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# How User-Innovators Pave the Way for a Sustainable Energy Future: A Study among German Energy Enthusiasts

**Matti Grosse** [1,2]

[1] Faculty of Economics and Management, Technical University Berlin, 10587 Berlin, Germany; m.grosse@tu-berlin.de; Tel.: +49-30-314-76862

[2] Alexander von Humboldt Institute for Internet and Society, 10117 Berlin, Germany

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**Abstract:** The existence of user-innovators in the household sector is undeniable. Prior research provided evidence on the vast scope of product developments by household sector users and documented a large set of individual user-innovator characteristics to explain their behavior. What has largely been neglected as a potential source of user innovation activities are product- and technology-specific factors. This study aims to fill this gap by identifying and analyzing user-innovators in Germany. On the basis of the results of a large-scale survey on German energy enthusiasts, we find dissatisfaction with existing products and time-consuming implementation as the main drivers of user innovation in our setting. The results show a negative correlation between data security concerns and the likelihood of becoming a user-innovator, pointing towards the maker culture among user-innovators. As an implication of our work, we provide a roadmap for all stakeholders aiming to harness the potential of user-innovators for future open innovation eco-systems.

**Keywords:** user innovation; open innovation; smart energy; energy transition; Germany; survey

## 1. Introduction

The need for a clean, secure, and sustainable energy future is more urgent than ever. Not only is Germany on its way to missing the climate targets for 2020, but also for the succeeding decades. Long-lasting heat periods are becoming increasingly noticeable and can cause social effects and negative consequences for nature, agriculture, and energy production [1]. Rifkin clarifies this importance and argues that the progress of our entire society is related to the energy system, with users and consumers playing an important role in shaping a sustainable energy future [2].

Smart energy products (e.g., smart home applications, smart meters, and energy monitors) are designed to help identify power guzzlers in households, to conduct energy-intensive processes in times of excess capacity, and to optimize energy consumption [3]. However, the sale figures for smart energy products are low [4]. Research reveals that disinterest and disenchantment are the main drivers of the lagging adoption [5]. Other studies identify data security concerns to explain the non-use [6].

In situations in which products available in the market do not fit user needs, consumers usually start innovating for themselves. This phenomenon called user or household sector innovation, which was comprehensively summarized in [7] for the first time, is an integral part of the open innovation idea [8,9]. As recent examples show, the range of user-innovated products include gadgets and tools facilitating the lives of people with disabilities [10] as well as solutions reducing the bacteria inside a baby-bottle and bottles facilitating the preparation of the baby formula [11]. Representative studies have been conducted in several countries since 2012. The results show that 1.5%–6.1% of individuals engage in user innovation [12]. A recent re-estimation of these findings reveals that the numbers of user-innovators may even be underestimated because of methodological issues concerning the data collection [13]. In any case, the number of user-innovators and the collectively spent amount of time and money are impressive and indicate the huge potential for creative ideas of new products and features.

Aside from providing broad evidence, previous research mainly focused on the characteristics and motivation of user-innovators at the individual level. The small part of variance explained by the individuals' attributes in national surveys [14] may be mainly due to the fact that other factors drive user innovation effort, for example, daily practices [15], product ownership [16], or normative considerations [17]. However, product- and technology-specific factors have been largely neglected as potential triggers for user innovation. Therefore, we consider framework conditions in a specific technological area to deliver an additional set of motives for users to start prototyping.

This study aims to identify and characterize user-innovators within the scope of smart energy technologies. Thus, we conducted a large-scale survey on German energy enthusiasts. The primary goal was to understand their reasons to innovate in this technologically complex product range as the market penetration of smart energy products is lagging on the one hand but the energy market situation (e.g., high-quality infrastructure, mainly low bills, and almost no black-outs) remains luxurious in comparison with those of other countries on the other hand.

On the basis of the results, we contribute to the literature in three ways. First, we detect an enormous potential of user-innovators among German energy enthusiasts. Second, we examine the effects of product- and technology-specific factors on the likelihood of being a user-innovator. That is, the results reveal that following intrinsic motivation, dissatisfaction with existing smart energy products and time-consuming implementation are the primary motives of user-innovators to spring into action. Interestingly, we find the variable data security concerns to be a negatively significant predictor of user innovation, as it indicates that user-innovators are makers who do not care much about laws and regulations. In this regard, our results are in accordance with previous research that hints towards the vigor of user-innovators and the tendency to invoke change [17,18]. Third, we provide a roadmap for all stakeholders, including active and potential user-innovators themselves and especially companies, policymakers, and society to emphasize the untapped potential of these creative minds and present a way how to make user innovation an integral part of future open innovation eco-systems. Moreover, we discuss why an understanding of user-innovators can help to understand consumer needs in general. We conclude our work by presenting the limitations of our study and providing suggestions for future research.

## 2. Literature Review

In our study, we understand user-innovators as individuals, that is, consumers: (1) practicing innovation activities in their discretionary time without payment; and (2) aiming to benefit from the usage of the innovation [12]. Following the Oslo Manual 2018, the output created by such user-innovators is described as an user innovation [9]. As companies or research institutes are usually not involved [19], user innovation activities commonly occur outside of formal research and development (R&D) processes and are thus classified as extra-organizational innovation practices [8]. Therefore, in the context of our research, we do not consider firm user-innovators [20], lead users [21], and user co-creation activities [19]. Moreover, we focus on single user-innovators and do not discuss collaborative user innovation [22].

### *2.1. Measuring User Innovation*

Measuring household sector innovation is important even if it has been largely excluded from official innovation statistics [13]. To identify and measure consumer household innovations, national surveys were conducted in six countries: the United Kingdom [14], the United States [23], South Korea [24], Japan [25], Finland [26], and Canada [27]. An overview of the studies can be found in [12].

All studies are representative and use a common questionnaire as basis for the survey [12]. The results show that the percentage of user-innovators differs between the examined countries, ranging from 1.5% in South Korea [24] to 6.1% in the United Kingdom [14]. In total, 25.91 million people can be identified as user-innovators who create and modify products for personal or family use, excluding service and process innovation [12]. While the expenditures range from nearly zero to high amounts on average, user-innovators spend between a few hundred and more than a thousand dollars per year on their developments. In the United Kingdom, the amount of privately invested resources even outnumbers the industry R&D spending for consumer products [14,28].

### *2.2. User-Innovators: Demographic Characteristics*

As the interest in user innovation increased in recent years, the evidence landscape in the determinants of user innovation has become more detailed but also more diverse. For example, the results on user-innovator demographic characteristics are heterogeneous. Thus, previous studies found that the education level is positively correlated with user innovation activities [24,28]. Other studies did not find any significant effect of education on the likelihood of being a user-innovator [25]. Regarding gender, most studies agreed on the fact that male consumers are significantly more likely to become user-innovators [24,25,28]. The study [29] found that user-innovators in the ideation and prototyping phase are more likely to be male. However, age seems to be important only in case different types of user-innovators are differentiated, namely, revealing, social, or silent innovators [25]. In general, the age of user-innovators does not seem to affect their innovation activities [14,24]. Regarding job possession, the study results vary. Whereas employed people are more likely to be user-innovators in Korea [24], no effect was found in other countries [14,28].

Study results became more consistent in the analysis of two other determinants of user innovation. User-innovators tend to be highly skilled in their respective fields of innovation, particularly in the technical context [14,24,29]. Further, ownership seems to be a critical factor affecting user innovation, both in the physical and digital world [30]. Recent results indicated that the separation of ownership and control negatively affects user innovativeness [16]. Therefore, users commonly have ideas for improving and modifying products but struggle with the realization under certain circumstances.

### *2.3. Users' Motives to Innovate*

The household sector user-innovators innovate for personal need [31]. Beyond this motivation, users start innovating because the process itself is self-rewarding [12]. Generally, intrinsic motivational drivers are identified as the key motives of users to innovate [32,33]. Aside from problem-solving ambitions, feelings of accomplishment and enjoyment are also important [34]. These feelings of inducing self-efficacy and self-expression, or the "I designed it myself" effect as framed in the literature, describe a psychological benefit to users [17,35].

The findings from these studies confirm the results of the national surveys [12]. In Finland, for example, the main motivations to innovate were "personal needs" and "fun and learning", and a minority of the respondents stated the "wish to help others" and "the prospect of selling the product" as motivation [26]. Consequently, a previous work showed that this perceived personal benefit of innovation positively predicts the likelihood to innovate and allocate private resources to these tasks [36].

### *2.4. User Innovation in Complex Technologies*

As the national surveys to measure user innovation are not limited in the scope of product creations or modifications, they investigate the number of user-innovators in various innovation categories [12]. In Japan and the United States, the category "dwelling-related" is the predominant user innovation category (45.8% and 25.4%, respectively), and the other categories of "gardening", "vehicles", "children", and "sports and hobbies" range between 4.4% and 14.3% [23,37]. In the United Kingdom and Canada, the category "crafts & shop tools" (23% and 22%, respectively) is the top innovation category, and "crafts & shop tools" and "dwelling" share the first position in Finland [12]. The category "household fixtures or furnishing" and "sports or hobby or entertainment related" share the first position, with at both 17.9% in South Korea [24].

Other studies focused on a particular market circumstances in which classical producer innovation could be lacking [38,39] or disenchantment and disinterest among consumers is the reason for slow market diffusion [5]. In these situations, users commonly start to innovate for themselves because local needs are not satisfied by the market [40,41]. Moreover, users identify technological gaps and start creating their solutions that fit their particular environment. The area of open-source hardware and software tools is predestined for these efforts, as both users are free to use, modify, and redistribute solutions [42,43], and contributors to those projects are driven by learning, challenges, and interaction with like-minded people [44]. Moreover, ideological reasons may be another driver of user innovation [17]. Thus, studies pointed at an increased willingness to contribute and actively participate in socially induced topics such as climate protection and sustainability [45,46].

## 3. Materials and Methods

This research adopts the approach of previous studies that determined the extent of household sector innovation activities in various settings [14,24,26,28]. Following these studies, our study aims to quantify the extent and understand user-innovators in the field of complex technologies in Germany. To achieve this aim, we followed a three-stage research design: First, we created a questionnaire appropriate to our research focus based on preparatory interviews. Second, we conducted a large-scale survey on energy enthusiasts in Germany. Finally, we applied multivariate regression analysis to identify the critical characteristics of German household sector innovations in complex technologies.

### *3.1. Data Collection*

Our survey design was based on the questionnaire for identifying and surveying consumer innovators that was developed by [47] and consistently used in six national surveys so far [12]. We decided to conduct six semi-structured interviews with potential user-innovators beforehand to understand the specific characteristics of smart energy technologies. The interview experts were randomly approached in the online forum of co2online and asked each one for a 60-min interview session. Using qualitative content analysis [48], we used the findings to double-check and complement the answer options of the questions focusing on technology-specific aspects. In doing so, we could reduce the number of missing or irrelevant answer items.

To collect our data on user-innovators in complex energy technologies, we conducted an Internet-based survey on the newsletter subscribers of the non-profit organization co2online. This think tank, which is supported by the German Federal Ministry for Environment, Nature Conservation, and Nuclear Safety, combines know-how, empirical analyses, and target-oriented online communication on climate protection issues. It is one of the largest non-profit organizations in Germany supporting the reduction of greenhouse gas emissions, climate protection, and energy transition. As our study focuses on the identification of user innovation in the specific context of energy technologies, we assume this data source to be of great value for our research objectives. We are fully aware of the fact that, in contrast to those of the aforementioned studies, our sample is not representative at the national level. Nevertheless, we assume to derive valid and reliable results in the context of our research focus.

The data collection process took place between April and June 2017. The final sample consisted of 1260 answers.

### *3.2. Survey Design*

The survey was divided into three parts: (1) diffusion and acceptance of smart energy technologies; (2) user-innovator identification; and (3) follow-up questions on demographic characteristics. An introductory statement was initially provided to the respondents, including information on the study purpose, aims, and confidentiality aspects.

In the first part, we were interested in the different aspects of smart energy technologies. For example, we asked for the motives for dealing with energy-related issues, the energy products used by the respondents, the problems they encounter in using smart energy technologies, and the knowledge sources of the respondents.

The questions in the second part followed the survey script taken from [47]. This script includes a queue that helps respondents to recall innovation activities and thus provide information on their household sector product innovations, namely, money and time expenditures, diffusion efforts, and collaboration intentions [12]. This information is critical because it helps to exclude "false positives" in the screening phase [14]. Following the suggestion of [12] in the case of a specific research scope, we included questions related to particular problems faced by user-innovators in the field of complex energy technologies and asked for the respondents' assessments.

### *3.3. Data Screening*

In the screening process, we applied the procedure initially developed by [14] and refined in [26]. This method identifies the respondents whose innovations are qualified as user innovations and are thus (1) not job-related; (2) not available in the market; and (3) functionally novel and consequently contains user-developed content [14].

Out of the 1260 respondents, 319 reported the realization of at least one idea in smart energy technologies. Thus, 914 cases were excluded from the sample because the respondents could not recall any innovation-related activity within the last three years. In the second step, we screened 27 cases in which innovation was part of the respondent's job or business. As we are only interested in creations or modifications that are at least new to the user, we excluded 145 respondents because they only replicated existing products in the market. The remaining 147 were identified as potential user innovations.

In the final screening phase, the remaining cases were analyzed in terms of the respondents' answer to the following open-ended question: "What was new about your creation/innovation?" This step is essential because it enables the researchers to assess the description of the respondents' self-claimed innovations in terms of the creation's degree of novelty. In this analysis, we found 31 "false positives", which were discarded at this point. Thus, a sample of 116 validated cases of user innovation was identified, accounting for 9.2% of the initial sample of 1260 respondents. Looking at concrete examples from the survey data, it becomes clear how complex the solutions developed by user-innovators can be, e.g., participants report on the development of control elements for a three-way valve to support heating by solar panels, a self-developed dashboard to monitor and control the charge of the electric car, solutions for heating their own swimming pool by solar energy, and the linkage of proprietary standard components by their own interface solutions.

In all the evaluation steps, the two raters were strict in applying the judging criteria, and thus all the cases were initially assessed independently in terms of their fulfillment levels. In case a respondent had a different assessment, we consulted a third rater and made the final decision after a discussion. Further, we particularly excluded instances in which the respondent's information was insufficient in the final stage. Figure 1 summarizes the results of the screening procedure.

