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The Impact of Economic and Non-Economic Incentives to Induce Residential Demand Response—Findings from a Living Lab Experiment

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Abstract: This study assesses the impact of economic and non-economic incentives to induce demand response in private households. The experiment was realized by a three-months residential phase in which two tenants lived in the Energy Smart Home Lab, an experimental lab with the equipment of a modern smart home. The tenants received calls to action (CtAs) on a regular basis, incentivized economically or by moral nudges with a social or environmental background. A mixed-methods approach, consisting of smart meter data analysis, a value scale assessment, surveys and interviews, assessed the tenants' reactions on their energy consumption behavior towards the CtAs. The smart meter data shows that the tenants performed the majority of CtAs, revealing no significant difference between economic or non-economic incentives. Results from the value scale, the interviews and the surveys indicate that this behavior might be due to the tenants' high tendency towards biospheric and altruistic values and a high self-efficacy. Furthermore, the consequences of the COVID-19 pandemic caused a 100% home-office situation, suggesting a higher flexibility of the tenants. Although the results are not representative and need further experiments to be confirmed, the incentives show a promising potential to evoke residential demand response.

Keywords: technology acceptance; smart home; technology adoption; residential demand response; flexibility; (non)-economic incentives; energy consumption behavior; behavioral change; COVID-19 pandemic; living lab

Citation: Scharnhorst, L.; Sandmeier, T.; Ardone, A.; Fichtner, W. The Impact of Economic and Non-Economic Incentives to Induce Residential Demand Response—Findings from a Living Lab Experiment. *Energies* **2021**, *14*, 2036. https://doi.org/10.3390/en14082036

Academic Editors: Ben McLellan and Valentin Bertsch

Received: 15 February 2021
Accepted: 2 April 2021
Published: 7 April 2021

1. Introduction

The transition from conventional to renewable energies as a reaction to the political will to minimize climate change and thus reduce carbon dioxide emissions is one of the great challenges in the modern era. In Europe, this aim is put into action by the "European Green Deal" [1] with the decarbonization of the energy sector as one of the most important measures. One possibility to approach this goal is the expansion of renewable energy sources, resulting in a more distributed and volatile energy generation system (e.g., in Germany the share of renewable energies in the total electricity generation in 2019 increased to about 42% [2]). This transition brings a number of challenges with it. Due to the temporal asynchronicity of generation and demand either huge energy storage capacities have to be established or the demand needs to be adjusted to the current generation. Additionally, electrical distribution networks will be more heavily utilized and operated closer to their capacity limits. One possibility to make better use of the potential of renewable energies and reduce the stress in distribution grids is the so-called demand-side management (DSM), where consumers adjust their electrical load to the current state in generation and the grid. This way the need for additional energy storage systems, energy generation units and power lines can possibly be reduced. While DSM is already common practice in the industrial sector, it is not yet established in private households. With the rise of smart meters and intelligent, programmable household devices, the technical requirements for the provision of flexibility in private households are theoretically fulfilled, for example by shifting the use of energy-heavy devices such as the washing machine, tumble dryer or dishwasher in the night. However, besides the technical requirements, the willingness and acceptance of the private consumers to participate in programs such as demand-side management or dynamic electricity tariffs have to be met as well.

The idea to reduce or influence the energy consumption of private households by external interventions is not new. Midden et al. [3] carried out a field experiment to test the effects on energy conservation of different strategies, including the provision of information, feedback to the energy consumption and its costs, comparative feedback and financial incentives for decreases in energy use. In [4] the effects of comparative feedback, energy-saving tips and feedback to financial or environmental costs on the overall energy demand were examined. A review of 38 studies on the effectiveness of interventions aiming to encourage households to reduce their energy-use was done in [5]. Another review article on the use of feedback as a tool to reduce the amount of energy consumption lead to the conclusion, that a higher feedback frequency also leads to a higher effectiveness [6]. In [7], special attention was given to possible boomerang effects when applying comparative feedback incentives. Monetary rewards were added to comparative feedback in [8], with the goal to reduce the yearly energy consumption. Several other studies come to the conclusion that non-economic interventions and incentives can substantially change consumer behavior and even can outperform economic ones [9–11].

In addition to the general energy preservation in private households, more recently published studies often focus on shifting energy consumption from peak times to times where the general demand is low compared to the generation from renewables. Royal et al. [12] evaluated demand-side interventions aimed at reducing residential energy consumption during peak periods, using a set of text message reminders and intra-day increases in the electricity price for peak-hours. The additional price increases achieved significant reductions in peak hour consumption, significantly higher than with only the text messages. The idea of evoking load-shifting by different electricity prices for different times of the day is also called the time-of-use tariff (TOU). In [13], the authors provide a review about TOU tariffs and their enrolment across 27 studies. Dutschke et al. [14] used a survey including a conjoint analysis design and a field study to examine which dynamic pricing programs for demand-side management are preferred by the consumers, coming to the conclusion that consumers prefer simpler programs to complex and highly dynamic ones. In [15] different platform pricing strategies in order to incentivize consumers to participate in automatic demand response programs are analyzed. The authors in [16] conducted a choice experiment to examine consumers' acceptance of TOU tariffs in Germany, with the result that 70% of the 1398 respondents would be willing to choose a TOU tariff. In order to reduce the stress and limit further needed cost-intensive infrastructure expansion in domestic electricity grids, the authors in [17] aim to reduce the peak demand of private households, using a time-of-use tariff and a peak capacity pricing tariff, where the electricity price rests on the daily maximum power demand.

In order to evaluate or strengthen the results made from surveys or choice experiments, the use of living labs is common practice in research. The Energy Smart Home Lab (ESHL), a living lab located on the Campus of KIT, presented the ideal infrastructure to conduct our research, as it had been part of several studies in this research field already. The authors in [18] used the ESHL as a demonstration object for smart meters, smart appliances, home automation and dynamic electricity tariffs and analyzed the consumers' reactions to this smart home environment. In [14] the lab was used as an experimental environment for the conducted field tests. A real residential period of several weeks in the ESHL was conducted in [19], where different smart home technologies were analyzed in their effects on the inhabitants and their behavior. The authors identified real-time feedback systems as the most important technology for consumers' ability to shift loads. They conclude that future designs of smart home environments have to provide sufficient amounts of information as well as cost-saving potential and secure high levels of the consumers' flexibility as well as easy use in everyday life.

Even though various studies have already assessed the incentivization of user acceptance regarding load shifting and various electricity tariffs, most of them rely on surveys or choice experiments and are not conducted under real-world conditions. The combination of a long-term experiment under real-world conditions, a variety of tariffs and incentives with the aim to alter and not only reduce the tenants' energy consumption and close scientific monitoring has to our knowledge not yet been realized. In order to fill this gap we carried out a residential phase lasting several months in the living lab "Energy Smart Home Lab" (ESHL) and thus aimed to drive forward the initial research conducted by [14,18,19]. This study adds further aspects to the research scope by asking the following research questions:

- Considering economic and non-economic incentives, which ones impact the energy consumption behavior adaption of the residents?
- What differences in impact can be distinguished regarding economic, social and environmental incentives?
- What are the motivations, drivers and barriers for the residents to react to the respective incentive?

The insights of this experiment could help to better understand peoples' motives and drivers when interacting with such tariffs or energy management systems as well as serve as a basis for future large-scale experiments.

2. Materials and Methods

2.1. Energy Smart Home Lab Setup Description

The Energy Smart Home Lab is a fully functional smart home located at Campus South of the Karlsruhe Institute of Technology. It is built from a container and consists of a 60 m^2 living area and a 20 m^2 technical room. The ESHL is designed as a living lab. This means scientific research and the normal usage of the building as a flat inhabited by KIT-external persons go hand in hand. The building is equipped according to the standards of a modern smart home. The heating system consists of a micro combined heat and power plant (mCHP), which can also be used for electricity generation, a controllable heating rod, an inverter air-to-water heat pump and a 750 L hot water storage.

For the electricity supply, the building is connected with the local low voltage grid and additionally a PV-system is installed on its roof. To enable the possibilities for more efficient usage of the generated electricity by the PV-system an electrical energy storage system is available. The residential area of the building is divided into two bedrooms, one bathroom and a large living room with a kitchen. A schematic overview of the building is presented in Figure 1. The bigger household appliances with rather high energy consumption, like the dishwasher or washing machine, are "smart" appliances, which means they can be programmed to start the desired program at a given time and also can be controlled via an Ethernet connection by an energy management system. This makes it possible to start energy-intensive applications even at night or when the inhabitants are not at home, thus opening up even more possibilities in terms of potential load shifting.

Additionally to the household and technical appliances, the building is equipped with an extensive sensor and measuring system. Besides heat quantity meters, occupancy sensors or contact sensors for doors and windows, especially the measuring system for the consumption and generation of electrical energy is of relevance for our study. The measured values can be consulted on a big tablet in the kitchen area as well as on smaller tablets in the bedrooms and near the entrance of the building. In order to be able to communicate with the tenants another tablet was installed, where the current messages including the calls to action (CtAs) and the corresponding incentives are displayed.

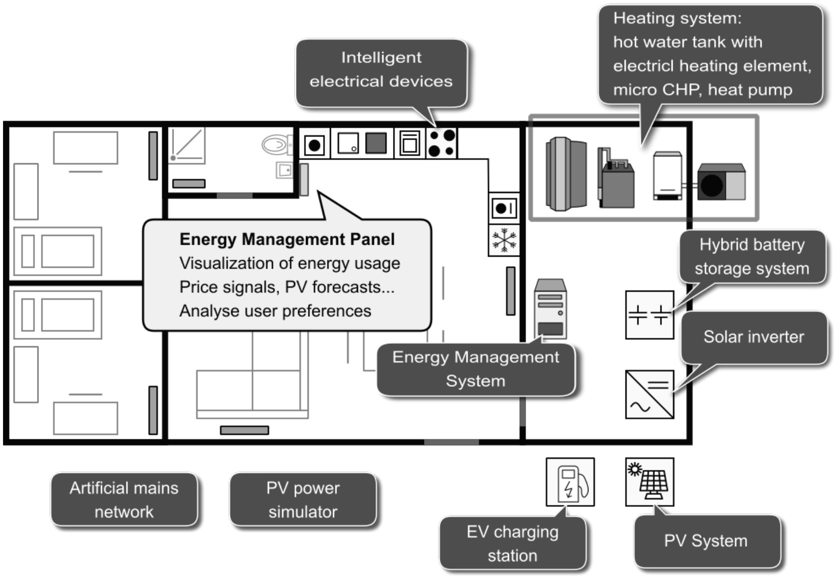

Figure 1. Schematic overview of the Energy Smart Home Lab.

2.2. Residential Period

2.2.1. Procedure

The residential period took place in 2020 and lasted for 13 weeks, consisting of a two-week acclimatization period and consecutive eleven weeks of experimental periods, as Figure 2 presents. Nine experimental periods were conducted, each lasting between five and eleven days. Hereby, one incentive category (social, environmental or economic incentives) was tested in each period, alternating the period, so that overall each category was tested in three experimental periods. Between each experimental period lay one day without experiments, meaning that the residents did not receive any messages with CtAs on these days and only were asked to answer a survey about the most recent experimental period. Hence, nine surveys were taken considering the experimental period, plus one survey at the beginning of the residential phase itself. Furthermore, the tenants assessed the value scale, a method for self-assessment of one's values considering egoistic, hedonic, altruistic and biospheric values, which is further explained in the progress of this chapter. In addition, three interviews took place, one interview with each tenant individually after fifty percent of the experimental periods time and one interview with both tenants directly after the residential period. This mixed-methods approach was based on the aim to receive feedback from the tenants about their experience, motives, ideas and adaption to the smart home environment and the experimental setting in order to complement the data collected by the sensor and measurement system considering the energy consumption.

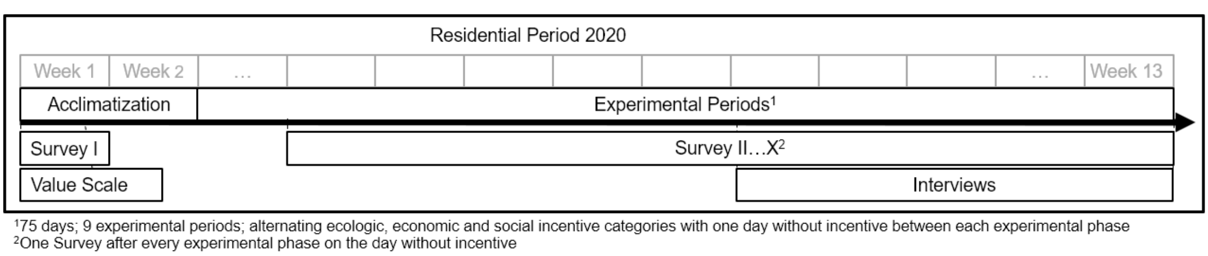

Figure 2. Schematic overview of the residential period 2020.

2.2.2. Rental Conditions

The tenants signed the rental contract, as well as giving their consent about the privacy agreement prior to moving into the ESHL. They were thoroughly informed about the data collected by the sensor and measurement system of the ESHL and agreed to be aware that the energy consumption data, as well as the data gained from the research methods (surveys, interviews and value scale) would be used for research purposes. Due to the experimental setting, no rent or additional costs were charged. It was emphasized that participation and reaction to the CtAs were on a voluntary basis, so that the participants would not experience negative consequences except for the ones linked to the incentives.

2.2.3. Demographic Details

Considering demographic information, both tenants came from South America, were between 25 and 35 years old and were male and female. Both were students, already holding one university degree and having several years of work experience in industry, having lived and worked in an urban area before coming to Germany for further education in an engineering study field. The industry fields they had worked in were process engineering and project management and hence not related to the research field addressed in this study. The tenants were not affiliated with the research institute beforehand and decided to participate after we had introduced the research procedure to them, while they had at any time access to the German housing market. Both motivated their decision by being curious about the implementation of the energy transition in Germany and that participating in such an experiment would be a unique experience, since they did not have had experience with incentive systems and energy management systems before. It cannot be excluded that the non-existent rent might have been also a motivational factor, which is addressed later in this study in Section 4.3. This might correlate with the household's income level (both tenants) of net ≤ 1000 € per month. The two shared the flat and were counted as one household, both being single regarding their family status.

2.3. Experimental Framework

2.3.1. Incentive System

In this study, the concept of incentives is defined as a motivation for the tenants to realize a certain kind of behavior, or to change their present behavior to take a desired course of action. Hereby, economic, as well as non-economic incentives are assessed.

Various studies that have tested the impact of economic and/or non-economic incentives on consumption behavior or household peak electricity consumption have so far had contradicting results [20–22]. Reasons can be varying methodologies and experimental settings, e.g., from a few up to several thousand households, or treatment duration from a few events up to several months, as well as different ways of communication with the households [20]. The non-economic incentives considered in this study distinguish environmental as well as social incentives. Both schemes rely on the principle of moral suasion [23], with the aim of promoting intrinsic motivation to induce pro-environmental or pro-social behavior. Besides moral suasion, both non-economic incentives show also characteristics of altruistic incentives as [20] describes altruistic incentives as being used when households are influenced to change their electricity consumption behavior, as soon as they realize "that their actions can have a positive effect on the well-being of others". In addition to altruistic incentives, the social incentives in this study may also rely on normative messages, to nudge the participants towards the kind of energy consumption behavior that gets social approval [20,21]. The economic incentives in this study - similar to the approach in [23] - are set to initiate extrinsic motivation, by applying various tariffs and cost schemes. As both social and environmental incentives rely on moral suasion, the tenants receive the information about their bonus (praise) or malus (complaint), whether they adapt their energy consumption behavior in the sense of pro-social or pro-environmental behavior or not. For the economic incentive, the tenants receive as a bonus a financial gain ($+x$ €) or a financial loss ($-x$ €) according to their energy consumption behavior considering a respective CtA.

Furthermore, the economic, as well as the non-economic incentives in this study, include aspects of informational incentives [21]. The informational aspect in this study is not tested as an incentive itself but is used as an additional part of the CtAs to enable the tenants of the ESHL to make informed decisions about how to adapt their energy consumption behavior.

2.3.2. Defining the Calls to Action (CtAs)

We defined 26 calls to action, of which 25 were tested during the residential period. To every CtA, belong one, two or three messages from the three different incentive categories, see Table A1 in the Appendix A. Due to the restricted time period of the residential phase, not all CtAs could be tested on every incentive category. Consequently, the most relevant CtAs were tested by applying all incentive categories one at a time. An overview of the most important CtAs is given in Table 1.

Table 1. Overview of the most important calls to action (CtAs).

Name	Description	Aim
Power Limit	A max. power limit is proposed for the duration of one or multiple days. If the tenants exceed this limit, they have to pay a one-time fee (or get a malus) but are allowed to exceed the limits for the remaining duration without extra consequences.	Reducing the peak load.
Load-Dynamic Tariff	The day is divided into time intervals of 15 min. Every time the power demand exceeds a given threshold, the electricity price for the current time intervals raises from a base level to a higher one.	Avoid long-going and high amounts of power peaks.
Grid Bottleneck	The inhabitants get rewarded with a bonus if they manage to stay below a given power limit for specific time intervals.	Reducing the load in domestic distribution grids for specific time slots.
Time-of-Use Tariff	Three different price levels are defined. Each hour of the day is assigned one of the price levels.	Shifting load to time periods where e.g., the generation from renewables is high or the load in the grid is low.
Sell to/buy from your neighbors	The tenants can decide if they are willing to pay or receive a higher or lower electricity price than the normal one for selling energy to or buying energy from their neighbors.	Testing the tenants' neighborly cohesion, social values and attitude.

CtAs may furthermore vary according to their sensitivities. This applies e.g., for the Grid Bottleneck, where sensitivities such as time periods as well as the power threshold vary in order to test different degrees of intensity. The sensitivities evolved throughout the residential phase, in response to the tenants' reactions. Since in the near future not only the amount of consumed energy but also the demanded power peaks will play a significant role in terms of security of supply and the stability of electricity grids, tariffs were introduced with the aim to encourage load shifting and tariffs with the aim to reduce power peaks.

2.3.3. Messages

The CtAs and bonus-malus details from the incentive categories together form the messages sent to the residents of the ESHL. Figure 3 shows the message sent on the 24th day comprising the CtA to stay below 5 kW for three days or to get the Power Limit for a one-time fee of 15 € by exceeding the power threshold once. Hence, if exceeding the power threshold once, the Power Limit would apply with a fee of 15 €. From that moment onwards the power threshold could be exceeded as often as wished.

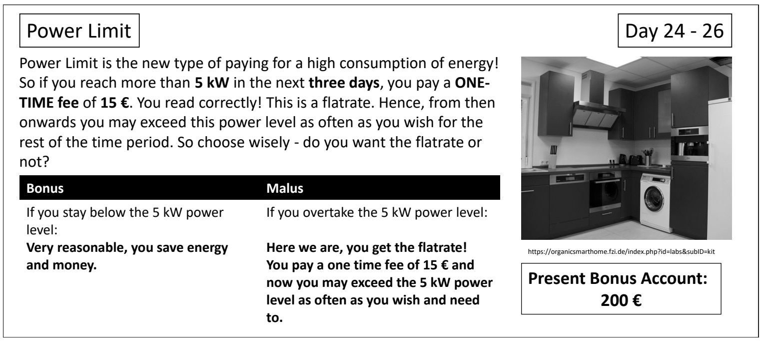

Figure 3. This message, called "Power Limit", has been sent to the residents of the Energy Smart Home Lab (ESHL) in the morning of the 24th day, comprising the CtA, as well as the incentives formulated as bonus (positive) and malus (negative) consequences of performing the CtA or not.

The box on the bottom right corner of the message indicates the present bonus account of the residents. Since the economic incentives started on Day 24 the box indicates the starting bonus of 200 € which the residents received not bound to any prior condition.

2.3.4. Smart Meter Data

As already mentioned the building is equipped with an extensive measuring system. The focus hereby lies on the demand and production of electrical energy. We are able to measure the consumed or produced power for every electrical device and power socket with a temporal resolution of one second. This enables us to capture even short peaks in power demand and to get a clear picture of the tenants' behavior in regard to the use of electrical devices. In order to be able to better understand and interpret the collected data we used information about the average energy consumption in German households [24] and standard load profiles [25] for comparison.

2.3.5. Value Scale

The value scale taken at the beginning of the residential phase can be compared to the value scale data gathered by [26], in a study to assess sustainable transportation in South America. In this study as well as in [26] the assessment of values was realized by an adapted version of Schwartz's value scale (1992) [27] by [28–30] and extended by [31] in 2014. Steg et al. [31] showed that four types of values are especially suitable for the analysis of environmental beliefs, norms, intentions, behavior and policy acceptability [26]. Biospheric and altruistic values, representing a vital interest in the quality of nature and the environment and the well-being of other human beings respectively, have been showing to promote pro-environmental attitudes and behaviors in various studies [26,29–32]. Egoistic and hedonic values, which represent a core interest in the costs and benefits of individual resources, as well as increasing one's pleasure and reducing or avoiding suffering, in contrast, expressed themselves as to impede with pro-environmental attitudes and behaviors [31]. The hedonic, egoistic, altruistic and biospheric values are assessed in a value scale, in which the participants are asked to rate a set of representative values, by indicating the importance as a "guiding principle in their lives", assessing the values on a nine-point range from −1 "opposed to my values", 0 "not important", 1 to 5 "important" to 7 “extremely important” [26]. Additionally, they were asked to vary their scores as much as possible.

Since the sample size of only two participants does not allow a statistical evaluation, a plausibility check is done by comparing the tenants’ mean values to the results of two studies with a statistically relevant sample size, which applied the value scale in South America in the research context of sustainable transportation [26] and in Europe in the research context of transport policy [29]. In [26] the in this study used term “self-indulgent” as a representative value of hedonic values was formerly called “gratification for oneself”. However, this is considered a minor difference that does not majorly affect the resulting value scales or the further analysis. In [26] the participants where asked not to rate more than two values as extremely important in the study form. This was not the case in our study. In [26] the reliability of the value scales was satisfactory to good. Additionally, in [26] the assumption is validated that the structure of values is similar across countries and cultures, validating the assumption of [27]. Consequently, the value scale’s results of this study can be compared to [26,29], which is realized in Section 4.2.

2.3.6. Surveys

Between these experimental periods, one day of break was included, on which the participants, instead of receiving a CtA, were asked to answer a survey. Ten surveys were conducted, all were answered by the participants and each took around 30 min to answer. The survey’s content developed throughout the residential phase, with further questions being added where needed. The surveys covered topics such as familiarization with the smart home and the CtAs, self-assessment of one’s energy consumption, the performance of the CtAs, interest and willingness to follow-up with the experiment and assessing the tenants’ self-efficacy. These sections build the pages of the survey, in order to keep a clean and clear structure [33]. To assess the tenants’ self-efficacy, a further section was added from survey eight onwards. Self-efficacy is the perceived capability of people to perform a certain attainment [34] and influences the peoples’ choice of behavior to pursue a certain course of action, their commitment to it, their persistence and the effort they put into it [35]. Regarding the influence of self-efficacy on pro-environmental behavior, several studies concluded that a high self-efficacy has a positive and significant effect on pro-environmental behavior [36,37]. Environmental self-efficacy is primarily influenced by people’s awareness about environmental degradation [37]. Hence, in this survey, one item asking about the energy transition as an imperative to combat climate change was added. Furthermore, Wu et al. [37] found that people tend to perceive a greater ability to act locally than on a national level. These findings were considered in the ESHL-surveys, by asking about the general self-efficacy considering the ability to have an impact on the energy transition and second by diving onto the local level considering the ability to positively impact the energy transition by taking part in the residential period and the experiments. Additionally, the ability to impact the future in a positive way by continuing to be aware and implement the load shifting and reduction methods promoted during the residential phase was introduced as an item. The latter, however, is more a statement of intention than a judgment of capability, having phrased the item with “will do” rather than “can do” [35].

2.3.7. In-Depth Interviews

In-depth interviews have been deployed in previous studies during residential periods in the ESHL as a method to gain detailed feedback from the residents about the progress of the experiment [19]. In this study, in-depth, semi-structured interviews have been used as a qualitative research method, in order to enable the interviewees to express their experiences, feelings and thoughts about the topic in a rich and detailed way [38]. The interview guide was created following the style of [33], giving openness a priority, as well as considering clarity and being adjustable to the narrative thread that would develop differently in each interview. The interview guide contained questions related to the tenant’s adaption to and interaction with the smart home environment and the energy management system (the messages, CtAs and incentives) to develop a thorough understanding of the correlation of the tenants' energy consumption behavior and their motives behind it. The first interviews took place after two-thirds of the residential phase, consisting of one researcher talking to each tenant individually for 60 to 90 min. The interviews took place online, as video calls, due to COVID-19 safety measures. The second interview was conducted in the week after the residential phase had ended, consisted of two researchers, as well as the two tenants and took an hour. All interviews were recorded and transcribed. A structured qualitative content analysis followed, where relevant aspects were defined as categories, so that the interviewees' statements could be assigned to the specific category of the category system, considering the approach and characteristics of [33,39–41]. Hence, relevant implications were first taken from the interview guide, adding secondly aspects arising from the interviews and introducing sub-categories where needed.

3. Results

This chapter summarizes the results of the residential period, to assess how the tenants reacted to the CtAs and incentives and why they did so. The analysis starts with the measured data, as well as consecutively presenting the analysis of the data collected by the mixed-methods approach, using interviews, surveys and the value scale.

3.1. Comparison to the Average German Household

Before we dive deeper into the analysis of the inhabitants' behavior, we want to have a look at some more general aspects of their energy consumption. The total electricity demand over the whole period of residence was 645 kWh, counting only devices in the residential area, which means the energy demand of the heat pump is not included. Compared to the German average for a two-person household this is a low to moderate demand. At first sight, this might seem odd since the tenants spent nearly all their time at home due to the COVID-19 restrictions at that time, but you have to keep in mind that the electrical devices in our lab are state of the art and therefore much more efficient than the devices found in an average German household.

For further comparison of our tenants' behavior to the German average, we aggregated the measured electrical data and calculated the mean values of the energy consumption for every 15 min of the day over the whole three months of the experimental phase. We then compared the results to the German standard load profile for households. Due to the COVID-19 restrictions in Germany at the time of the experiment the inhabitants spent most of their time at home and did not leave for work or other regular activities. Tenant A: "We cook lunch at home, the computers are connected to the electricity system and the lights are on. We spend at least eight hours more per day here at home than we were expecting to initially". That is why we chose the standard load profile for a Saturday and the transitional period from winter to summer as a comparison. The two load profiles are depicted in Figure 4a. It is eye-catching that there is some form of temporal displacement between the two curves. This can be explained by the origin of the two tenants. They both come from South America and thus have to stay up late in order to be able to have contact with their family and friends. That is why we assumed their daily routine was shifted back by about three hours, which was later confirmed by the tenants during the in-depth interviews. If we consider this in our comparison with the standard load profile and adjust the time accordingly, we get Figure 4b. The two plots resemble each other very much, which leads to the conclusion, that, under consideration of the previously discussed time shift, the tenants are a suitable sample of the average German household.

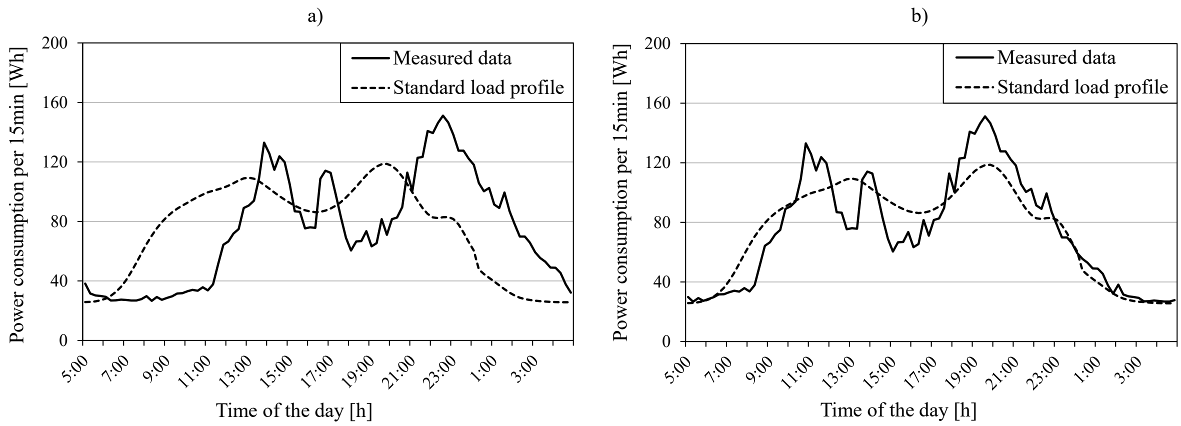

Figure 4. Comparison of the inhabitants' energy consumption profile with the German standard load profile for comparable household size and time of the year. (**a**) No time shift, (**b**) time shift of −3 h.

3.2. Reactions on the Calls to Action

In the following, we want to discuss the residents' reactions to the different CtAs. Therefore we consulted the quantitative smart meter data and the tenants' qualitative statements in the surveys and interviews.

3.2.1. Findings from Smart Meter Data

An overview of the CtAs in combination with the respective incentive and a categorization of the reactions into "the CtA was followed" (√), "no clear reaction" (-) and "behavior contrary to the CtA" (X) is presented in Table 2.

Table 2. Overview of the CtAs and if they were followed by the inhabitants. √: CtA was followed, -: No clear reaction, X: behavior in contrast to the CtA.

Economical		**Environmental**		**Social**	
CtA	**Reaction**	**CtA**	**Reaction**	**CtA**	**Reaction**
Power Limit 5 kW	√	Sunny day	-	Grid restriction 4 kW	√
Power Limit 5 kW	√	Sunny day	-	Grid bottleneck 3 kW	√
Power Limit 5 kW	√	Sunny afternoon	√	Sell to neighbour	√
Grid bottleneck 3 kW	√	Cloudy day	√	Buy from neighbour	√
Grid bottleneck 2 kW	√	Sunny day	-	Grid bottleneck 2 kW	√
Buy from neighbour	√	Sunny day	X	Buy from neighbour	√
TOU (20, 30, 40 ct/kWh)	√	Sunny day	√	Higher cons. than avg.	√
TOU (20, 30, 40 ct/kWh)	√	Sunny day	√	Higher cons. than avg.	-
TOU (20, 30, 40 ct/kWh)	√	Sell to neighbour	√	Higher cons. than avg.	-
Load-dynamic 3 kW	-	Sunny morning	-	Higher cons. than avg.	√
Load-dynamic 3 kW	-	Sunny morning	X	Higher cons. than avg.	-
Load-dynamic 3 kW	-	Neighbour vs. grid	√	Neighbour vs. grid	√
TOU (30, 60, 100 ct/kWh)	-	Grid bottleneck 3 kW	√	Grid bottleneck 3 kW	√
TOU (30, 60, 100 ct/kWh)	√	Grid bottleneck 2 kW	√	Grid bottleneck 2kW	√
Power flat rate 2.5 kW	-	Grid bottleneck 2 kW	-	Grid restriction 4 kW	√
Power Limit 2.5 kW	√	Cloudy day	√	Buy from neighbour	√
Power Limit 2.5 kW	X	Grid bottleneck 1 kW	√	Grid bottleneck 2 kW	√
Load-dynamic 2 kW	√	Heating control	√	Grid bottleneck 1 kW	√
Grid bottleneck 1 kW	√	Heating control	√	Grid restriction 2 kW	√
Sell to neighbour	-	Power Limit 2.5 kW	√	Grid bottleneck 2 kW	√
	X	Power Limit 2.5 kW	√	Grid bottleneck 1 kW	√
	√	Power Limit 2.5 kW	√	Grid restriction 2 kW	X
				Grid restriction 2 kW	X

For some of the CtAs the categorization was rather easy, for some it was more difficult. For the power limit, grid bottleneck and grid restriction CtAs, we assigned a $\surd$ if the inhabitants stayed within the proposed power limit and an X, if they exceeded it. One example for a load profile for a day with a grid bottleneck CtA is depicted in Figure 5. The residents successfully followed the CtA since they stayed below the power limit in the critical time slots. For the load-dynamic tariff, we assigned a $\surd$ if the power demand did not exceed the given threshold, a minus if they exceeded it for a maximum 5 min and a maximum of three times a day and an X if they exceeded the threshold for more than 5 min or more often than three times a day. The buy from/sell to your neighbor CtAs was listed as "followed" if the inhabitants agreed to the proposed deals and were listed as "not followed" if they declined it. For the "Your energy consumption is higher than the average" CtA we assigned a $\surd$ if the tenants managed to lower their energy consumption significantly for the respective day, a minus (-) if there was no significant difference and an X if their consumption increased. For the remaining CtAs, "Sunny day/morning/afternoon", "Cloudy day" and the "Time-of-use tariff", there was a rather subjective division into the different reaction categories, based on the amount of load that was shifted into the intended time periods (e.g., time slots with the lowest electricity price for the time-of-use tariff or the morning for the sunny morning CtA). We can see a very high willingness of the residents to follow the proposed CtAs through all three incentive categories. Especially the CtAs with a hard power limit, like the power limit, grid restriction or grid bottleneck, showed a lot of success in leading the tenants' energy consumption in the desired direction. The calls with softer limits, like the time-of-use and load-dynamic tariff, did not have quite as much impact on their behavior. It seems that either it was easier for the inhabitants to follow the strict and clearly defined CtAs or they saw a bigger benefit/drawback in the incentives linked to them.

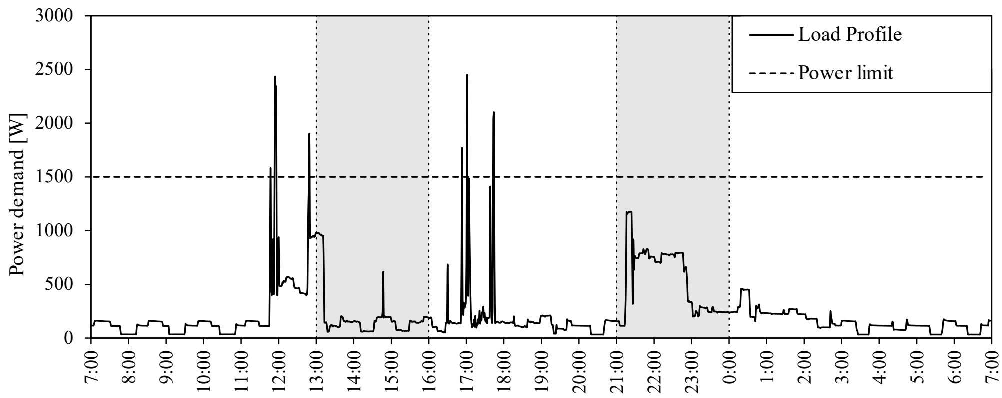

Figure 5. Exemplary load profile for one of the grid bottleneck CtAs. In this case, for the time slots from 13:00 to 16:00 and 21:00 to 24:00 a power limit of 1.5 kW was suggested. The CtA was paired with a social incentive (reduce the chances of a power outage in your community by staying below the proposed power limit).

3.2.2. Self-Assessment of the Tenants' CtA Performance

In addition to the smart meter evaluation, we asked the tenants about their assessment of the different CtAs in the surveys and interviews. In the surveys, the tenants were asked specific questions about each message they received during the previous experimental period. This included the assessment of their ability to perform the CtAs, whose answers are presented in Figure 6. The results show that the tenants (strongly) agreed (somewhat) that they were able to follow the CtA on most days, rating only seven days as undecided considering economic and social incentives. Three days existed where the tenants disagreed with the statement, with two days where both disagreed considering social, and one day where one tenant disagreed regarding economic incentives. Furthermore, the tenants were asked to point out the easiest, the most challenging, the least attractive, the most frustrating and impossible CtA to perform in every experimental phase. Considering the

CtAs evaluated as easy, the tenants chose those ones where only a one-time decision or no major energy consumption behavior adjustments needed to be taken, which was also confirmed during the interviews. Messages where a decision was taken comprised e.g., "Purchase or Sell PV electricity from/to your Neighbor" or "Neighbor vs. Grid", while e.g., "Power Limit 5 kW" or "Sunny day" were messages with CtAs evaluated as easy due to not needing to adjust the energy consumption behavior too much. More challenging CtAs comprised CtAs where the tenants were directly involved and asked to adjust their daily routines or schedules in order to perform the CtA successfully or make the most of it. This comprised e.g., grid bottleneck CtAs with a 2 kW power threshold or lower, as well as grid restriction, time-of-use tariffs or the power limit with a 2.5 kW threshold. The most challenging CtAs were not necessarily also the least attractive ones. The most challenging CtAs were in the interviews also described as motivating or exciting, even though they were perceived as difficult, as soon as the power threshold became lower than 2 kW. The surveys showed that the least attractive CtAs were often also the most frustrating ones, e.g., the 2.5 kW Power Limit in the ninth experimental phase or the 1 kW Grid Bottleneck CtA in the tenth experimental phase. In survey nine, both tenants expressed the difficulties and challenges of performing the Power Limit (2.5 kW) CtA. They highlighted the fact that it was also more frustrating since this CtA had prevented them from using appliances such as the oven for three consecutive days, as well as using just one appliance at a time.

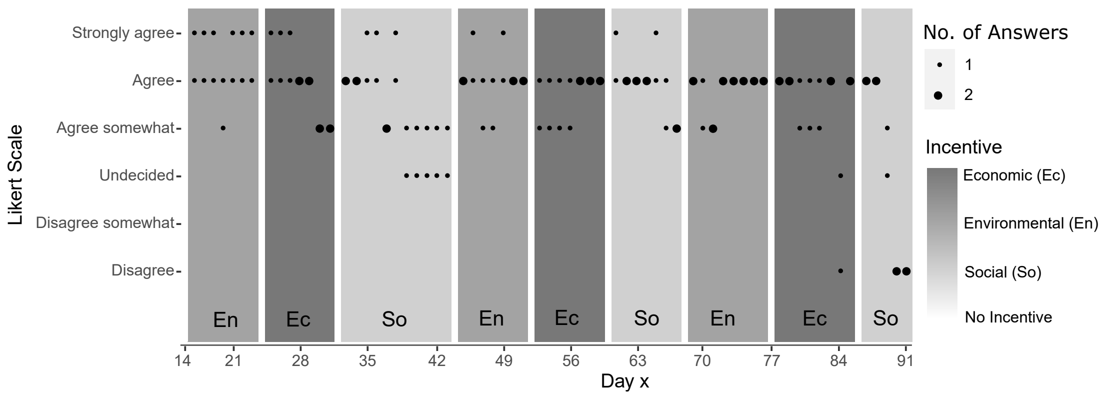

Figure 6. Self-assessment of the residents about their ability to perform the CtAs.

As more restrictive and more intense were the CtAs after the midterm interview perceived, which was accurate, since at this time various CtAs' sensitivities were intensified to see if the tenants would be still able or willing to perform these more challenging CtAs. One tenant noted in the ninth survey "I felt that the last week was a little more intense, regarding the CtAs compared to the other weeks", adding that the time-of-use tariff, as well as the load-dynamic tariff, had been challenging to perform. The only CtA defined as impossible to perform was the load-dynamic tariff with a threshold of 2 kW, which was applied on the last weekend of the residential phase. In survey ten, as well as in the interview, the tenants emphasized their reduced flexibility on the last weekend due to the preparation of moving to a new apartment, including cleaning and washing activities that were energy-intensive. One tenant explained "The load-dynamic tariff was interesting to follow, but impossible for us because we were moving on Sunday evening and we couldn't shift some of the loads".

3.3. Value Scale Results

The value scale has been assessed for each tenant individually at the beginning of the residential period. The values rated comprise hedonic, egoistic, altruistic and biospheric values, whose mean was computed to assess their importance with regard to each tenant. The importance was rated on a nine-point scale starting from −1 "opposed to my values", 0 "not important", 1 to 5 "important" to 7 "extremely important". Tenant A rated the altruistic value highest (M_{alt} = 6.00), followed by the hedonic (M_{hed} = 3.67) and biospheric value

(M_{bio} = 3.60) and the egoistic value (M_{ego} = 2.75) being least important. Tenant B indicated a similar tendency with giving altruistic values (M_{alt} = 5.50) the highest importance, followed by both biospheric and hedonic values ($M_{\text{bio}} = M_{\text{hed}}$ = 4.00) and also egoistic values (M_{ego} = 3.00) being least important.

3.4. Spotlights on Adaption, Self-Assessment, Tariffs and Self-Efficacy

Various surveys and interviews were taken to receive detailed feedback about the tenant's familiarization, self-assessment, their experience of the incentives and CtAs during the experimental phases and their motives considering their reaction to the messages they received. Since the results of the surveys and interviews support each other, with more in-depth answers gathered during the interviews, this chapter summarizes the results of both methods to create a comprehensive picture.

3.4.1. Familiarization and Self-Assessment

From the second survey onwards (which took place after the first experimental phase and three weeks after the start of the residential phase) the tenants agreed that they had become familiar with the smart home appliances. Furthermore, both tenants expressed in the midterm interview that they had adapted well to the smart home features, learning about how much energy the appliances consume and integrating them into their daily routine. The learning process included switching the appliance on and verify its load on the panel. Furthermore, the tenants identified certain CtAs that raised their consciousness about their energy consumption behavior and how they could alter it to either decrease their energy consumption or shift the bulk of it to certain time periods. Furthermore, the tenants were asked to rank the applied incentives considering their personal priorities. Table 3 presents the results of both interviewees.

Table 3. Prioritization of economic, environmental and social incentives by each tenant.

Priority Level	Tenant A	Tenant B
Highest Priority	Economic	Social
Medium Priority	Social	Economic
Lowest Priority	Environmental	Environmental

Tenant A explained the prioritization in the following way: "For example, when we have a bonus to help the environment, we always try to do it. However, with the economic one, we try a bit more. And when we can choose to buy the energy from our neighbor without cost we say 'Yes, of course I would buy it.' But at times where it is more expensive to buy the electricity from our neighbor it is not so sure that we are going to buy it, we have to talk about it. In this case we then bought the electricity from our neighbor, but it made us think a bit more about the additional expenses". Tenant B explained the prioritization, saying: "I am very conscious about the environment, I am also working in this field, but I think that the focus regarding pro-environmental behavior should lie on the production of electricity and not on the consumption. Hence, regarding the consumption, social and monetary incentives count more for me". Even though both tenants rated the environmental incentives as their lowest prioritization, the previous illustrated results show that they both mostly performed the CtAs with environmental incentives successfully.

Both tenants emphasized in the interviews that collaboration was key to perform the CtAs successfully. Tenant A mentioned that they both had the priority to perform the CtAs, so that in the case of one of them wanting to use a certain appliance, while the other one wanted to use another one, they would solve the impasse via communication and finding a compromise. Furthermore, as tenant B puts it: "For example the washing machine was running; it lasted five minutes to finish the program. Then, I went and pressed the button of the coffee machine to get a coffee. [Tenant A] told me 'Wait just five minutes and you won't generate a peak.' We weren't supposed to fulfill a task at that time. I then realized what I was doing and pushed the stop button, saying 'Yes, I wasn't conscious about it, sorry.' And I remember that because it touched me, I felt guilty and I think that was kind of a change in the way we perceived things".

Mean Daily Energy Consumption

The tenants assessed their mean daily energy consumption, compared to the actual measured energy consumption in every survey, Figure 7. The intervals between which the tenants could choose ranged from 0 kWh to more than 12 kWh in intervals of 4 kWh. The results show that the tenants tended to overestimate their energy consumption at the beginning of the residential period, which changed from surveys five and six onwards. Towards the end, the assumptions made were more accurate, but the tenants still rather overestimated than underestimated their consumption.

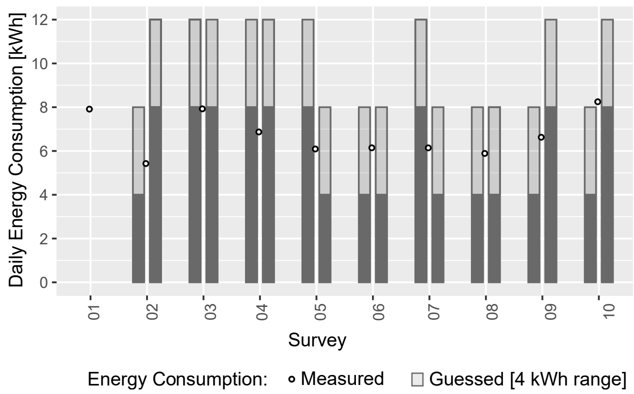

Figure 7. Self-assessment of the residents about their mean daily energy consumption vs. actual measurements taken.

Daily Peak Power Time Intervals

Figure 8 shows the measured daily power demand in intervals of two hours and the tenants self-assessment of the power peak time intervals. The tenants guessed the peak power consumption mostly in the correct time intervals, which supports the fact that the tenants performed almost every call to action, especially the ones where a power shift was needed, since they knew when their peak power time intervals occurred and which appliances to not use in order to prevent such a power peak.

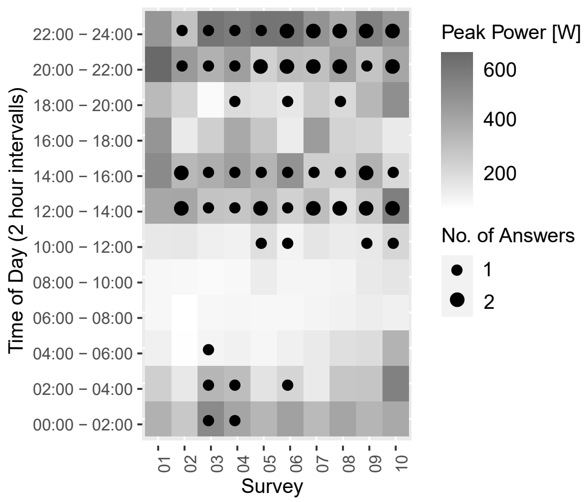

Figure 8. Self-assessment of power peaks during the day compared to the measured highest energy consumption during the residential period 2020.

3.4.2. Tariff Rating

In Figure 9 the residents assessed their perceived financial benefit of various electricity tariffs during the residential period on a Likert scale, ranging from "Strongly Agree" to "Strongly Disagree" in seven steps. Five different tariffs were proposed: Time-of-Use Tariffs with two, three or five price levels (TOU2, TOU3, TOU5), a load-dynamic tariff (LD), and a power limit tariff (PL). Each tariff could have varying variables between the six assessments. The more relevant a tariff to the experiment, the longer it stayed in the surveys.

The time-of-use tariff with three price levels (TOU3) got the highest agreement among the time-of-use tariffs and was seen as a financially beneficial tariff, except for one tenant in survey eight, in which it was rated as "undecided". This correlates with the price level raise from TOU3_2 to TOU3_3, see ID 10 to 11 in Table A1. However, after experiencing TOU3_3 in the experimental phase, both tenants agreed to see a financial benefit in this tariff. In the interviews, tenant A found the TOU3 tariff interesting and furthermore stated: "It was a bit more complicated than other tasks because this tariff changed from time to time and we wanted to use the appliances when it was the cheapest. It became tricky when we wanted to cook, since e.g., at night the highest tariff applied when we wanted to cook dinner. This affected my schedule more than I wanted".

The load-dynamic tariff shows a varying degree of agreement, starting with (strong) disagreement in the first assessment for LD1, with the characteristics of 28 ct/kWh and 34 ct/kWh to stay below or exceed 1.2 kW, respectively. It is assumed that both tenants saw the threshold of 1.2 kW as too low, referring to their interview statements, that 2 kW was already seen as a restrictive threshold. However, tariff LD2 found agreement by both tenants in the subsequent surveys, with the characteristics of 25 ct/kWh and 35 ct/kWh to stay below or exceed 3 kW, respectively. Since most appliances had a power demand below 3 kW, one can assume the tenants knew they would be able to stay below the power threshold and hence stay in the lower price region. This correlated with the load-dynamic tariff tested in the experimental phase prior to survey six, as well as the tenants stating that they were able to follow this CtA in the survey. In survey eight, LD3 applied with intensified prices and threshold, implying 30 ct/kWh and 60 ct/kWh to stay below or exceed 2 kW respectively. Here, both tenants disagreed somewhat to the potential financial benefit, which might have been, as for LD1, the mix of a low threshold and a very high price for exceeding the threshold. However, both tenants changed their opinion after their first hands-on experience with LD3 in experimental week nine, agreeing about a potential financial benefit in the following survey. Tenant A evaluated the LD2 in the interview as being easier to perform than TOU3, arguing that they did not have to pay attention to the time periods with the lowest price level. Tenant A furthermore stated: "Here, we sometimes exceeded the power limit of three kilowatt, because of the oven. However, we then tried to use the appliances as fast as possible and after each other in order not to create a peak". Even though the tenants were not asked in the CtA to avoid the creation of peaks, the tenants tried to avoid it, although this would mean consequently a longer period of time where the appliances would exceed the power threshold and consequently higher costs of electricity, if the time interval exceeded 15 min.

The power limit's (PL) evaluation shares a disagreement as well as a somewhat agreement on its financial benefit in the assessment of surveys six, seven and eight. PF1 combined a payment of 15 € with a 5 kW threshold and applied for three consecutive days. This tariff had been implemented as CtA prior to survey three, in which the tenants (strongly) agreed that they were able to perform this CtA. The reason for one of the tenants' disagreements with the potential financial benefit of PF1 could not be deduced from the gathered information. Tenant A gave in the interview the feedback that communication was key during the performance of the PF, stating: "We said 'We are not going to make a peak up to five kilowatts.' However, sometimes one of us just forgot it, but communicating with each other prevented us from turning on anything unintended or we then turned the appliance off immediately. This CtA wasn't difficult, because as long as we remembered to not to use two appliances at the same time it was fine". Tenant B expressed the same opinion, being comfortable with this kind of CtA. In survey eight PF2 (15 € fee, 2.5 kW threshold), had been implemented in the prior experimental period with an environmental incentive instead of the 15 € fee. Both tenants agreed that they were able to follow the CtA, which explains that one tenant agreed somewhat to the potential financial benefit of PF2. It is assumed that the other tenant disagreed with the financial potential, because of a relatively low power threshold compared to PF1, as well as the high fee stated in the survey in comparison, in contrast to the sustainable incentive in the experimental phase.

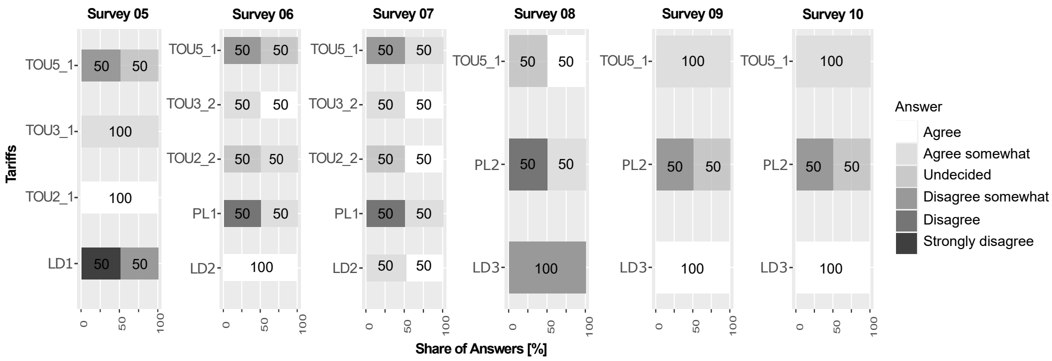

Figure 9. Assessment of the potential financial benefit, comparing various electricity tariffs during the residential period.

3.4.3. Self-Efficacy

In survey eight, nine and ten, the tenants' awareness regarding the importance of the energy transition to combat climate change as well as their perceived self-efficacy was assessed.

Overall, the tenants agreed to the item that the energy transition is imperative to combat climate change in the long-term. The answers suggest a high awareness of the tenants regarding the perceived importance of the energy transition in order to combat climate change. Both tenants agreed that they can have a positive or negative impact on the energy transition depending on their actions, plus that by living in the ESHL and following the CtAs, they contributed to a successful energy transition. These results are supported by the interview findings, where both tenants expressed their agreement of feeling to have contributed to this item in a positive way. This implies a high self-efficacy for both tenants considering self-efficacy on a local level. In the surveys, both tenants expressed their intentions to continue the energy consumption behavior that they adjusted to during the residential period afterwards in order to contribute to a successful energy transition in the long-term. This suggests a high self-efficacy on the long-term, even though this item was unspecific about the exact kind of energy consumption behavior (since various schemes of load shifting, load reduction and no schemes at all were tested), as well as the fact that the tenants would not have the same living standards (smart home) and conditions (incentives sent every day) in the near future. Both tenants agreed furthermore that they identified themselves with the measures promoted in the ESHL to contribute to a successful energy transition, with measures meaning the interaction with an EMS to optimize one's energy consumption.

The fact that the tenants agreed to participate in the residential phase in the first place indicates a positive attitude towards pro-environmental behavior, as well. Overall, the preceding answers to the items about self-efficacy indicate that the tenants have a high self-efficacy regarding their personal contribution to realize the energy transition, as well as strengthen the solidarity on a local basis and benefiting of the participation in the experiment on an economic basis.

3.5. Impacts on the Amount of Energy-Use

In this section, we take a deeper look into the effect the messages had on the amount of the residents' energy consumption. For this purpose, we compare the average of the energy consumption for each hour of the day where there was no CtA active to the average consumption in the hours with an active CtA. This enables us to draw conclusions about the flexibility potential at different times of the day. Since none of the used CtAs were sent more than five times individually, we cannot draw statistically significant conclusions about individual calls for action. Therefore, we clustered them into two groups, CtAs with the aim to reduce the power demand and CtAs with the aim to increase it. Together with the hours not inflicted by any CtA at all, we get three different groups of samples. For the group of CtAs that encourage the inhabitants to higher energy demands (e.g., "The sun is shining, use the full potential of the PV-system by using the energy-heavy devices in the next few hours") the sample size was not big enough to make significant assumptions. Hence, we will only consider times where no CtA was active and times, where a CtA to limit the energy consumption or peak power demand, was active.

The mean values for the hourly electrical energy consumption for the two samples are depicted in Figure 10a. We can see that the average energy consumption between 12:00 and 15:00 was reduced drastically by the given CtAs, whereas the peak in the evening was shifted in time but did not get smaller at all. During the night, the consumption was constantly higher in times with active CtAs than in times without. This behavior can be explained by having a closer look at the CtAs. Most of them had the aim to reduce power peaks in general or during specific time intervals. That is why the inhabitants tried to shift the use of energy-heavy appliances like the washing machine or dishwasher from daytime to night, which leads to the increased energy consumption between 00:00 h and 06:00 h. This way they were still able to cook at noon without exceeding the proposed peak power limits. In the evening, however, most of the energy consumption comes from the lighting and the use of multimedia devices, like the TV, stereo and computers. Either the inhabitants were not willing to sacrifice their comfort by turning off the lights or the TV or they just were not aware of the high energy demand of these appliances. One problem in this regard is the lighting, which consists of relatively old fluorescent tubes which are not nearly as energy-efficient as modern LED lamps. Therefore, it is possible the inhabitants misjudged the lighting's energy demand and left it switched-on carelessly. However, the results lead to the conclusion that the peak in energy-use at noon can be shifted to other times of the day relatively easily, whereas this is not the case for the peak in the evening.

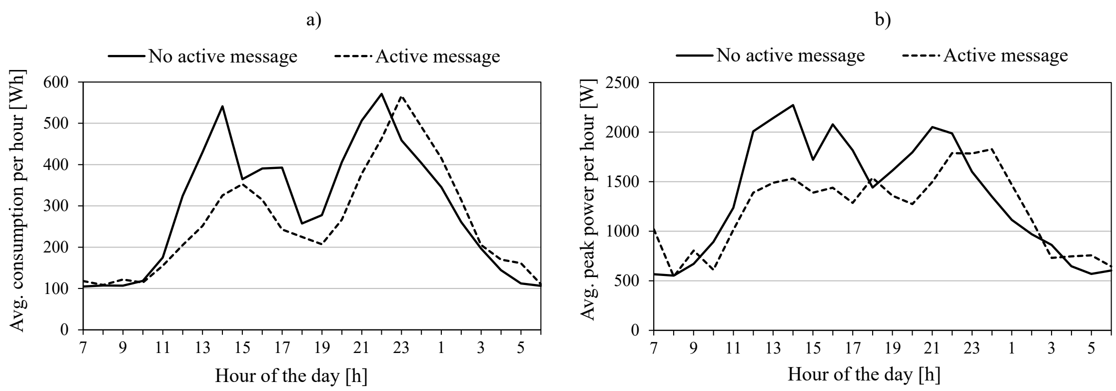

Figure 10. Comparison of the average power demand in times of no active call for action and in times of active CtAs to maintain different power limits. (**a**) Comparison of the average power consumption per hour, (**b**) Comparison of the average peak power per hour.

We also had a look at the hourly demanded peak power. The average values for the two samples are depicted in Figure 10b. Since most of the incentives aimed at limiting the peak power demand and keeping the previously discussed results in mind, it is not surprising that the mean values for the sample with an active CtA are lower than the ones for the sample without CtA, especially in times of high power demand.

Finally, we asked the tenants to classify energy-heavy activities and appliances in the categories *shiftable* and *non-shiftable*. Their assessment is depicted in Table 4, strengthening our previous assumptions.

Table 4. Shiftable and non-shiftable activities identified by the tenants.

	Activities
Shiftable	washing machine, dishwasher, tumble dryer, vacuum cleaner
Non-shiftable	food preparation, lighting, computer usage

4. Discussion

4.1. Reaction to Economic and Non-Economic Incentives

The first hypothesis was that the tenants would react differently to economic and non-economic incentives. Hereby, the non-economic incentives differentiated between social and environmental incentives, where also a varying degree of reaction was assumed prior to the experiment. These three incentive categories have been tested successively in repetitive order, so that overall three experimental phases of each incentive category were conducted, with one day without incentives between each experimental period.

The results show, that no distinctive difference regarding the performance of the CtAs and incentives could be found, meaning that the tenants followed the majority of the CtAs across all three incentive categories. The few exceptions were either inadvertently or if on purpose just on the last weekend of the residential phase were the tenants prioritized to use energy-intensive household appliances in order to clean the smart home and prepare to relocate over the performance of the CtA. Both reasons were expressed by the tenants themselves via the in-depth interviews and surveys conducted in addition to the data collected by the sensor system of the smart home. The mixed-method approach allowed to gather extensive information about the motivations, motives and detailed feedback about the tenants' interaction with the incentivized CtAs. Since the first hypothesis was not fulfilled, the following reasons suggest why the tenants followed almost every CtA.

The value scale answered by both tenants at the beginning of the residential period indicated that both have a strong tendency towards altruistic and biospheric values. As previous studies have shown, if these values are strong, individuals are more likely to show pro-environmental behavior than individuals with a tendency towards egoistic and hedonistic values. In addition to the value scale, the survey results suggest a high environmental self-efficacy for both tenants which indicates furthermore that the tenants perceive themselves as capable to have a positive impact on the energy transition, e.g., by participating in this study, as well as adapting their future energy consumption behavior to the CtAs that served as role models in this study. Based on the tenants' altruistic and biospheric values, as well as their high self-efficacy it can be concluded that the tenants had not only a high motivation but also changed their behavior in order to perform the CtAs, which is known to be influenced positively by a high self-efficacy.

4.2. Plausibility Check on Value Scale Assessment

Since the sample size of two tenants cannot show representative results, a plausibility check is applied, comparing the value scale results with the results from two studies with a large enough sample size. Table 5 presents the comparison of mean hedonic, egoistic, altruistic and biospheric values, as well as the sample size and the geographic background of the studies dealing with sustainable transportation (STS) [26] and transport policy (TPS) [29], as well as the value scale results of the ESHL tenants in the residential period in spring 2020.

The biospheric values of STS and TPS have similar mean scores, and thus support previous studies that found out about the importance of environmental concern and universalism values to people also in less developed countries [42–44]. Comparing these results to the mean scores of the value scales taken during the residential period indicates tendencies of the tenant's values in the same direction. The comparison shows, that both tenants give less importance to egoistic values, while altruistic values are most important to both of them. Both hedonic and biospheric values have the same importance for tenant B, and almost as well for tenant A with a small difference of 0.07 giving slightly more importance to the hedonic values. It appears in the results, that the tenants' value-self-assessment was accurate, considering that they performed the majority of the CtAs linked to social incentives, which indicated a strong altruistic behavior.

Table 5. Mean hedonic M_{hed}, egoistic M_{ego}, altruistic M_{alt} and biospheric M_{bio} values, as well as sample size and geographic background of studies dealing with sustainable transportation (STS) [26] and transport policy (TPS) [29], as well as the value scale results gathered from each Tenant A and Tenant B in the residential period at the ESHL.

Assessed Categories	STS [26]	TPS [29]	Tenant A	Tenant B
M_{hed}	5.10	-	3.67	4.00
M_{ego}	2.12	2.50	2.75	3.00
M_{alt}	5.44	5.10	6.00	5.50
M_{bio}	4.91	5.00	3.60	4.00
Sample size	130	489	1	1
Geographic background	Argentina	Europe	South America	South America

Furthermore, even though biospheric and hedonic values were more or less equally important for both tenants, also the CtAs with environmental incentives were mostly performed successfully, Table 2. This happened despite the fact that the tenants would have to restrict themselves and behave contradictory to their hedonic values, since these restrictions would mean a decrease in amenities, like making fresh coffee, cooking the food in the oven or use the appliances in general at the time they originally had planned to.

4.3. Further Implications Regarding the COVID-19 Pandemic

On a further note, the high flexibility that the tenants showed regarding their energy consumption adaption to the CtAs was influenced externally by the measures realized due to the COVID-19 pandemic. The measures started two weeks after the start of the residential phase, right when the experimental period started. This caused a 100% home office situation which meant that the tenants moved their daily routine from an originally expected nine-to-five day out of home. In addition, the German government suggested staying at home as much as possible, so that socialising, as well as other recreational activities such as weekend trips, were not taken into consideration by the tenants. Consequently, the tenants were home most of the time except for e.g., grocery shopping or recreational walks in the park, which may have given them a higher degree of flexibility to adapt their daily schedules to the CtAs ahead. Since the COVID-19 pandemic has a significant effect on peoples' daily lives on a global scale, measures to mitigate the spread of the virus promote people to stay at home for work, where possible. With a rising number of people working in a home office situation, the hypothesis can be drawn that the future residential flexibility potential may rise as well. The more people working from home, the higher the residential flexibility potential compared to households where no individual works from home or is at home during working hours. Of course, this hypothesis needs to be addressed in future studies and also consider varying kinds of working hours, as well as the heterogeneity of household composition (regarding the number of individuals, age, kind of job, demographics, etc.). On the other hand, flexibility can also be provided if the household appliances can be remotely assessed e.g., via a smartphone app or a website. Remote access, as well as heterogeneity regarding demographic variables, are also planned to be considered in future residential periods in the ESHL.

4.4. Limitations

The sample size of this study is based on the two tenants living in the ESHL for several months. Due to this, the results presented in this study are not representative. Furthermore, the tenants' behavior could have been biased regarding the fact that they might have behaved differently in the ESHL compared to their behavior in their usual apartment. The fact that they did not have to pay rent also could have influenced the tenants' actions, since they had the benefit of saving the money for a rental apartment and had as such more money to their disposal compared to their real-life situation in which they would have needed to pay rent. A wide range of variables impacts a person's behavior, of which not all were respected in this study. The interpretations regarding the motives of why and how the tenants reacted to the CtAs are based on the measured sensor data, as well as the interviews, surveys and the value scale. This allowed a retrospective analysis of the tenants' behavior on the respective day and event, which depends heavily on the tenants' perception and memory of these respective events. Hence, the interpretations are influenced by the subjective output that the tenants shared with us. As the results from the value scale and surveys show, the tenants had a quite positive attitude towards energy preservation before the start of the experiment. This means the successful reaction to the CtAs could have been expected and the results are not applicable to persons with an extremely different mindset in this regard. Furthermore, tenants with a German nationality might have been easier to compare to German residential energy consumption behavior. However, regarding the time restriction (three months) of participation, and other aspects, the above-described tenants were the only ones available and fitting into the research scheme and willing to participate at that time.

4.5. Further Research

Further residential phases shall be conducted in the future. The aim hereby is to again test the incentive system with the same framework but a smaller variation and therefore longer application periods of incentives. Variations in the setting can come from tenants that do not work from home, tenants with a different demographic background (e.g., age, country origin) and maybe without COVID-19 measures. The latter depends on the further development of the present pandemic and the political measures consequently taken. Additionally, the willingness-to-accept, as well as the willingness-to-pay are planned to be assessed regarding the privatization of security of demand in future residential periods. A refinement of the surveys, as well as the incentive system, e.g., more detailed answer options for the tenants' self-assessment, adding more background information to the CtAs, or adding gamification concepts, are also taken into consideration.

5. Conclusions

The study assesses the impact of economic and non-economic incentives to induce residential demand response by gathering evidence from a living lab experiment realized by a residential period in the Energy Smart Home Lab. Two tenants lived in the ESHL for three consecutive months and received messages with CtAs linked to varying incentives. The tenants could react to the CtAs according to their own free will and were not forced into following the calls by any means. The setting allowed close scientific monitoring and accompanying of the tenants' behavior, which was realized by the collection of highly resolved smart meter data and frequent surveys and interviews. The results show that through all three incentive categories, economic, social, and environmental, the tenants fulfilled the vast majority of CtAs. This leads to the conclusion, that the economic, as well as the non-economic incentives, were effective in causing adaptions in the tenants' energy consumption behavior. This is in line with the results of several other studies mentioned in the literature review, which also come to the conclusion that the prospect of a financial bonus is not always mandatory in order to motivate private households to provide flexibility. Multiple reasons were found why the tenants' reaction did not differ between the extrinsic and intrinsic incentives. As main drivers, the strong self-efficacy, as well as biospheric and altruistic values were identified. These drivers have already been shown in previous studies to support pro-environmental behavior. Another considerate aspect that needs to be mentioned is the COVID-19 pandemic that created a 100% home-office situation, which led to an increased flexibility and ability to respond to the calls to action according to the tenants' interview statements.

The study contributes to the research field by providing various tariffs and incentives as well as detailed insights about the tenants' motives, motivation and thoughts behind their reactions to the CtAs. The presented methods and results can help research and industry when conducting field experiments with a larger amount of households or designing frameworks for user interaction with energy management systems that aim to optimize residential load profiles. This becomes crucial in the wake of the energy transition, where a future scheme of demand following supply will need to be introduced successfully.

Author Contributions: Conceptualization, T.S. and L.S.; methodology, T.S. and L.S.; software, T.S. and L.S.; validation, T.S. and L.S.; formal analysis, T.S. and L.S.; investigation, T.S. and L.S.; data curation, T.S. and L.S.; writing—original draft preparation, T.S. and L.S.; writing—review and editing, T.S., L.S., A.A. and W.F.; visualization, T.S. and L.S.; supervision, W.F. and A.A.; project administration, A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), for the project C/sells, grant number 03SIN123 and by the Helmholtz Association "Energy System Design", grant number 37.06.03.

Institutional Review Board Statement: Ethical review and approval were waived for this study, due to the fact that the participants were able to live without restrictions in their daily life in the Energy Smart Home Lab. This means that the participants were at no point obliged to restrict their energy consumption behavior, since the calls to action sent provided nudges or incentives that the participants could but did not have to or need to follow. At no point during the experiment the participants had to fear or face negative consequences related to a non-following of the calls to action, nudges or incentives. In accordance with the data protection officer of the KIT, the anonymity of the participants was ensured, so that in this case also no ethical obligations exist. Furthermore, the participants were thoroughly informed as well as gave their written consent prior to their participation in the study.

Informed Consent Statement: Written informed consent has been obtained from the patient(s) to publish this paper.

Acknowledgments: Our thanks go to all the partner institutes involved in the research at the Energy Smart Home Lab and the continuous good cooperation.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CtA	Call to Action
DSM	Demand Side Management
ESHL	Energy Smart Home Lab
ESM	Energy Management System
KIT	Karlsruhe Institute of Technology
LD	Load-Dynamic
mCHP	micro Combined Heat and Power plant
No.	Number
PL	Power Limit
PV	Photovoltaic
STS	Sustainable Transportation Study

TOU	Time-of-Use
TPS	Transport Policy Study

Appendix A

Table A1. Message per incentive category allocated to their respective CtA and incentives (P/C: Praise or Complaint).

ID	CtAs	Environmental	Social	Economic
1	Sunny Day	P/C		
2	Cloudy Day	P/C		
3	Sunny Afternoon	P/C		
4	Sunny Afternoon + Forecast	P/C		
5	Cloudy Day + Forecast	P/C		
6	Cold Dark Doldrums	P/C		
7	Sunny Morning	P/C		
8	Purchase PV from your Neighbor	P/C	P/C	−5 €
9	Sell PV to your Neighbor	P/C	P/C	+5 €
10	TOU3			20, 30, 40 ct/kWh
11	TOU3			30, 60, 100 ct/kWh
12	Load-Dynamic (3 kW)			25, 35 ct/kWh
13	Load-Dynamic (2 kW)		P/C	30, 60 ct/kWh
14	Grid Bottleneck (1–4 p.m., 9–12 p.m., 1.5 kW)		P/C	
15	Grid Bottleneck (1–4 p.m., 9–12 p.m., 1 kW)	P/C	P/C	+5 €
16	Grid Bottleneck (1–4 p.m., 9–12 p.m., 2 kW)	P/C	P/C	
17	Grid Bottleneck (8–11 a.m., 6–9 p.m. −2 kW)		P/C	+5 €
18	Grid Bottleneck (8–11 a.m., 6–9 p.m. −3 kW)	P/C	P/C	+5 €
19	Grid Bottleneck (9–11 a.m., 6–9 p.m. −3 kW)		P/C	+5 €
20	Grid Restriction (10 a.m.–6 p.m. <2 kW)		P/C	
21	Grid Restriction (10 a.m.–6 p.m. <4 kW)	P/C	P/C	
22	Higher consumption than avg. Household		P/C	
23	Lower consumption than avg. Household		P/C	
24	Neighbor vs. Grid	P/C	P/C	
25	Power Limit 2.5 kW	P/C		0, −15 €
26	Power Limit 5 kW			0, −15 €

References

1. European Commission. Communication from the Commission: The European Green Deal. 2019. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 8 February 2012).
2. Umweltbundesamt. Erneuerbare Energien in Zahlen. 2020. Available online: https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#uberblick (accessed on 30 October 2012).
3. Midden, C.J.; Meter, J.; Weenig, M.H.; Zieverink, H.J. Using feedback, reinforcement and information to reduce energy consumption in households: A fiel experiment. *J. Econ. Psychol.* **1983**, 3, 65–86. [CrossRef]
4. Brandon, G.; Lewis, A. Reducing Household Energy Consumption: A Qualitative and Quantitative Field Study. *J. Environ. Psychol.* **1999**, *19*, 75–85. [CrossRef]
5. Abrahamse, W.; Steg, L.; Vlek, C.; Rothengatter, T. A review of intervention studies aimed at household energy conservation. *J. Environ. Psychol.* **2005**, *25*, 273–291. [CrossRef]
6. Fischer, C. Feedback on household electricity consumption: A tool for saving energy? *Energy Effic.* **2008**, *1*, 79–104. [CrossRef]
7. Schultz, P.W.; Nolan, J.M.; Cialdini, R.B.; Goldstein, N.J.; Griskevicius, V. The constructive, destructive, and reconstructive power of social norms. *Psychol. Sci.* **2007**, *18*, 429–434. [CrossRef]
8. Mizobuchi, K.; Takeuchi, K. The influences of financial and non-financial factors on energy-saving behaviour: A field experiment in Japan. *Energy Policy* **2013**, *63*, 775–787. [CrossRef]
9. Allcott, H. Social norms and energy conservation. *J. Public Econ.* **2011**, *95*, 1082–1095. [CrossRef]
10. Asensio, O.I.; Delmas, M.A. Nonprice incentives and energy conservation. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, E510–E515. [CrossRef]
11. Nolan, J.M.; Schultz, P.W.; Cialdini, R.B.; Goldstein, N.J.; Griskevicius, V. Normative social influence is underdetected. *Personal. Soc. Psychol. Bull.* **2008**, *34*, 913–923. [CrossRef]
12. Royal, A.; Rustamov, G. Do small pecuniary incentives motivate residential peak energy reductions? Experimental evidence. *Appl. Econ.* **2018**, *50*, 6193–6202. [CrossRef]

13. Nicolson, M.L.; Fell, M.J.; Huebner, G.M. Consumer demand for time of use electricity tariffs: A systematized review of the empirical evidence. *Renew. Sustain. Energy Rev.* **2018**, *97*, 276–289. [CrossRef]
14. Dütschke, E.; Paetz, A.G. Dynamic electricity pricing—Which programs do consumers prefer? *Energy Policy* **2013**, *59*, 226–234. [CrossRef]
15. Richter, L.L.; Pollitt, M.G. Which smart electricity service contracts will consumers accept? The demand for compensation in a platform market. *Energy Econ.* **2018**, *72*, 436–450. [CrossRef]
16. Sundt, S.; Rehdanz, K.; Meyerhoff, J. Consumers' Willingness to Accept Time-of-Use Tariffs for Shifting Electricity Demand. *Energies* **2020**, *13*, 1895. [CrossRef]
17. Hall, N.L.; Jeanneret, T.D.; Rai, A. Cost-reflective electricity pricing: Consumer preferences and perceptions. *Energy Policy* **2016**, *95*, 62–72. [CrossRef]
18. Paetz, A.G.; Dütschke, E.; Fichtner, W. Smart Homes as a Means to Sustainable Energy Consumption: A Study of Consumer Perceptions. *J. Consum. Policy* **2012**, *35*, 23–41. [CrossRef]
19. Paetz, A.G.; Becker, B.; Fichtner, W.; Schmeck, H. Shifting Electricity Demand with Smart Home Technologies: An Experimental Study on User Acceptance. In *Redefining the Energy Economy: Changing Roles of Industry, Government and Research, Proceedings of the 30th USAEE/IAEE North American Conference, Washington, DC, USA, 9–12 October 2011*; IAEE: Dallas, TX, USA, 2011.
20. Azarova, V.; Cohen, J.J.; Kollmann, A.; Reichl, J. Reducing household electricity consumption during evening peak demand times: Evidence from a field experiment. *Energy Policy* **2020**, *144*, 111657. [CrossRef]
21. Buckley, P; Llerena, D. *Demand Response as a Common Pool Resource Game: Nudges Versus Prices*; HAL-Id:hal-01704457; Centre pour la Communication Scientifique Directe (HAL Archive Ouverte): Villeurbanne, France, 2018.
22. Moser, C.; Cometta, C.; Frick, V. *How Do Different Residential Consumer Groups React to Monetary and Unconventional Non-Monetary Incentives to Reduce Their Electricity Consumption?* Final Report; Swiss Federal Office of Energy (SFOE): Bern, Switzerland, 2016. [CrossRef]
23. Ito, K.; Ida, T.; Tanaka, M. Moral Suasion and Economic Incentives: Field Experimental Evidence from Energy Demand. *Am. Econ. J. Econ. Policy* **2018**, *10*, 240–267. [CrossRef]
24. Bundesverband der Energie- und Wasserwirtschaft e.V. Stromspiegel für Deutschland 2019. 2019. Available online: https://www.stromspiegel.de/fileadmin/ssi/stromspiegel/Broschuere/Stromspiegel-2019-web.pdf (accessed on 8 February 2021).
25. Verband der Elektrizitätswirtschaft e.V. Repraesentative VDEW-Lastprofile. 1999. Available online: https://www.bdew.de/media/documents/1999_Repraesentative-VDEW-Lastprofile.pdf (accessed on 8 February 2021).
26. Jakovcevic, A.; Steg, L. Sustainable transportation in Argentina: Values, beliefs, norms and car use reduction. *Transp. Res. Part Traffic Psychol. Behav.* **2013**, *20*, 70–79. [CrossRef]
27. Schwartz, S.H. Universals in the Content and Structure of Values: Theoretical Advances and Empirical Tests in 20 Countries. In *Advances in Experimental Social Psychology*; Zanna, M.P., Ed.; Academic Press: Cambridge, MA, USA, 1992; Volume 25, pp. 1–65. [CrossRef]
28. De Groot, J.I.M.; Steg, L. Value Orientations to Explain Beliefs Related to Environmental Significant Behavior: How to Measure Egoistic, Altruistic, and Biospheric Value Orientations. *Environ. Behav.* **2008**, *40*, 330–354. [CrossRef]
29. De Groot, J.I.; Steg, L. Value Orientations and Environmental Beliefs in Five Countries. *J. Cross Cult. Psychol.* **2007**, *38*, 318–332. [CrossRef]
30. de Groot, J.; Steg, L. General Beliefs and the Theory of Planned Behavior: The Role of Environmental Concerns in the TPB. *J. Appl. Soc. Psychol.* **2007**, *37*, 1817–1836. [CrossRef]
31. Steg, L.; Perlaviciute, G.; van der Werff, E.; Lurvink, J. The Significance of Hedonic Values for Environmentally Relevant Attitudes, Preferences, and Actions. *Environ. Behav.* **2014**, *46*, 163–192. [CrossRef]
32. Steg, L.; Bolderdijk, J.W.; Keizer, K.; Perlaviciute, G. An Integrated Framework for Encouraging Pro-environmental Behaviour: The role of values, situational factors and goals. *J. Environ. Psychol.* **2014**, *38*, 104–115. [CrossRef]
33. Baur, N.; Blasius, J. (Eds.) *Handbuch Methoden der empirischen Sozialforschung*; Springer: Wiesbaden, Germany, 2014. [CrossRef]
34. Bandura, A. *Self-Efficacy: The Exercise of Control*, 13th ed.; Freeman: New York, NY, USA, 2012.
35. Bandura, A. Guide for contructing self-efficacy scales. In *Self-Efficacy Beliefs of Adolescents*; Adolescence and Education; Pajares, F., Urdan, T.C., Eds.; IAP-Information Age Pub: Greenwich, CT, USA, 2006; Volume 14, pp. 307–337.
36. Shafiei, A.; Maleksaeidi, H. Pro-environmental behavior of university students: Application of protection motivation theory. *Glob. Ecol. Conserv.* **2020**, *22*, e00908. [CrossRef]
37. Wu, H.; Mweemba, L. Environmental self-efficacy, attitude and behavior among small scale farmers in Zambia. *Environ. Dev. Sustain.* **2010**, *12*, 727–744. [CrossRef]
38. Bryman, A. *Social Research Methods*, 4th ed.; Oxford University Press: Oxford, UK, 2012.
39. Schreier, M. Varianten qualitativer Inhaltsanalyse: Ein Wegweiser im Dickicht der Begrifflichkeiten. *Forum Qual. Sozialforschung (FQS)* **2014**, *15*, 27.
40. Mayring, P. *Qualitative Inhaltsanalyse: Grundlagen und Techniken*, 12th ed.; Beltz Pädagogik, Beltz: Weinheim, Germany, 2015.
41. Kuckartz, U. *Qualitative Inhaltsanalyse. Methoden, Praxis, Computerunterstützung*, 4th ed.; Grundlagentexte Methoden, Beltz Juventa: Weinheim, Germany; Basel, Switzerland, 2018.

42. Schultz, W.P.; Zelezny, L. Values as Predictors of Environmental Attitudes: Evidence for Consistency Across 14 Countries: Values as Predictors of Environmental Attitudes: Evidence for Consistency Across 14 Countries. *J. Environ. Psychol.* **1999**, *19*, 255–265. [CrossRef]
43. Dunlap, R.E.; Gallup, G.H.; Gallup, A.M. Of Global Concern: Results of the Health of the Planet Survey: Environment: Science and Policy for Sustainable Development. *Environ. Sci. Policy Sustain. Dev.* **1993**, *35*, 7–39. [CrossRef]
44. Steg, L.; de Groot, J.I.M. Environmental Values. In *The Oxford Handbook of Environmental and Conservation Psychology*; Clayton, S., Ed.; Oxford University Press: Oxford, UK, 2012; pp. 81–92. [CrossRef]