

The flexible prosumer: Measuring the willingness to co-create distributed flexibility

Merla Kubli^{a,b}, Moritz Look^a, Rolf Wüstenhagen^{a,*}

^a University of St. Gallen, Institute for Economy and the Environment, Tigerbergstrasse 2, CH-9000 St. Gallen, Switzerland

^b Zurich University of Applied Sciences, Institute of Sustainable Development, Technoparkstrasse 2, CH-8401 Winterthur, Switzerland



ARTICLE INFO

Keywords:

Solar photovoltaics
Battery storage
Vehicle-to-grid
Consumer behavior
Business models
Smart grid

ABSTRACT

Rising shares of fluctuating renewables increase the need for flexibility in the power market. At the same time, the emergence of the prosumer has created new opportunities for co-creation of distributed flexibility. As of yet, there is surprisingly little empirical analysis in terms of whether individuals are actually ready to co-create flexibility, and if so, under which conditions these resources can be mobilized by grid operators or electricity supply companies. We address this gap in the energy economics literature with three studies analyzing in total 7'216 individual decisions in a series of choice experiments with 902 study participants in three main domains of residential energy presumption: (1) solar PV plus storage, (2) electric mobility, (3) heat pumps. We develop a novel measure of the prosumers' willingness to co-create flexibility, and solicit their preferences for power supply contracts with varying levels of flexibility to derive implied discomfort costs. Our results indicate that current and potential electric car and solar PV users exhibit a higher willingness to co-create flexibility than heat pump users. Reaping the potential in those two domains requires taking the prosumer perspective into account when designing policy instruments and creating adequate business models.

1. Introduction

Matching supply and demand over time is a key challenge in power markets. In traditional electricity markets, demand has largely been taken for granted, while the necessary flexibility has been built into the supply side through peak power plants and centralized storage. Increasing shares of fluctuating renewable energies have enhanced the need for flexibility to avoid imbalances in the power system. Established and new companies develop novel business models to provide flexibility (Helms et al., 2016). Decentralization trends in the energy market offer new opportunities for matching supply and demand in a distributed manner. Distributed flexibility provision can take different forms: Shifting demand and supply over time and/or building up local storage capacity. Successfully mobilizing flexibility in distribution grids can help to delay or avoid investments in extending centralized grid infrastructure (Gordijn and Akkermans, 2007; Veldman et al., 2013), resulting in cost efficient energy systems and allowing smooth integration of renewables (Denholm and Hand, 2011). While centralized sources of flexibility (e.g. gas-fired power plants or hydro-power reservoirs) are well understood, the tendency of decentralized electricity consumers becoming prosumers (producers and consumers at the same time, cf. (Bergman and Eyre, 2011; Kotler, 1986; Toffler,

1980)) provides a potentially valuable source of – so far underutilized – flexibility (Gordijn and Akkermans, 2007; Kubli, 2017; Veldman et al., 2013). Decentral prosumers can provide flexibility by optimizing the timing of their electricity production and consumption, and by making decentralized storage available (e.g. through investing in batteries or providing heat reserves through a more flexible heating behavior). A better understanding of whether and under which conditions prosumers are actually ready to contribute to flexibility provision is important if these resources are to be mobilized.

This paper empirically investigates prosumers' willingness to co-create flexibility with a series of studies across three main domains of energy use: (a) solar PV plus storage, (b) electric vehicles, (c) heat pumps. By conducting three choice experiments with a unique sample of actual and potential flexible prosumers in Switzerland (N = 902), we aim to answer the following two research questions:

1. To what extent are prosumers willing to co-create flexibility?
2. Are there differences between the three technology domains?

Our paper makes three main contributions to the extant literature on smart grids and flexibility in the power market. First, we answer the call for “putting people in the loop” (e.g. Sowe et al., 2016) and for

* Corresponding author.

E-mail addresses: merla.kubli@unisg.ch (M. Kubli), moritz.look@unisg.ch (M. Look), rolf.wuestenhagen@unisg.ch (R. Wüstenhagen).

revealing determinants of social acceptance of smart grids (Wolsink, 2012), by investigating the preferences of end users as important agents in the diffusion of distributed flexibility. Second, we develop an innovative way of operationalizing and measuring the willingness to co-create flexibility. Third, we provide a pilot application of this measurement instrument that can serve as a role model for policymakers and energy companies who seek to effectively engage prosumers.

This paper is structured as follows. In the second section, we discuss existing literature on distributed generation, energy consumer preferences, and the role of prosumers in co-creating flexibility. In the third section, we introduce our methodological approach. Section 4 presents the results of the three studies and a discussion, while Section 5 concludes the paper with implications for energy policy and flexibility business model design, as well as a section on limitations and further research.

2. Literature review

2.1. Energy system flexibility and smart grids

As Lund et al. (2015) point out, energy system flexibility is “definitely a ‘hot topic’”. Their review of close to 400 academic publications presents a comprehensive overview of all the available options to integrate increasing shares of renewables in the grid, from large-scale centralized to small-scale decentralized, from supply-side to demand-side, and across a range of different time horizons. As another indication of the “hot” nature of this topic, the European Commission under its Horizon 2020 research programme is currently investing 337 million Euros of R&D funding in projects related to accelerating smart grids and storage deployment.¹ While there is an increased understanding of the large technical potential of distributed flexibility, previous attempts to assess the market potential are handicapped by the lack of reasonably fine-grained empirical data (Kondziella and Bruckner, 2016). This is particularly true for the emergence of decentralized battery storage, which could potentially revolutionize the power market (Agnew and Dargusch, 2015; Ebers and Wüstenhagen, 2015; Kubli, 2017), but are still in a nascent stage of market development. As a result, there is currently a wave of search processes for viable business models to deploy distributed flexibility options like demand response, energy management systems, electricity and thermal storage, and distributed solar photovoltaics (Burger and Luke, 2017). While both the need for and the potential of distributed flexibility options are now widely acknowledged, whether or not business models in this realm will be economically viable ultimately depends on whether they create customer value. This is increasingly understood by policymakers and business model developers, as evidenced for example by the creation of a Working Group on customer engagement in the above-mentioned EU initiative.² The following section contributes to this debate by offering a structured review of starting points for investigating prosumer preferences for flexibility co-creation.

2.2. Consumer preferences for electricity, demand response and the rise of the prosumer

The literature on preferences of energy consumers has gradually evolved from the traditional view of taking demand as given towards including aspects of flexibility and the rise of the prosumer (Fig. 1).

Traditional studies investigating consumer preferences have focused on explaining consumer choice in liberalized electricity markets, determining the role of factors like price and contract duration (Burkhalter et al., 2009). It was found that switching behavior has remained below expectations in many markets, pointing to the nature of electricity as a low involvement product and the strong role of routines and inertia in electricity consumer behavior (Herbes and Friege, 2017).

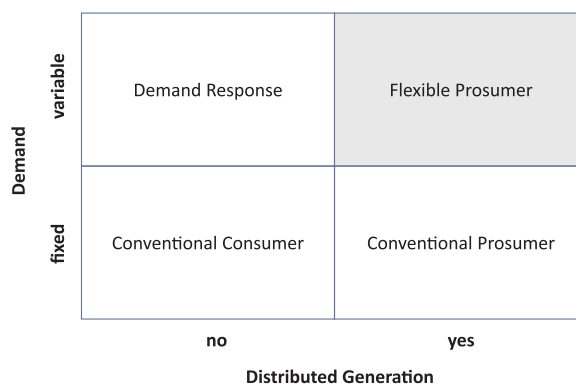


Fig. 1. From conventional consumer preferences towards flexible prosumers.

One factor that has been found to be relevant is the electricity mix, in that offering electricity products with a high share of renewables can be a way to overcome customer inertia (Kaenzig et al., 2013; Roe et al., 2001; Tabi et al., 2014). By measuring respondents' stated preferences, these studies provide insights into consumers' willingness to pay for changes in the attributes of electricity products.

A second stream of research looks at consumers' willingness to participate in demand response programmes, i.e. to allow utilities to shift some of their demand in time (Cappers et al., 2010; Torriti et al., 2010), to develop consumer segment-specific product and service offerings (Kaufmann et al., 2013) or to advance detailed understanding of personal traits as drivers of consumer acceptance of smart grids (Gamma, 2016) such as for instance perceived control over appliances (Moser, 2017). A common finding is that consumers request a relatively high financial incentive in order to voluntarily sign up for demand response programmes, and the likelihood of participation increases if required changes in daily routines are minimized (Annala, 2015). Apart from stated preference surveys, there are also some analyses of revealed preferences, for example tracking the behavior of participants in pilot programmes (e.g. Wemyss et al., 2016). A common finding of these studies is that the individual and societal advantages of participating in a demand-response program are not obvious to consumers, unless they actually get a chance to experience what this implies in everyday life (Dütschke and Paetz, 2013). Paterakis et al. (2017) even conclude that “the greatest challenge is related to the successful engagement of customers in demand response programmes”, illustrating the need for further research on end-user preferences.

A third stream of research, represented by the lower right quadrant in Fig. 1, investigates what makes consumers become actively engaged in their energy supply, i.e. to become prosumers. A popular theme here is to explore determinants of homeowners' decision to install solar photovoltaics on their roof (Curtius et al., 2017; Rai and Robinson, 2013; Sigrin et al., 2015). There is mixed evidence on the role of traditional socio-demographic factors like income, education and environmental awareness (for a review, see Dharshing, 2017). In contrast, preferences for independence and peer effects have been shown to be effective drivers of installing solar PV (Bollinger and Gillingham, 2012; Dharshing, 2017; Kubli, 2017; Kubli and Ulli-Beer, 2016; Rode and Weber, 2016).

The fourth quadrant in Fig. 1 represents the logical combination of quadrants two and three, namely prosumers actively engaging in flexibility provision. Such flexible prosumers go beyond the electricity production activities of conventional prosumers (which for instance, install a solar photovoltaic system on their roof and feed the electricity into the grid). Flexible prosumers in turn co-create flexibility by different means. A well-known example is demand response and the flexible timing of consumption (e.g. through smart appliances, smart heat pumps or smart charging of batteries). However, also the production of electricity can now be flexible, as for instance PV-battery systems allow prosumers to be more flexible in regard to when to feed electricity into the grid. Also novel heating systems facilitate the

¹ http://www.h2020-bridge.eu/wp-content/uploads/2017/06/BRIDGE_presentation_EUSEW17.pdf.

² <http://www.h2020-bridge.eu/working-groups/customer-engagement/>.

Table 1
Attributes that describe the power contract including flexibility provision.

Attributes	Levels			
Power costs per month	110 CHF ^b	90 CHF	70 CHF	50 CHF
Use of flexibility	Super Flex ^a	Flex Medium ^a	Flex Light ^a	No Flex ^a
Power mix	100% uncertified grey power	100% nuclear power	100% hydro power	100% solar power
Contract duration	4 years	2 years	1 year	Can be cancelled anytime

^a For details of flexibility attribute, see Table 2 below.

^b 1 CHF = 0.93 EUR = 0.98 USD (as of December 31, 2016).

emergence of flexible prosumers and enable the utilization of heat reserves for ancillary services.³ Empirically, this space is surprisingly uncharted territory, but given the future importance of flexible prosumers, it is important to close this gap and learn more about what influences prosumers' willingness to co-create flexibility. What would be of particular interest is a quantification of the premium required by prosumers to give up full autonomy, as this implies that the prosumer incurs a cost of discomfort (Good et al., 2015; Pournaras et al., 2014). The next section of our paper outlines the methodological approach to tackle this important question.

3. Methodology and data

Borrowing from previous studies investigating preferences related to consumers' electricity choice, demand response and becoming a prosumer, we investigate prosumers's willingness to co-create flexibility with choice experiments. Choice experiments have been widely applied in energy economics and related fields (Aravena et al., 2016; Chau et al., 2010; Heinzle and Wüstenhagen, 2012; Kaenzig et al., 2013; Lüdeke-Freund and Looock, 2011; Lüthi and Wüstenhagen, 2012; Park et al., 2013; Salm, 2017; Sammer and Wüstenhagen, 2006; Tabi et al., 2014; Tabi and Wüstenhagen, 2017), but for the purposes of the present paper, two important methodological challenges have to be addressed. First, distributed flexibility is a rather complex technological phenomenon, which average electricity customers may be unfamiliar with. Second, the number of flexible prosumers is still somewhat limited. To address the first challenge, we have decided to focus our experimental design on a choice situation that is more familiar to customers, namely the choice of an electricity product. To address the second challenge, the easiest solution would be to wait until the number of prosumers is larger than it is today. This, however, would be unsatisfactory because knowing more about the (emerging) preferences of flexible prosumers at an early point in time can provide valuable information for business model design and energy policy. Our approach here was to carefully craft three subsamples of respondents who can be expected to become early adopters of the concept of flexible prosumers in the respective domain of energy use. The following sections will explain both aspects of our methodological approach in more detail.

3.1. Choice experiments

Choice experiments are a popular method to elicit consumer preferences. They are based on classical random utility theory, assuming that individuals seek to maximize their utility, which can be described as the sum of the part-worth utilities for the different attributes of a choice object (Lancaster, 1966; Louviere et al., 2010). A popular application is the development of new products, where actual purchasing behavior cannot be observed yet and hence stated preference data is not available (Hensher et al., 2005). A choice experiment consists of a number of choice tasks, in which respondents have to select their preferred option from a range of choice objects (e.g. products or services), which are described by their most important attributes. Repeating the choice task with varying attribute levels requires respondents to make

trade-offs between desired attributes, and hence allows to effectively elicit their underlying preferences. In this study, we use choice-based conjoint (CBC) analysis (Sawtooth, 2017), which is one of the most widely-applied method in the family of choice experiments. We designed the CBC experiment in an iterative process, which included refining the CBC design in various steps among the three researchers, soliciting feedback from domain experts, and a pretest of the online questionnaire. The final CBC design is discussed in detail in Section 3.2.

The respondents of the three studies received an online questionnaire with eight choice tasks where they are asked to select their most preferred power supply contract. The number of required choice tasks were defined based on Sawtooth (2009b). The choice tasks are a randomized constellation of the defined attribute levels (see Tables 1 and 2). No adaptation of the constellations is made based on the previous selections of the respondents.

To derive part-worth utilities and attribute importances, we use Hierarchical Bayes (HB) estimation. Estimation based on HB is one of the standard procedures for CBC studies, and is reported to reach superior hit rates of individual choices and higher choice share validations compared to alternative estimation approaches (Moore, 2004; Orme, 2000; Sawtooth, 2009a). For validation purposes, we compared the estimation results based on HB with logit estimations. As the estimated coefficients showed no important differences, similar as in model comparisons of previous research (Wuebker et al., 2015), we did not include the results of the logit model in the paper. The data is available on request from the authors and has been presented to the reviewers.

3.2. Experimental design

Choice experiments in the area of new product development have to strike a balance between realistically mirroring the possible features of the (future) product and not overstretching the respondents' imagination. While smart grids and distributed resources are a hot topic in expert circles, these issues are not very familiar to the average electricity consumer as mass market-diffusion is yet to come. And yet, it is the final consumer who is the ultimate bottleneck in the adoption of distributed flexibility. We solved this issue by embedding our object of interest, the flexibility option, in a choice context that is familiar to respondents, namely choosing between different electricity tariffs. The rationality here is that even solar prosumers with storage will usually not strive for full autarky, as it is in most cases more economical to stay connected to the electricity grid so that backup power can be acquired in times where consumption exceeds own production. Hence we explained to respondents that what they are choosing from is the supply contract for their residual electricity needs. Table 1 shows the overarching design of the choice task for all three studies. The electricity offering is described by four attributes with four levels each, and each respondent had to complete eight choice tasks.

Apart from the usual attributes of electricity contracts like monthly power cost, electricity mix and contract duration, which we adapted from Burkhalter et al. (2009) and Kaenzig et al. (2013), these choice tasks included a flexibility option with four levels, which are described in more detail below. The general idea is that a contract with this option allows the supplier to intervene in the prosumers' normal demand pattern to mobilize distributed flexibility, implying that the customer

³ <http://www.nano-tera.ch/projects/360.php>.

Table 2

Levels of the attribute “Use of flexibility” in the three technology domains.

Technology domain	Levels of the attribute “Use of flexibility”			
PV-battery	Super Flex 30% PV Self-Consumption; consumption data transmitted and used for forecasting	Flex Medium 45% PV Self-Consumption; consumption data transmitted	Flex Light 60% PV Self-Consumption; only data on battery charging level transmitted	No Flex 75% PV Self-Consumption; no data transmitted
Electric vehicles	Super Flex Guaranteed charging level 40%; Unlimited amount of discharging cycles per 24 h	Flex Medium Guaranteed charging level 60%; max. 3 discharging cycles per 24 h	Flex Light Guaranteed charging level 80%; max. 1 discharging cycle per 24 h	No Flex No access to battery for the utility
Heat pumps	Super Flex Guaranteed room temperature 16°C; 5 min hot shower per day	Flex Medium Guaranteed room temperature 18°C; 10 min hot shower per day	Flex Light Guaranteed room temperature 20°C; 15 min hot shower per day	No Flex Guaranteed room temperature 22°C; Unlimited hot shower per day

gives up some autonomy and control over her infrastructure.

The ideal-type flexible prosumer would be characterised by high electricity consumption, distributed generation, and local storage, which enables fast and high-capacity buffering between production and consumption. In order to bring our experimental design as close as possible to real decision-making and to answer our second research question, we surveyed specific subsamples in three domains and adapted the flexibility attribute levels in the choice task correspondingly. The closest approximation to such ideal-type flexible prosumers which already operate on today's energy markets are owners of PV-battery systems, electric vehicles and heat pumps. Consequently, these are the target groups for our empirical analysis:

- 1) Owners of PV plus battery systems, who can offer flexibility by storing local generation and allowing the utility to access the battery
- 2) Electric vehicle owners, where flexibility is related to shifting charging times and accessing the battery when the vehicle is connected to the grid
- 3) Heat pump owners, where flexibility is provided by load shifting of the heat pump operation, making use of the thermal storage capacity of the building

It is important to note that energy companies and prosumers have opposing interests when it comes to the provision of flexibility. From the utilities' point of view, these options increase their flexibility in matching demand and supply. From the prosumers' point of view, in contrast, accepting the flexibility option implies a discomfort. By adopting four levels, from “No Flex” to “Super Flex”, our experimental design mirrors the continuum between a contract design that maximizes the degrees of freedom for the supplier and one that minimizes the discomfort for the prosumer, as displayed in Fig. 2. As our choice experiments measure the prosumers' preferences, we expect increasing levels of flexibility to translate into decreasing part-worth utilities of this attribute, reflecting a rising cost of discomfort.

The specific levels of the flexibility attribute for each of the three technology domains are presented in Table 2. In line with our objective to measure prosumer (rather than supplier) preferences, these levels are described in terms of the degrees of discomfort that they imply for the customer.

3.2.1. Study 1 – PV plus battery

We assume that in the absence of a flexibility option, the solar prosumer

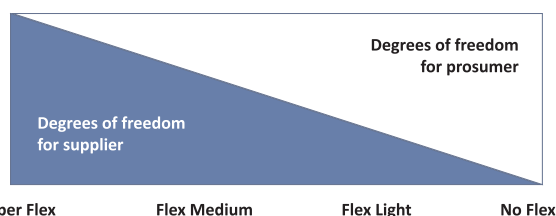


Fig. 2. Flexibility attribute and the trade-off between supplier and prosumer freedom.

would run the system to maximize self-consumption and have full control over its production and consumption data. By allowing the utility to intervene and operate the battery according to its flexibility needs, the prosumer faces two inconveniences: a decreasing share of self-consumption (Santos et al., 2014), and granting the utility data access. The levels of the flexibility attribute describe different shades of those aspects. From No Flex to Super Flex, the self-consumption rate decreases from 75% to 30% (Weniger et al., 2014). In terms of data use, the levels increase from no data access to transmission of consumption data that is used for forecasting, reflecting potential privacy concerns (Efthymiou and Kalogridis, 2010).

3.2.2. Study 2 – electric vehicles

In the “No Flex” scenario, the user has full control over the charging level of her EV battery. With increasing levels of the flexibility attribute, the EV owner will face two inconvenient consequences: A car that is not fully charged when she wants to use it, and increased wear and tear of the battery due to additional discharging cycles caused by the utility. In the Super Flex scenario, only 40% charging level is guaranteed, implying a significant discomfort if the car does not have sufficient range for certain trips, and an unlimited number of discharging cycles per day may occur, implying lower battery lifetime.

3.2.3. Study 3 – heat pumps

In contrast to a “No Flex” scenario, increasing levels of the flexibility attribute imply constraints on the provision of heating and warm water, which allows the utility to react to temporary shortages in electricity supply. To express those inconveniences in terms that are familiar to respondents, we operationalized this as deviations from a desired room temperature, set at 22 °C,⁴ and constraints in the duration of hot showers per day. At the “Super Flex” level, only a room temperature of 16 °C was guaranteed, and hot showers could be limited to five minutes per day. The other levels of the flexibility attribute gradually released those constraints.

In choosing the specific levels of the flexibility attribute, we considered prosumer, supplier and technological perspectives. We wanted to make sure that the levels spanned a spectrum of feasible options in each domain, while also including levels that would stretch the prosumers' comfort zone. At the same time, we attempted to design the experiment in a way that would represent similar amounts of flexibility across the three domains.⁵

⁴ Note that the survey was done in a Northern hemisphere context, where it is reasonable to assume that higher (rather than lower) room temperatures are positively correlated with comfort. To validate this assumption, the questionnaire included a separate question on preferred room temperature, which confirmed our baseline of 22 °C.

⁵ We estimated the amount of flexibility provided per day assuming a 10 kW PV system and 10 kWh battery storage in the solar case, a 40 kWh battery in the electric vehicle case, and a heat pump with a daily consumption of 20 kWh, and applied domain-specific availability factors, reflecting, for example, the fact that electric vehicles, in contrast to stationary PV-battery systems, are not connected to the grid all the time.

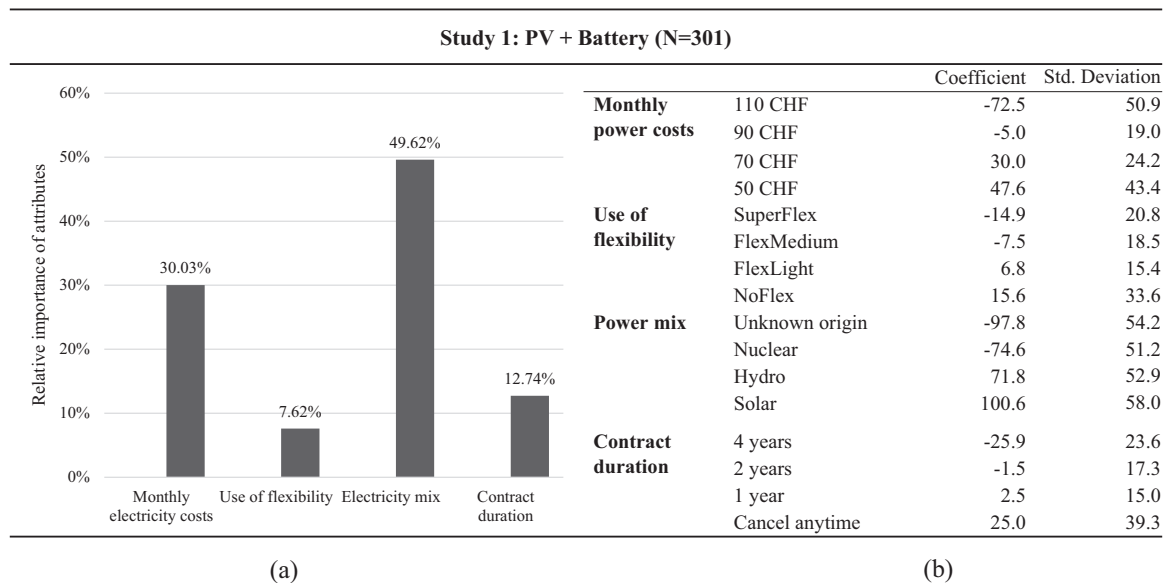


Fig. 3. Importances and part-worth utilities of study 1: PV and battery.

3.3. Sample

Our total sample consists of 902 respondents in German-speaking Switzerland, conducting eight choice tasks each, resulting in a total dataset of 7'216 experimental decisions. Respondents were recruited through the consumer panel of a leading Swiss market research agency⁶ in December 2016. The sample consisted of three subsamples, one for each technology domain, with $N = 300$ to 301 each. The target population were actual or potential prosumers, split up in three technology domains: PV plus batteries,⁷ electric vehicles and heat pumps. A screening question was used to make sure that every respondent either owned one of these devices or intended to buy one in the next three years. If respondents owned (or were interested in buying) more than one of the systems, they were assigned to the group that had the lower response rate until the three samples reached similar size. As Table A1 in the appendix shows, between one third and half of the respondents in any particular domain were also interested in the other technologies, supporting our conjecture that we selected the technologies that will form important cornerstones for the rise of the flexible prosumer. Table A2 in the appendix presents the socio-demographic characteristics of the three subsamples.

4. Results and discussion

In the following, we report the results of the three studies along two main factors: the relative importances of the attributes and the part-worth utilities for attribute levels. Subsequently, we conduct a qualitative comparison of the three studies based on the willingness to co-create flexibility.

4.1. Study 1: PV and batteries

In Fig. 3a, we present the relative importances of the attributes for study 1 addressing the domain of energy use of PV and batteries. The relative importance describes the weight of an attribute in the average respondent's decision. Importances sum up to 100% over the four attributes included in our choice experiment. The part-worth utilities for individual attribute levels are presented in Fig. 3b. They can be

interpreted as the change in average respondents' preference relative to the average level of a given attribute, *ceteris paribus*. Positive values indicate increasing utility, negative values express decreasing utility. The ideal product would combine no flexibility, a green electricity mix, and the possibility to cancel anytime with the lowest power costs of 50 CHF per month, and the part-worth utilities indicate under which conditions respondents' would accept less desired attribute levels.

Respondents of study 1 put the highest importance on the attribute "power mix", when deciding for a power supply contract. The flexibility attribute in contrast received the lowest importance, indicating that respondents do not react particularly sensitively to the discomfort that would be implied by providing flexibility with the battery.

4.2. Study 2: electric vehicles

Fig. 4 displays the results from study 2 focussing on providing flexibility with electric vehicles.

While the EV respondents also exhibit relatively low sensitivity for the flexibility attribute, it is remarkable to observe the concave function of the part-worth utilities for different levels of the flexibility attribute, suggesting that the acceptability of flexibility options shows a sharp drop if guaranteed charging levels decline below 60% of a full charge.

4.3. Study 3: heat pumps

Fig. 5 highlights the findings for study 3 which surveyed actual and potential heat pump customers. Unlike in the other two studies, the attribute "use of flexibility" is the most important attribute for this subsample. This indicates that heat pump customers are very sensitive to changes in levels of this attribute.

4.4. Qualitative comparison across studies

The design of the three studies was defined in a manner that providing flexibility implies critical trade-offs for the respondents. At the same time, the attributes were set so that a similar amount of flexibility is provided with the attribute levels across the three studies. We therefore aim for a qualitative comparison across the three studies.

As can be seen from Figs. 3 and 4, the PV and EV studies show a similar ranking of attribute importances, with electricity mix and monthly cost being the two most important attributes. The attribute use of flexibility is comparatively less important for these respondents, and even the least important attribute in the PV plus battery study. Given

⁶ <https://www.intervista.ch/panel/?lang=en> - The overall panel includes nearly 70'000 consumers.

⁷ The monthly electricity cost for this subsample includes the cost of battery leasing.

