Original research article

Rising with the sun? Encouraging solar electricity self-consumption among apartment owners in Sweden

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Abstract

Studies suggest that householders who turn prosumers become more energy aware, change their pattern of electricity use and may even start to engage in other pro-environmental activities. However, few of these studies were equipped to investigate such causal relationships—mainly because most prosumers are inherently self-selected. However, as real estate companies and building owners have begun installing photovoltaics on their customers’ behalf, a new breed of non-self-selected prosumers is emerging, which presents new opportunities to address questions of causality and thus improve our understanding of the possible implications of a more prosumer-dense future. Using a sample of 54 apartment households with a shared rooftop PV installation, this article presents the first causal analysis on non-self-selected prosumers’ response to information about having become prosumers, what that means for themselves and the collective they are part of, how to self-consume solar electricity and why they should do so. Using a stepped wedge design and stratified randomization procedure we were able to design an experimental study with sufficient power. A panel regression model and various statistical analyses on pre and post treatment survey- and electricity use data were used to evaluate the intervention. In line with studies of self-selected prosumers, the self-reported measures suggest that householders have shifted the use of major appliances to increase their self-consumption. However, based on the electricity use data, we find no evidence of a such a shift and no indications of spillovers to other pro-environmental behaviours—highlighting the need to use multiple measures to assess behavioural change.

1. Introduction

With depleting fossil fuel stocks and global climate change, transitioning to renewable energy sources (RES) is one of the most pressing challenges that society faces. Distributed micro-generation using photovoltaics (PV) is one potential part of the solution that has gained attention during the last decade. However, as we cannot yet store electricity in a financially and environmentally sustainable manner on a large enough scale (e.g. [1,2]), we must do what we can to make use of the electricity we generate while it is being generated.

Studies have suggested that solar prosumers, that is, electricity consumers who also produce electricity via PV, are often willing and able to change the timing of their electricity use to increase their self-consumption, that they are more energy aware and may even engage more in pro-environmental behaviours than others. However, few studies have been able to address what actually happens to householders' electricity use, practices and other pro-environmental actions and motivations after they become prosumers. Furthermore, very little has been said about the subsection of prosumers that live in apartments. This study aims to investigate how householders, living in apartments with a shared rooftop PV installation, who are unaware of that they are prosumers and what that entails, respond to information about having become prosumers, what that means for themselves and the collective they are part of, how to self-consume solar electricity and why they should do so. We address three key questions: (1) Do they shift their electricity use to daytime?; (2) If so, why and how? If not, why not?; (3) Do they change their perceptions of, opinions about, and habits of engaging in pro-environmental behaviours other than those addressed by the intervention?
### 1.1. Solar electricity and the issue of self-consumption

The increase of global energy demand, combined with the negative impact of burning fossil fuels, makes the adoption of RES pivotal for a sustainable future. Encouragingly, the deployment of RES like PV have taken off in the last few decades [3,4]. Of all newly installed power production across the world, about 70% was renewable in 2018, and of this part, 55% was accounted for by solar PV [3].

Though the rise of distributed PV is a promising development, without financially and environmentally viable storage solutions, locally produced solar electricity will have to be fed back to the grid unless it is used where it is produced. That is not necessarily a problem, as it might help to resolve imbalances in the grid, but it is not ideal from a climate perspective. It is inefficient to redistribute locally produced electricity because of distribution losses, and large amounts of distributed PV may lead to increased strain on local grids [5]. Furthermore, installing PV only to send the electricity elsewhere does not make sense, unless there are other users—who are currently relying on more carbon intensive sources of electricity—who can make use of it. If large amounts of PV are installed, "surplus" solar electricity may however be used for purposes that would not otherwise have existed, i.e. creating a negative rebound effect where the availability of solar electricity is seen as a justification for an increased energy consumption.