### *3.4. Variables and Models*

#### 3.4.1. Dependent Variable

On the basis of the screening, we generated the variable *userinnovator*, which is a binary variable that takes the value of one if the respondent's user innovation successfully passed the screening procedure. This variable served as the dependent variable in all subsequent regression models.

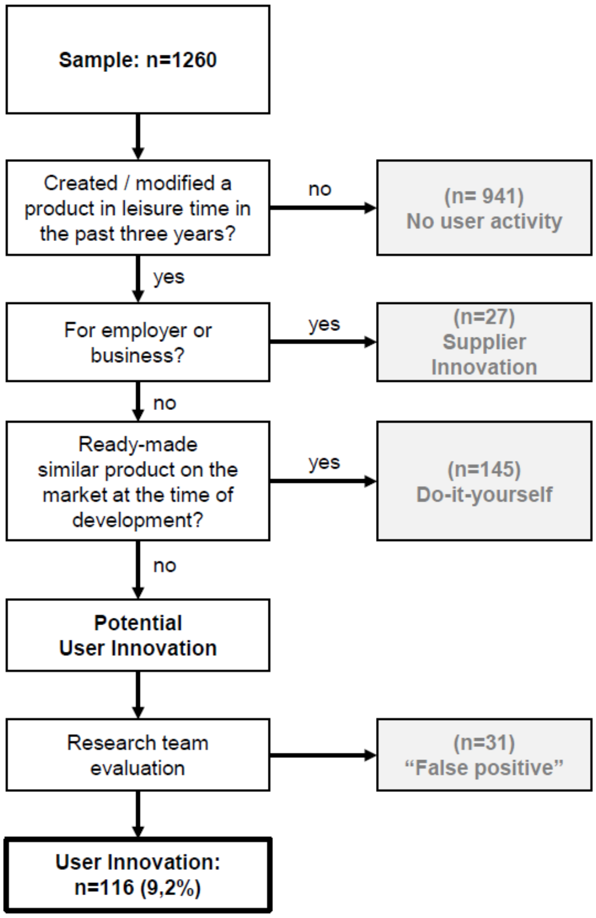


**Figure 1.** Screening procedure to identify user innovations.

### 3.4.2. Independent Variables

As our study focused on the motives and characteristics of user-innovators in complex technology settings, we collected relevant data in the survey and coded a set of context-related independent variables. Table 1 summarizes these variables.

**Table 1.** Description of variables.

| Variable | Description | Values/Range |
|---|---|---|
| **userinnovator** | The respondent successfully worked on a user innovation within the last three years. | 0 = no; 1 = yes |
| **intrinsic** | The respondent's work is characterized by intrinsic motivation. | 0 = no; 1 = yes |
| **techknow** | Respondent's level of technical knowledge. | 0–10 |
| **opensource** | Usage of open-source software or hardware. | 0 = no; 1 = yes |
| **costs** | The purchase and implementation costs are high. | 0 = no; 1 = yes |
| **ignorance** | I do not know which product is suitable for me. | 0 = no; 1 = yes |
| **dataconcern** | I have concerns about what happens to my data. | 0 = no; 1 = yes |
| **functrange** | The functionalities are not enough. | 0 = no; 1 = yes |
| **operatdiff** | The operation is difficult. | 0 = no; 1 = yes |
| **dissatisfaction** | The product does not deliver what it promises. | 0 = no; 1 = yes |
| **impltime** | The implementation is time-consuming. | 0 = no; 1 = yes |
| **gender** | Gender of the respondent. | 0 = female; 1 = male |
| **age** | Age of the respondent. | 17–83 |
| **ownership** | Binary variable indicating if the respondents own the house or flat, they live in. | 0 = tenant; 1 = home owner |
| **largecity** | Binary variable indicating if the for respondents live in a city with at least 20,000 inhabitants | 0 = no; 1 = yes |
| **unidegree** | Binary variable indicating if the respondents own a university degree. | 0 = no; 1 = yes |
| **income** | Binary variable that is one if the household income is 4000 Euro per month or higher. | 0 = no; 1 = yes |

First, we asked the respondents to rate the importance of various reasons to engage with the topic of smart energy technologies on a Likert scale from totally unimportant to very important (e.g., cost- and energy-saving considerations, a professional interest, him/herself a producer of energy). A cluster analysis using Ward linkage clustering [49] revealed three underlying clusters of motivation: cost-saving, job, and fun. For subsequent analyses, we generated the variable *intrinsic*, which is a binary variable that takes the value of one if the respondent falls into the third motive cluster that includes individuals who are driven by enjoyment, fun, and willingness to learn.

Second, we suspect technology-related drivers of innovation activities to be part of the motivational landscape of potential user-innovators aside from personal motives [5]. Thus, we asked the respondents for an assessment of the following reasons to be potentially dissatisfied with smart energy technologies available in the market: costs (*costs*), ignorance in the usage (*ignorance*), data protection concerns (*dataconcern*), limited functional range (*functrange*), operational difficulties (*operatdiff*), dissatisfaction in quality (*dissatisfaction*), and a considerable implementation time (*impltime*). For the analyses, we coded the motives as dichotomous variables taking the value of one if the respondents rated the respective reason as relevant or highly relevant in their context.

Third, we were interested in the type of technology that the respondents used. Thus, we generated the variable *opensource*, which is a binary variable that takes the value of one if the respondent stated using either open-source hardware or software products.

As the probability of being a user-innovator is likely to be determined by further characteristics, we included a number of control variables in the subsequent regression models. Following previous studies [14,26], we included the variables *gender* (binary variable), *age* (continuous variable), education (*unidegree*, which is a binary variable that takes the value of one if the respondent stated having a university degree), and *income* (a binary variable that takes the value of one if the respondent belongs to the highest income class in the survey, i.e., with a monthly household income of above 4000 euros). Apart from these demographic characteristics, we considered three context-specific factors, namely, ownership, level of technical knowledge, and city size. As a previous work identified that the separation of ownership and control negatively affects user innovativeness [16], we included another binary variable (*ownership)* that takes the value of one if the respondent stated owning a flat or a house and zero if the respondent is a tenant. Further, we asked the respondents for a self-assessment of their degree of technical knowledge. As we assume technical knowledge (*techknow*) to be an essential prerequisite of user-innovators in the field of complex technologies, we included this variable in the subsequent analyses. Finally, we controlled for city size, as discussions in the energy transition context usually differentiate between large-city-solutions and remote solutions for rural areas [50,51]. Thus, we coded a dichotomous variable (*largecity*) that takes the value of one if the respondent lives in a city with more than 20,000 inhabitants.

#### 3.4.3. Regression Models

As the dependent variable in all our model specifications is a binary viable, we modeled the probabilities of the dependent variable *userinnovator* with respect to our independent variables $x$ by

$$\pi_i \equiv Prob(userinnovator_i = 1 \mid x) = F(x'_i\beta) \quad (1)$$

where $x$ is the $(kx1)$ regressor vector, and $\beta$ is the $(kx1)$ vector of coefficients to be estimated. Further, we specified $F$ as the cumulative distribution function of the logistic distribution [49]. Subsequently, the probit regression model coefficients were estimated using the maximum likelihood approach. Our standard errors were robust to heteroskedasticity.

We estimated three model specifications. The first specification focuses on the effect of intrinsic motivation on the likelihood of being a user-innovator. In this step and all other model specifications, we included the level of technical knowledge and all controls. In the second specification, we added all technology-related motives to innovate. Then, we checked for the effect of using open-source technologies on the likelihood of being a user-innovator.

## 4. Results

### 4.1. Amount and Expenditures of User-Innovators

We started our analyses by identifying the share of user-innovators in Germany that created or modified a product or a solution in the context of smart energy technologies within the last three years. In our sample, we found 9.2% of our respondents, aged 18 or older, to be innovating users. As described earlier, these individuals were successfully audited in the previously discussed identification procedure [12]. Comparing our results with those of previous studies, i.e., 6.1% in the UK [14], 5.2% in the US [28], 3.7% in Japan [28], 5.4% in Finland [26], 5.6% in Canada [27], and 1.5% in Korea [24], the share of user-innovators in Germany was relatively high. This finding is mainly due to two reasons.

First, as the registration for the mailing list of co2online is voluntary and self-initiated, registered people may be more likely to be interested in energy and energy-related aspects than the average German population (self-selection bias). Thus, we assume that the probability of being a user-innovator is higher in our sample than the likelihood in Germany on average. Similarly, we expect an oversampling of people with technical expertise, as the topic of smart energy products is a technical issue. As people with a technical background are more likely to be user-innovators [14,29], we conclude that the share and number of user-innovators found in our sample may be overestimated.

Second, in contrast to previous results [12], we did not aim to draw from a representative sample but to investigate instead the potential of user innovation in the specific field of smart energy technologies in Germany. Thus, we sent out our questionnaires to energy enthusiasts who subscribed to the mailing list of co2online. We induced a sampling bias because we are not able to obtain valid demographic data of the mailing list subscribers owing to the data protection regulations. Further, we did not apply a weighting scheme to our data set, as done in previous studies [14], because we expected the weighting scheme techniques not to compensate for the distortion of our sampling. Thus, we generated results in the frame of our sample dataset.

Regarding the time investment and expenditures of user-innovators, we found relatively high numbers compared with previous studies. The identified user-innovators in our sample spent 39.8 days per year on average for innovation activities in their private contexts. We calculated on average €1456 per year as the annual material expenditures by user-innovators. Again, both numbers may be overestimated. Nevertheless, we suspect that even powerful correction methods would still result in above-average spending in terms of the time and money of user-innovators in energy technologies as we look at a specific, cost-intensive technological field.

### 4.2. Motives of German User-Innovators in Complex Energy Technologies

As this study aimed to explore the drivers of user-innovators in complex technologies, we performed multivariate probit regression analyses using three model specifications (Table 2). To investigate the extent to which user-innovators are driven by intrinsic motivation, we included the variable *intrinsic* and all the control variables in the first model specification.

The results show that the respondents who have a high level of intrinsic motivation are significantly more likely to be user-innovators than those acting out of external motivational drivers, that is, job or cost-saving considerations. Among the controls, age is significantly negatively correlated with the dependent variable, indicating that the older the people are, the less likely they come up with innovative solutions in the field of smart energy technology. Further, *income* is a positive predictor for being a user-innovator. This finding hints at the fact that user innovation activities in the field of complex technologies are costly and require a certain degree of financial resources, although user-innovators generally rely on inexpensive, home-made solutions [14,24,52].

**Table 2.** Regressions results.

| Variables | Specification 1 | Specification 2 | Specification 3 |
|---|---|---|---|
| **intrinsic** | 0.527 *** (0.149) | 0.570 *** (0.183) | 0.601 *** (0.189) |
| **costs** | | −0.0921 (0.188) | −0.122 (0.192) |
| **ignorance** | | 0.0964 (0.183) | 0.193 (0.190) |
| **dataconcern** | | −0.432 ** (0.174) | −0.439 ** (0.179) |
| **functrange** | | 0.109 (0.180) | 0.107 (0.185) |
| **operatdiff** | | −0.327 (0.228) | −0.347 (0.234) |
| **dissatisfaction** | | 0.380 ** (0.189) | 0.318 (0.195) |
| **impltime** | | 0.419 ** (0.199) | 0.349 * (0.204) |
| **opensource** | | | 0.739 *** (0.203) |
| **gender** | 0.313 (0.290) | 0.298 (0.408) | 0.156 (0.409) |
| **techknow** | 0.0893 ** (0.0373) | 0.0773 (0.0472) | 0.0528 (0.0483) |
| **age** | −0.0138 ** (0.00565) | −0.0124 * (0.00710) | −0.00950 (0.00729) |
| **ownership** | 0.0933 (0.205) | 0.275 (0.274) | 0.229 (0.282) |
| **largecity** | 0.203 (0.146) | 0.243 (0.182) | 0.223 (0.187) |
| **unidegree** | −0.0880 (0.153) | −0.164 (0.189) | −0.174 (0.193) |
| **income** | 0.250 * (0.144) | 0.268 (0.180) | 0.195 (0.186) |
| **Constant** | −1.871 *** (0.469) | −1.894 *** (0.669) | −1.796 *** (0.678) |
| Observations | 746 | 400 | 400 |
| Pseudo R2 | 0.0765 | 0.116 | 0.156 |
| log likelihood | −206 | −143.2 | −136.7 |
| Wald Chi2 | 34.11 | 37.47 | 50.52 |
| Wald df | 8 | 15 | 16 |
| Wald $p$-value | $3.88 \times 10^{-5}$ | 0.00108 | $1.90 \times 10^{-5}$ |

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

In the second step, we determined the reason why users innovate for themselves, included technology-related factors, and considered the context of the innovation activities. Based on the results, three technology-specific factors affect the likelihood of starting user innovation: *dissatisfaction*, *impltime*, and *dataconcerns*. First, dissatisfaction with the existing products and solutions in the field of smart energy technologies is a significantly positive predictor for starting user innovation activities. This finding is in accordance with that of a previous work that proves that personal problems or needs are the leading source of user innovation [41]. Second, the extensive time required for the implementation of the prevailing energy product is another factor that significantly raises the probability of starting the development of personally designed solutions to energy problems. This finding hints at the conclusion that user-innovators are creators and prefer to do it themselves instead of buying off-the-shelf products mainly when the implementation is time consuming. Third, respondents with data security concerns are significantly less likely to start innovating. In other words, user-innovators do pay less attention to regulatory processes and begin to create or modify solutions even before policies or the industry has agreed on a regulatory framework and implemented standards and privacy protection requirements. Again, user-innovators are creators and seem to be less concerned about a cultivated field of action.

Among the other variables, intrinsically motivated people are more likely to become user-innovators again, and age is significantly negatively related to the dependent variable. Income becomes insignificant in this model specification, as we expect the monetary aspect to be covered by the technology-related factors that we included in this analysis step. Similarly, the variable related to the degree of technical knowledge became insignificant. We suspect that the technology-related variables absorb the effects of the technical expertise of the respondents on the probability of being a user-innovator.

Finally, we estimated a model specification including all the presented variables, as we were interested in determining the effect of open-source usage on the likelihood of being a user-innovator in the context of energy technologies. As expected, the respondents who claimed to use open-source hardware or software components are significantly more likely to become user-innovators than those who used predominantly proprietary off-the-shelf solutions. The effects of the other variables remain fairly constant in this specification. Interestingly, the variable *dissatisfaction* becomes insignificant possibly because of the nature of open-source users. As these users are usually characterized by having a high level of technical knowledge and experience in engaging in this movement and thus in the community [53], we assume that open-source users do not rely on proprietary products from the beginning and are therefore less dissatisfied because they do not use many off-the-shelf solutions.

### *4.3. Robustness Checks*

First, standard measures, such as the Wald $x^2$ test statistics and pseudo $R^2$, provide evidence that our model specifications fit the data quite well. We tested our estimated models against various alternatives containing few variables by employing likelihood ratio tests [49]. As the null hypothesis was rejected in all cases, the test results confirm that additional variables (e.g., employment status, living space, and persons per household) have no added explanatory power and do not increase the model fit significantly. Thus, our model specifications fit the data significantly better than the alternative models.

Second, the initial robustness checks are strongly supported by the fact that our results, including the estimated coefficients and the standard errors, are relatively constant over all the three models, thus indicating a sufficient degree of robustness of our findings. There are a few exceptions for which we have provided intuitive explanations.

Third, we checked for correlations among the variables considered in the various estimations (Results are available from the authors upon request.). Overall, the relevant correlation matrix seems satisfactory. We found some increased correlation values in the range of 0.3–0.4 in the variables that portray the problems users have with existing energy products (e.g., *dissatisfaction*, *impltime*, and *operatdiff*). However, as users seem to face more than one single problem with an existing solution and the questionnaire is allowed to assess various problems with high relevance, we accept the identified correlation values and assume robust results.

Fourth, the fact that only 9.2% of the respondents were identified as user-innovators could be considered as a search for rare events (small-sample bias). Therefore, the problem of separation may occur [54]. This is a case in which the maximum likelihood estimates may tend toward infinity and become inestimable. A method introduced by [55] addresses this problem and allows convergence to finite estimates. We re-estimated our model specifications using Firth's method (Results are available from the authors upon request.). The significance levels remained constant in all specifications, with the estimated coefficients changing only marginally. The problem of separation seems to be absent in our analyses.

## 5. Discussion

### 5.1. The Need to Support User-Innovators

Our results show the potential of user innovation in smart energy technologies. We prove the existence of user-innovators in a complex technological field. Therefore, 10% of German energy enthusiasts can be identified as user-innovators in the area of smart energy products. Despite the potential overestimation of the share in our study, the results indicate the expected rise in household sector innovation because of better education and access to innovation-required resources [28,56].

A vast but largely untapped potential is apparent. Users have ideas and usually start implementing them. Our results are in accordance with those of previous work confirming the importance of intrinsic motives as drivers of user-innovators [43]. However, previous research has not sufficiently covered all aspects of the motives of user-innovators to innovate. Technology-related factors are another set of important triggers for household sector innovation activities, especially in complex technology scenarios. Regarding the question related to the realization motives again, the data indicate the lack of diffusion efforts among user-innovators. The majority innovated for themselves, whereas only a few respondents opted for dissemination. Here, our data confirm the results of previous research showing the tendency of user-innovators to act for intrinsic reasons and not to invest funds in the diffusion [57,58]. From a welfare–theoretical perspective, the diffusion is essential because the innovation of one individual can be useful for many others. Consequently, the efficiency of user innovation efforts increases as diffusion takes place.

The goals must be to increase the macrosocial awareness of user innovation and to stimulate discussions on how to better support these creative people. We suggest support at five levels:

- Technical support (e.g., user-friendly toolkits for designing and prototyping, creating open developer platforms);
- Informational support (e.g., information campaigns, establishing communication channels);
- Financial support (e.g., financial support and reward programs for user-innovators through policy and business);
- Structural support (e.g., information events for users with their own ideas, user innovation workshops, hackathons);
- Regulatory support (e.g., new working-time models such as the 20% rule, Free Friday).

The basis of all these efforts is the rising awareness and the associated increase in the self-efficacy of user-innovators. Therefore, we intend to demonstrate the opportunities and action space to user-innovators and give them a vocabulary for their actions. Doing so helps them to understand the phenomenon of user innovation in their self-perception as a user-innovator and in companies, policymaking, and society.

### 5.2. Understanding User-Innovators Entails Understanding Customers

Understanding user-innovators in the field of complex energy technologies means understanding the needs of people in the context of smart energy products, as user innovations arise primarily where existing market solutions do not satisfy the customers. Moreover, user-innovators can help to better understand the role of people in the future energy system. Our results illustrate the diversity of users' needs and concerns as well as their different requirements for smart energy products and solutions. There is no "the" user or "the" customer of smart energy products. Instead, there are heterogeneous user groups with different questions and problems, diverging levels of knowledge, and varying degrees of willingness to invest time and money in their own "small-scale energy transition". Thus, we need a more substantial heterogeneity of smart energy products and solutions that address the specific requirements and questions of the corresponding user groups. Energy-related user innovations can act as an idea pool and thus a source of innovation [14] in the creation of smart energy products and services. As our results show, users do have many ideas while using products at home. These ideas must be pursued and realized either by the users themselves or by companies that can assist and scale up solutions. In this context, an appropriate incentive, risk, and organization management is important as various user-innovator types react differently to diverse stimuli and approaches [25,59].