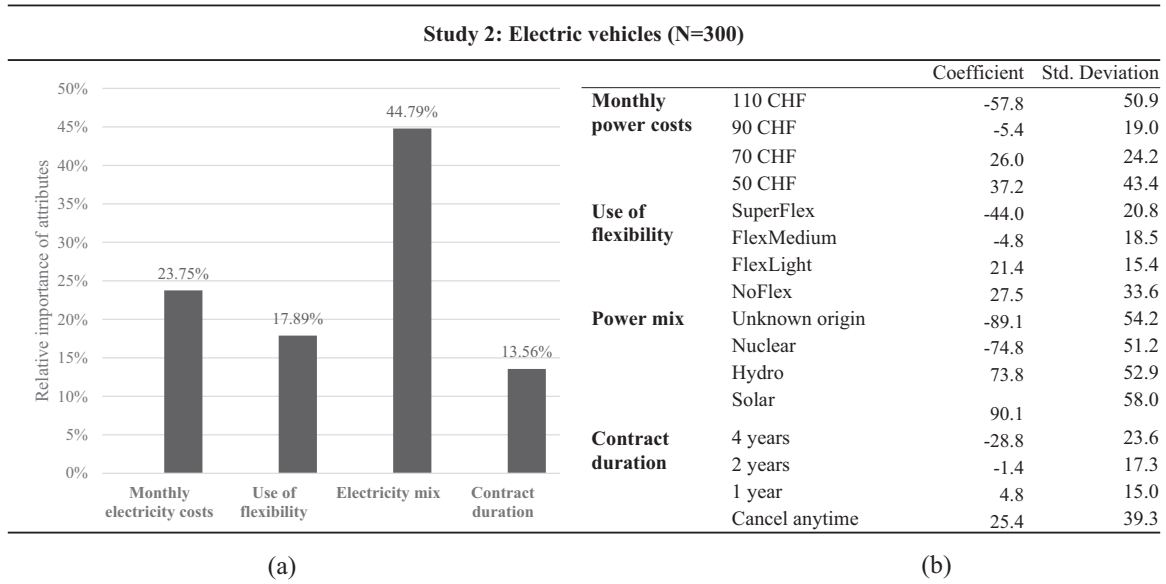


Fig. 4. Importances and part-worth utilities of study 2: Electric vehicles.

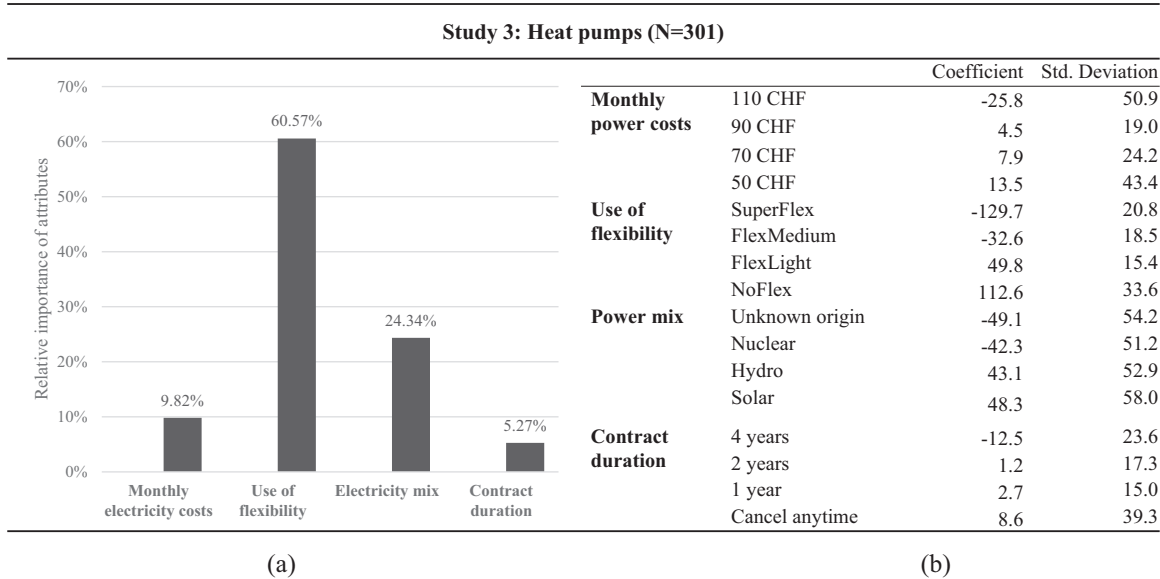


Fig. 5. Importances and part-worth utilities of study 3: Heat pumps.

our operationalization of flexibility as reflecting varying levels of discomfort, this suggests that current and potential PV plus battery owners perceive the lowest level of inconvenience from the flexibility options included in the experiment. Quite to the contrary, as can be seen in Fig. 5, flexibility is by far the most important attribute for the heat pump owners, followed by electricity mix and monthly cost. Across all studies, the importance of contract duration is rather limited, suggesting that – all else being equal – respondents prefer shorter contract duration, but this preference is relatively weak compared to the other attributes.

Apart from the differences in importances discussed above, the preference order within attributes is remarkably consistent across the three studies. For example, when it comes to the attribute *electricity mix*, owners of EV, PV and heat pumps all prefer renewable energies like solar and hydro over nuclear power or electricity of unknown origin.

Finally, we can also express the results of the flexibility attribute in monetary terms, as a willingness-to-accept the discomfort of sharing control over one's energy use. We calculate this required flexibility

premium with a fixed cost coefficient and on the basis of average preference levels (Sillano and Ortúzar, 2005), by dividing mean-centered utilities by the monetary coefficient of the monthly power costs (MC). We applied the following definitions:

$$WTCC = \frac{\beta_{flex, max} - \beta_{flex, j}}{MC} \quad (1)$$

$$MC = \frac{\beta_{pc, max} - \beta_{pc, min}}{PC_{max} - PC_{min}} \quad (2)$$

where $\beta_{flex, j}$ represents the part-worth utility value of the flexibility attribute at level j and $\beta_{flex, max}$ indicates the highest part-worth utility value within the flexibility attribute (corresponding to the “no flex” option in all three studies). MC is the linear monetary coefficient, which is the ratio of the minimum and maximum values of the part-worth utilities of the attribute “monthly power cost” ($\beta_{pc, max} - \beta_{pc, min}$) to the levels of that same attribute ($PC_{max} - PC_{min}$). Using study 1 (PV + battery) as an example, respondents would ask for 4.40 CHF to shift

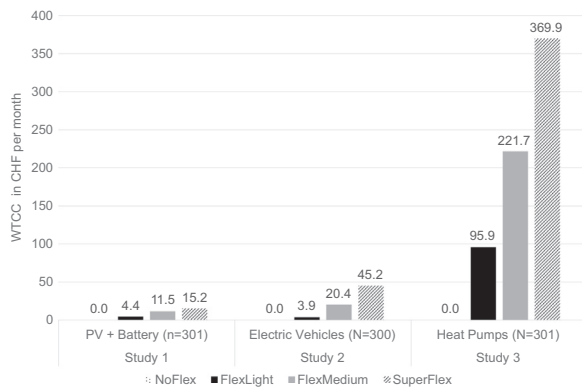


Fig. 6. Implicit discomfort cost (willingness-to-co-create) for flexibility.

from the NoFlex option to FlexLight.⁸ As Fig. 6 shows, the implicit discomfort cost ranges from 3.85 to 45.16 CHF per month for electric vehicle users and 4.40–15.24 CHF per month in the PV plus battery case. Especially for the LightFlex and MediumFlex levels, moderate discounts on the electricity bill would allow utilities to access affordable flexibility. In contrast, the implicit discomfort cost for actual and potential heat pump owners is prohibitively high, exceeding the average monthly power cost in all cases except for the NoFlex scenario.