From a prosumer's perspective, it is often financially beneficial to use one's own electricity, because the profit of each kilowatt hour sold is usually less than the costs of buying a kilowatt hour from the grid. Increasing one's self-consumption thus helps to increase the profitability of the investment [5]. Ideally, prosumers would replace as much as possible of the electricity that they would otherwise draw from the grid with the solar electricity they generate themselves, and only send back what is left.

### 1.2. Electricity use flexibility

The flexibility of householders’ electricity use has been studied for over three decades, with the purpose of understanding whether and how users can help reduce strain on the grid to free up capacity and defer costly investments—and more recently, how they can help to balance an increasingly intermittent electricity supply. Hundreds of studies now suggest that householders can be encouraged to use electricity at other times than they normally would using time-varying price signals, both with and without the support of enabling technologies (for overviews, see [6–11]). In-depth explorations of how this demand response is achieved show that householders may manually shift the use of electrical appliances in time (such as the dishwasher and washing machine), change the way they go about doing things (such as how they heat or cool themselves) and/or use automation technologies (such as smart thermostats and timers) [12–17].

What we know about householders’ willingness and ability to load-shift may however not be directly applicable to prosumers. Dynamic pricing usually provides an incentive to shift electricity use away from daytime, as this is when electricity grids are usually congested. By contrast, prosumers usually have the opposite financial incentive. Householders’ willingness and ability to shift electricity use to, rather than away from, daytime may not be the same, since the temporal rhythm of daily life has a large influence on how and when electricity is used [14,15,17–19]. If dynamic pricing is added to the equation, things get more complicated still, as prosumers then face multiple, and quite possibly divergent, dynamic financial incentives to load-shift.

A handful of studies have looked at how prosumers use electricity in their everyday lives. Hansen and Hauge [20] found that prosumers who work during daytime used the built-in timer on their washing machines, dishwashers and tumble dryers to engage in load-shifting—sometimes in combination with checking the weather forecast. Prosumers with electric vehicles (EVs) also avoided charging during non-peak periods, and a number of prosumers with heat pumps wanted to load-shift their heating but did not know how to. Winther et al. [21] found that the majority of householders they interviewed engaged in load-shifting of dishwashers and washing machines. A few also manually tried to load-shift things such as their heat pump, boiler and food preparation activities. By contrast, Palm et al. [22] found that prosumers who worked full-time could not see any particular activities that could easily be shifted to daytime. However, the authors also noted that the prosumers’ overall knowledge about the existence of built-in timers and how to use them was low. The main barrier to engage in load-shifting was said to be a lack of financial incentive to do so. Some were also convinced that their personal actions did not matter and that exporting electricity to the grid was better than using it themselves, as they would make more money and/or reduce fossil fuel use during peak hours by doing so.2

There seems to be a larger agreement between studies regarding prosumers who are retired or able to work from home. Examples of activities that such prosumers have reported having shifted are washing [20,22], dishwashing, EV charging and vacuum cleaning [20]. In general, they seem to engage in manual load-shifting to a larger extent.

### 1.3. Spillover effects

In addition to the direct effects discussed above, it has been hypothesized that the adoption of PV might bring about indirect effects as well, such as that householders could become more aware of their energy use as they start producing their own electricity, possibly resulting in reduced energy use [12,22–26]. Indeed, studies have suggested that prosumers are more energy aware [20–22,27–29]. However, descriptive before and after comparisons as well as comparisons with non-prosumers suggest that prosumers do not necessarily reduce their electricity use [21–23,30]. A possible explanation for this, which is sometimes provided by prosumers themselves, is that they were already aware and conscious about their energy use and have carried out energy efficiency measures before becoming prosumers [21,22,24,27,31]. However, prosumers have also been found to deliberately try to increase their electricity use [20,22,28], for example, because it is perceived as free, because they do not want to send it back to the grid when the financial compensation for doing so is perceived as too low and/or because they do not know who receives it and whether it is used in a sensible way.

At the same time, some studies have found positive associations between being a prosumer and engagement in a wider range of pro-environmental behaviours. