibility to the grid operator and can therefore usually be provided at lower cost. As feed-in management is a costly measure, the savings that occur by avoiding the measure can be re-distributed at least partly to the consumers. Short charging periods require the operator to act quickly and are therefore more costly. The prices can be controlled by the distribution grid operator but in the spirit of unbundling this might also be done by an independent third party. Now the operator does forecasts of the demand over the next hours and the renewable generation and sets according prices to ensure that the demand is below the capacity and the renewable generation is sufficiently marketed. These prices are communicated to the users through an information system by the time that they set their charging deadline. This should incentivize truthful communication of their flexibility as a later deadline results in lower prices.

Building experiments for the evaluation. Such a design can be very well analysed in a lab experiment letting an operator play with a number of market participants. The operator can set incentives and the users try to optimize their personal portfolio. For example, users can be induced with range anxiety that was introduced in the previous paragraph through high penalties if their vehicle is not sufficiently charged for an unexpected trip. Then the operator needs to evaluate different premia that need to be paid for providing charging flexibility.

Analytics and re-iteration. Following this test experiment the results need to be evaluated with regards to a stable outcome: Does the operator find a level of prices that balances the system or is the system so volatile that such prices cannot be administratively set? In the latter case, the mechanism needs to be re-designed into a market mechanism as in the local market case study to let participants find the necessary prices dynamically. Furthermore, the individual behaviour and the behavioural changes over several rounds need to be considered. Do participants improve in the anticipation of low prices? Do they react to the actions taken by their peers? These questions can be answered by clustering the participants or by analysing the evolution of their behaviour. Possibly, a decision support system needs to be designed that helps the operator to determine the correct price curve and helps the consumers with their charging decision. Both designs then need to be re-tested in experiments beginning the next cycle through the proposed process. During the market engineering phase, existing market design theories need to be considered. A lab experiment lacks external validity. Therefore, ideally, such a design should be re-evaluated in the field.

5 Conclusion

In this paper we propose a framework and research process for behavioral studies in energy research. Such a framework is necessary as individual behavior is becoming a more influential factor in electricity systems. We begin by providing an overview of the research field of behavioral economics in electricity market research and classify the identified work along the categories of experimental design, market engineering and energy analytics, which are also the pillars of the provided research framework. After a broad overview of the research area, the framework and research process are introduced. The research process is developed along the design science research cycle introduced by Alan R. Hevner et al., 2004. We describe the intended use of the framework and how it is embedded into the research process. In order to facilitate the use of the framework, we describe four use cases derived from contemporary research streams in energy economics. These use cases are local markets, tariff design, range anxiety and distribution grid congestion. This paper has the intention of promoting and facilitating behavioral economics and experimental design within the energy economics community. To this end, the provided framework offers a formalization of according research projects and serves as a formal basis for the development of incentive mechanisms on electricity markets.

Acknowledgements

This work was supported by the German Research Foundation (DFG) as part of the Research Training Group GRK 2153: Energy Status Data - Informatics Methods for its Collection, Analysis and Exploitation.

We would also like to thank the reviewers for their feedback and constructive comments.

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