5. Conclusion and implications for energy policy

Increasing shares of renewable energies create new challenges for balancing supply and demand, but in combination with the rise of the prosumer, they also offer opportunities for providing distributed flexibility. In this paper, we have emphasized the important role of the prosumer in co-creating flexibility. By conducting a series of choice experiments with 902 actual and potential flexible prosumers across three domains of energy use, we confirm that there is actually a positive willingness to co-create flexibility. It is important to note that prosumers do not prefer flexibility per se, but they are willing to accept certain levels of inconvenience in exchange for higher utility through other product attributes, e.g. a cheaper or greener electricity tariff. In our experimental setting, we also find differences between the three domains, in that prosumers with PV plus battery systems and electric vehicle owners appear to be more willing to provide flexibility than heat pump owners. This suggests that even similar levels of technical flexibility provision may result in different reactions by prosumer, based on domain-specific discomfort cost. Apart from the specific use context, the way in which the consequences of flexibility provision are being framed may also influence prosumers' willingness to co-create distributed flexibility. For example, describing the consequences of flexibility provision in the heat pump sample as influencing room temperature and hence being closely linked to personal comfort levels may have emphasized the inconvenience in more concrete terms than the reduced charging levels of the car battery in the EV sample.

To our knowledge, this is the first study that systematically investigates consumers' willingness to co-create flexibility across three domains of energy use. The paper highlights novel opportunities to advance the search processes for smart grid solutions and flexibility business models by putting "humans in the loop". The paper provides for instance data and insights for more accurate energy system modeling based on consumers' willingness to co-create flexibility. Optimization and simulation models in the energy domain often operate based on static models of human agency, whereas accuracy of

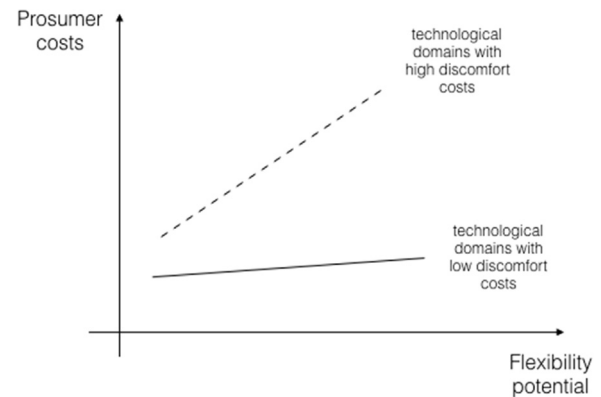


Fig. 7. A contingent view on flexibility potential with distributed prosumers.

energy system modeling can be increased by considering empirical insights on consumer decision making (Eichler et al., 2016; Kubli, 2017).

In terms of **implications for energy policy**, this paper confirms that there is indeed significant potential for distributed flexibility if prosumers' preferences are successfully addressed. Policymakers looking for ways of integrating high shares of renewables can therefore be encouraged to look beyond centralized solutions for the provision of flexibility (e.g. capacity markets for large power plants). Our study helps to take the prosumer perspective into account when designing policy instruments for distributed flexibility provision. Our findings also highlight the importance of prosumer heterogeneity across different domains of energy use, indicating that there may not be a one-size-fits-all solution to incentivizing the emergence of distributed flexibility provision. We would caution, though, that drawing policy conclusions from the latter insight is a non-trivial task: For example, sticking to opt-in models of flexibility provision, where consumers voluntarily decide whether or not they want to offer flexibility, would maximize consumer choice, but may at the same time be an obstacle towards maximizing the system benefits of distributed flexibility.

In terms of **implications for energy business model design**, our study provides three main insights. First, energy companies looking for low-hanging fruit in terms of mobilizing distributed flexibility resources may be well advised to target prosumers with PV plus batteries and drivers of electric vehicles. Heat pump owners, in contrast, appear to be more reluctant to provide flexibility, at least if it has the kind of direct impact on their personal comfort that our study design implied. Hence acquiring distributed flexibility is more costly in some domains than others. Second, another way of looking at the higher willingness to provide flexibility among EV drivers and solar prosumers is that they might be less opposed to more automated modes of flexibility provision, such as the "smart camouflage" business model described by Curtius et al. (2012). Third, our findings also suggest that prosumers expect to be compensated for the cost of discomfort that providing flexibility implies for them. Such compensation can take the form of lower monthly electricity bills, but also higher levels of other desirable product attributes, like the share of renewables in the electricity mix.

As an early contribution to an emerging research stream, our study is subject to **limitations** that can be the starting point for **further research** in this important domain. First, our study highlights the importance of taking a contingent view on the potential that flexible prosumers offer. Such a contingency perspective argues that the potential contribution of flexible prosumers to the power system can only be assessed by looking at the distinct specifics in which the flexible prosumer operates. While naturally it is important to consider features of the technological set-up (e.g. the capacity of the batteries or heat-pumps and the infrastructure, including specifics of charging systems or heating system configurations) our study shows how important also behavioral aspects are. Flexible prosumers differ considerably in how much they are willing to provide flexibility. It is an urgent need for future studies to consider and control for this important

⁸ This is calculated using the part-worth utilities from Figure 3. $MC = (\beta_{pc,max} - \beta_{pc,min}) / (PC_{max} - PC_{min}) = 47.6 - (-72.5) / (110 \text{ CHF} - 50 \text{ CHF}) = 120.1 / 60 \text{ CHF} = 2.00167 \text{ CHF}^{-1}$. $WTC_{FlexLight/NoFlex} = (\beta_{flex,j} - \beta_{flex,max}) / MC = ((15.6 - 6.8) / 2.00167) \text{ CHF} = 4.40 \text{ CHF}$.

insight. The model that emerges from our study is that the flexibility potential that is attributable to prosumer behavior is contingent to distinct, prosumer related costs. In our study, different technological set-ups provide high (heating) or low (batteries) discomfort costs, which in turn determine the behavior-based flexibility potential. Fig. 7 depicts the model which provides important guidance for future research on prosumer behavior in the energy sector.

Second, while we observe significant differences in prosumers' willingness to provide flexibility between the three technology domains, our analysis can only provide limited insights into the underlying reasons for those differences. Further research could investigate whether the preference for a given flexibility option is in fact explained by its impact on personal comfort levels, or whether other situational or personal factors play a role. Third, while we have attempted to design comparable choice contexts across the three domains, our findings are clearly influenced by how we operationalized the flexibility attribute in the three choice experiments. Future research can validate our findings with different ways of operationalizing flexibility. This implies two directions: First, it would be desirable to identify a commonly agreed upon technical measure to compare the potential of distributed flexibility options across different domains of energy use. Second, domain-specific studies could test different ways of describing the implications of distributed flexibility options on prosumer discomfort, and thereby disentangle framing effects from the

underlying variations in preferences. Such research would have direct benefits for designing flexibility products and services.

Finally, while we see consumer preferences as an important, so far neglected, determinant of the emergence of distributed flexibility markets, it would certainly be valuable in further research to combine this perspective with insights from electricity market modellers, electrical engineers and regulation specialists. Such interdisciplinary collaboration would also allow to iteratively design and test further flexibility options beyond the three specific cases mentioned in this paper.

Acknowledgements

The authors gratefully acknowledge funding from the nano-tera project HeatReserves, the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 646476 (EMPOWER) and from SCCER CREST and SCCER Mobility, which are financially supported by the Swiss Commission for Technology and Innovation (CTI). We thank Gianni Operto and Thomas Kubli for their expert advice on the technical assessment of flexibility options included in the choice experiments, as well as Stefanie Hille and Nina Hampl for their helpful methodological advice. Furthermore, we like to thank three anonymous reviewers for their valuable feedback on an earlier version of this manuscript. All remaining errors are our own.

Appendix

(See Tables A1 and A2).

Table A1

Prosumers express interest in further energy technologies across three domains.

Actual & Potential Owners of...	PV + Battery (N = 301)		Heat Pump (N = 301)		Electric Vehicle (N = 300)	
...are also interested in...	N	%	N	%	N	%
Solar PV			125	42%	136	45%
Heat Pump	87	29%			95	32%
Electric Vehicle	128	43%	114	38%		

Table A2

Socio-demographic characteristics of the three samples.

Sample	Study 1: PV+ (N = 301)		Study 2: EV (N = 300)		Study 3: HP (N = 301)	
		PV in %		EV in %		HP in %
Male	183	61%	194	65%	174	58%
Female	117	39%	106	35%	127	42%
Average age (years)	51.4		48.1		49.5	
Owner of technology	176	59%	56	19%	255	85%
Interested in technology	124	41%	244	81%	46	15%
Urban	72	24%	80	27%	44	15%
Agglomeration	167	56%	160	54%	168	56%
Rural	61	20%	59	20%	87	29%
Number of people per household	2.49		2.46		2.50	
Rental flat	71	24%	147	48%	70	23%
Rental house	9	3%	10	3%	16	5%
Own Flat	36	12%	41	13%	48	16%
Own House	183	61%	110	36%	175	57%
Education						
Compulsory education	1	0.3%	3	1.0%	2	0.7%
Secondary education	153	51.2%	135	45.0%	161	53.7%
Tertiary education	141	47.2%	161	53.7%	135	45.0%
none	4	1.3%	1	0.3%	2	0.7%
Monthly household income						
Less than 4'500 CHF	24	8%	21	7%	13	4%
Between 4'501 and 6'000 CHF	20	7%	27	9%	19	6%
Between 6'001 and 9'000 CHF	77	27%	72	25%	64	22%
Between 9'001 and 12'000 CHF	62	21%	57	20%	72	24%
More than 12'000 CHF	51	18%	54	19%	63	21%
No answer	55	19%	59	20%	65	22%