Open platforms and developer environments, that is, those that we know from the smartphone and tablet sectors, can help to speed up the creation of innovation eco-systems [60,61]. In these environments, users find a place to channel their ideas and developments, the producer can co-create new product developments with customers and user-innovators, and policymakers can observe user-producer-eco-systems to monitor and evaluate framework programs dedicated to foster open innovation. Nevertheless, these open eco-systems only work if standards are harmonized and data interfaces are created. In this regard, we see the need for policymakers, businesses, and standard-setting organizations to work together to build the necessary framework and to provide the technical infrastructure. To speed up the development, we suggest a roadmap defining the goals for each stakeholder group (Table 3).

**Table 3.** Roadmap for integrating user-innovators in innovation eco-systems.

| | Short-Term | Mid-Term | Long-Term |
|---|---|---|---|
| **Active user-innovators** | recognize the relevance of one's activity | strengthen self-efficacy; activate others; circulate ideas and achievements | increase self-confidence; contribute to professionalization efforts; networking; become a role model |
| **Potential user-innovators** | get inspiration; perceive examples of user innovation | identify starting points; start first innovation activities | strengthen self-efficacy; collaborate with others |
| **Business** | be aware of user innovation activities; give user-innovators credit | understand the potential in one's own context; evaluate possible scaling; provide access to volunteer help (e.g., experts) | offer testing sites for user-innovators; create developer toolkits and websites; build open innovation eco-systems |
| **Policy** | be aware of user innovation activities | empower user-innovator actions; identify possibilities to support and assist (e.g., funding or data access) | integrate user innovation support in funding and framework programs; build user competences through education initiatives |
| **Society** | observe user innovation as a phenomenon | recognize the activities of user-innovators | benefit from user innovation diffusion |

## 6. Conclusions

Users often innovate for themselves. As a rule, user-innovators do not act from an economic point of view but try to solve their problems; therefore, they are mainly intrinsically motivated. When individual users or groups of users become innovative themselves, the trigger is usually that existing solutions do not or no longer satisfy their needs. In cases in which consumers or users of products and technologies become innovators, they know their problems better than anyone else, but they are usually isolated. Consequently, the goal is to make the ideas and solutions of user-innovators available to all members of society, to promote broad diffusion, and thus to support the active participation of interested parties in a sustainable energy future.

By identifying user-innovators among German energy enthusiasts, we intend to further increase the attention of industry and policymakers for user innovation. On the basis of our work, we conclude that better framework conditions in the form of standards, uniform interfaces, and clear regulations in data security can help user-innovators to exploit the potential of their work. Further, we promote these processes and initiate a debate on how user innovation can play a more central role in both business decisions and political discussions. R&D funding programs should also consider user innovation activities more explicitly. If making ideas and solutions accessible to individuals and small groups of innovators in society is possible, then innovation efforts can benefit society as a whole.

*Limitations and Future Research*

Our study design and the results are not without limitations, which leave room for future research. Method-wise, the social desirability bias may play a role in the responses of our survey in terms of issues related to sustainability, climate-friendly behavior, and energy transition. However, as we used a survey approach, which is non-intrusive and presents no interviewer–interviewee contact, the bias could have a minor effect on our results [62,63].

Further, we distributed our call to participate through the subscriber base of the co2online newsletter. Therefore, we assume that most of the respondents in our sample are interested in both energy and climate issues. Consequently, our study is not representative of the German population but nevertheless reveals interesting results for energy enthusiasts. Future study designs may opt for nationally representative data to confirm our results and avoid the self-selection bias.

Similarly, the findings of our study may be specific to the German situation. As energy-related discussions and developments are country specific, we need more research on the effects of digitization on consumers, users, and society in energy-related issues in various scenarios. Identifying the mechanisms on how user innovation helps to reduce market uncertainty in new markets would be interesting. Further, we believe that innovating users should play a more central role in standardization and policymaking processes.

In any context, the active involvement of user-innovators in open innovation eco-systems induces some general implications. We need more research on the actual commercial potential of user ideas for the development of new products and services. The goal should be to create assessment models that provide user-innovators, companies, and policymakers with guidance on how to decide on effective strategies to manage and exploit collaborations. As user-innovators usually do not protect their innovations with intellectual property rights, a main topic of future researchers should be to address this issue that challenges the primary incentive system of investments in new product development.

Finally, as prior research shows, user-innovators increasingly exploit the opportunities of information and communication technologies and share insights and innovation outcomes with like-minded enthusiasts in Internet forums or other formats [52,64]. Conversely, our study analyzes and discusses the innovation activities of user-innovators at the individual level. Therefore, questions on collaborative innovation or peer-to-peer support were not addressed. The variables modeling these trends could have added explanatory power to our regression results.

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