References

- Agnew, S., Dargusch, P., 2015. Effect of residential solar and storage on centralized electricity supply systems. *Nat. Clim. Change* 5, 315.
- Annala, S., 2015. Households' Willingness to Engage in Demand Response in the Finnish Retail Electricity Market: An Empirical Study. *Acta Universitatis Lappeenrantaensis*.
- Aravena, C., Riquelme, A., Denny, E., 2016. Money, comfort or environment? Priorities and determinants of energy efficiency investments in Irish households. *J. Consum. Policy* 39, 159–186.
- Bergman, N., Eyre, N., 2011. What role for microgeneration in a shift to a low carbon domestic energy sector in the UK? *Energy Effic.* 4, 335–353.
- Bollinger, B., Gillingham, K., 2012. Peer effects in the diffusion of solar photovoltaic panels. *Mark. Sci.* 31, 900–912.
- Burger, S.P., Luke, M., 2017. Business models for distributed energy resources: a review and empirical analysis. *Energy Policy* 109, 230–248.
- Burkhalter, A., Kaenzig, J., Wüstenhagen, R., 2009. Kundenpräferenzen für leistungsrelevante Attribute von Stromprodukten. *Z. Energ.* 33, 161–172.
- Cappers, P., Goldman, C., Kathan, D., 2010. Demand response in US electricity markets: empirical evidence. *Energy* 35, 1526–1535.
- Chau, C.-K., Tse, M., Chung, K., 2010. A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes. *Build. Environ.* 45, 2553–2561.
- Curtius, C.H., Hille, S.L., Berger, C., Hahnel, U., Wüstenhagen, R., 2017. Shotgun or Snowball Approach? Accelerating the Diffusion of Rooftop Solar Photovoltaics Through Peer Effects and Social Norms Working Paper. University of St.Gallen.
- Curtius, C.H., Künzel, K., Loock, M., 2012. Generic customer segments and business models for smart grids. *der markt* 51, 63–74.
- Denholm, P., Hand, M., 2011. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. *Energy Policy* 39, 1817–1830.
- Dharshing, S., 2017. Household dynamics of technology adoption: a spatial econometric analysis of residential solar photovoltaic (PV) systems in Germany. *Energy Res. Soc. Sci.* 23, 113–124.
- Dütschke, E., Paetz, A.-G., 2013. Dynamic electricity pricing—which programs do consumers prefer? *Energy Policy* 59, 226–234.
- Ebers, A., Wüstenhagen, R., 2015. 5th Consumer Barometer of Renewable Energy.
- Efthymiou, C., Kalogridis, G., 2010. Smart grid privacy via anonymization of smart metering data, in: *Proceedings of the First IEEE International Conference on Smart Grid Communications (SmartGridComm)*, IEEE, pp. 238–243.
- Eichler, A., Darivianakis, G., Smith, R., Lygeros, J., 2016. Humans in the loop: a stochastic predictive approach to building energy management in the presence of unpredictable users, In: *Zurich, E. (Ed.)*.
- Gamma, K., 2016. Behavioral and attitudinal customer loyalty in the power sector. *Z. Energ.* 40, 211–232.
- Good, N., Karangelos, E., Navarro-Espinoza, A., Mancarella, P., 2015. Optimization under uncertainty of thermal storage-based flexible demand response with quantification of residential users' discomfort. *IEEE Trans. Smart Grid* 6, 2333–2342.
- Gordijn, J., Akkermans, H., 2007. Business models for distributed generation in a liberalized market environment. *Electr. Power Syst. Res.* 77, 1178–1188.
- Heinze, S.L., Wüstenhagen, R., 2012. Dynamic adjustment of eco-labeling schemes and consumer choice—the revision of the EU energy label as a missed opportunity? *Bus. Strategy Environ.* 21, 60–70.
- Helms, T., Loock, M., Bohnsack, R., 2016. Timing-based business models for flexibility creation in the electric power sector. *Energy Policy* 92, 348–358.
- Hensher, D.A., Rose, J.M., Greene, W.H., 2005. *Applied Choice Analysis: A Primer*. Cambridge University Press.
- Herbes, C., Friege, C., 2017. *Marketing Renewable Energy*. Springer International Publishing.
- Kaenzig, J., Heinze, S.L., Wüstenhagen, R., 2013. Whatever the customer wants, the customer gets? Exploring the gap between consumer preferences and default electricity products in Germany. *Energy Policy* 53, 311–322.
- Kaufmann, S., Kuenzel, K., Loock, M., 2013. Customer value of smart metering: explorative evidence from a choice-based conjoint study in Switzerland. *Energy Policy* 53, 229–239.
- Kondziella, H., Bruckner, T., 2016. Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies. *Renew. Sustain. Energy Rev.* 53, 10–22.
- Kotler, P., 1986. The prosumer movement: a new challenge for marketers. *ACR North Am. Adv.*
- Kubli, M., 2018. Squaring the sunny circle? On balancing distributive justice of power grid costs and incentives for solar prosumers. *Energy Policy* 114, 173–188.
- Kubli, M., Ulli-Beer, S., 2016. Decentralisation dynamics in energy systems: a generic simulation of network effects. *Energy Res. Soc. Sci.* 13, 71–83.
- Lancaster, K.J., 1966. A new approach to consumer theory. *J. Political Econ.* 74, 132–157.
- Louviere, J.J., Flynn, T.N., Carson, R.T., 2010. Discrete choice experiments are not conjoint analysis. *J. Choice Model.* 3, 57–72.
- Lüdeke-Freund, F., Loock, M., 2011. Debt for brands: tracking down a bias in financing photovoltaic projects in Germany. *J. Clean. Prod.* 1356–1364.
- Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev.* 45, 785–807.
- Lüthi, S., Wüstenhagen, R., 2012. The price of policy risk — empirical insights from choice experiments with European photovoltaic project developers. *Energy Econ.* 34, 1001–1011.
- Moore, W.L., 2004. A cross-validity comparison of rating-based and choice-based conjoint analysis models. *Int. J. Res. Mark.* 21, 299–312.
- Moser, C., 2017. The role of perceived control over appliances in the acceptance of electricity load-shifting programmes. *Energy Effic.* 1–13.
- Orme, B.K., 2000. *Hierarchical Bayes: Why All the Attention?* In: *Sawtooth Software, I. (Ed.), Research Paper, Sequim, WA*.
- Park, M., Hagishima, A., Tanimoto, J., Chun, C., 2013. Willingness to pay for improvements in environmental performance of residential buildings. *Build. Environ.* 60, 225–233.
- Paterakis, N.G., Erdinc, O., Catalão, J.P., 2017. An overview of demand response: key-elements and international experience. *Renew. Sustain. Energy Rev.* 69, 871–891.
- Pournaras, E., Vasirani, M., Kooij, R.E., Aberer, K., 2014. Decentralized planning of energy demand for the management of robustness and discomfort. *IEEE Trans. Ind. Inform.* 10, 2280–2289.
- Rai, V., Robinson, S.A., 2013. Effective information channels for reducing costs of environmentally-friendly technologies: evidence from residential PV markets. *Environ. Res. Lett.* 8, 014044.
- Rode, J., Weber, A., 2016. Does localized imitation drive technology adoption? A case study on rooftop photovoltaic systems in Germany. *J. Environ. Econ. Manag.* 78, 38–48.
- Roe, B., Teisl, M.F., Levy, A., Russell, M., 2001. US consumers' willingness to pay for green electricity. *Energy Policy* 29, 917–925.
- Salm, S., 2017. The investor-specific price of renewable energy project risk – a choice experiment with incumbent utilities and institutional investors. *Renew. Sustain. Energy Rev.*
- Sammer, K., Wüstenhagen, R., 2006. The influence of eco-labelling on consumer behaviour—results of a discrete choice analysis for washing machines. *Bus. Strategy Environ.* 15, 185–199.
- Santos, J.M., Moura, P.S., Almeida, A.Td., 2014. Technical and economic impact of residential electricity storage at local and grid level for Portugal. *Appl. Energy* 128, 254–264.
- Sawtooth, 2009a. *The CBC/HB System for Hierarchical Bayes Estimation*, In: *Sawtooth Software, I. (Ed.), Technical Papers, Sequim, WA*.
- Sawtooth, 2009b. *Sample Size Issues for Conjoint Analysis*, In: *Sawtooth Software, I. (Ed.), Technical Papers, Sequim, WA*.
- Sawtooth, 2017. *The CBC System for Choice – Based Conjoint Analysis*, In: *Sawtooth Software, I. (Ed.), Technical Papers, Orem, Utah*.
- Sigrin, B., Pless, J., Drury, E., 2015. Diffusion into new markets: evolving customer segments in the solar photovoltaics market. *Environ. Res. Lett.* 10, 084001.
- Sillano, M., Ortúzar, Jd.D., 2005. Willingness-to-pay estimation with mixed logit models: some new evidence. *Environ. Plan. A* 37, 525–550.
- Sowe, S.K., Simmon, E., Zettsu, K., de Vaulx, F., Bojanova, I., 2016. Cyber-physical-human systems: putting people in the loop. *IT Prof.* 18, 10–13.
- Tabi, A., Hille, S.L., Wüstenhagen, R., 2014. What makes people seal the green power deal? — customer segmentation based on choice experiment in Germany. *Ecol. Econ.* 107, 206–215.
- Tabi, A., Wüstenhagen, R., 2017. Keep it local and fish-friendly: social acceptance of hydropower projects in Switzerland. *Renew. Sustain. Energy Rev.* 68 (Part 1), 763–773.
- Toffler, A., 1980. *The Third Wave*. William Morrow and Company. Inc. Google Scholar, New York.
- Torriti, J., Hassan, M.G., Leach, M., 2010. Demand response experience in Europe: policies, programmes and implementation. *Energy* 35, 1575–1583.
- Veldman, E., Gibescu, M., Slootweg, H., Kling, W.L., 2013. Scenario-based modelling of future residential electricity demands and assessing their impact on distribution grids. *Energy Policy* 56, 233–247.
- Wemyss, D., Castri, R., Luca, V., De Cellina, F., Lobsiger-kägi, E., Bianchi, P., Hertach, C., Kuehn, T., Carabias, V., 2016. Keeping up with the Joneses: examining community-level collaborative and competitive game mechanics to enhance household electricity-saving behaviour, in: *Proceedings of the 4th European Conference on Behaviour and Energy Efficiency (Behave 2016)*, pp. 1–17.
- Weniger, J., Tjaden, T., Quaschnig, V., 2014. Sizing of residential PV battery systems. *Energy Procedia* 46, 78–87.
- Wolsink, M., 2012. The research agenda on social acceptance of distributed generation in smart grids: renewable as common pool resources. *Renew. Sustain. Energy Rev.* 16, 822–835.
- Wuebker, R., Hampl, N., Wüstenhagen, R., 2015. The strength of strong ties in an emerging industry: experimental evidence of the effects of status hierarchies and personal ties in venture capitalist decision making. *Strateg. Entrep. J.* 9, 167–187.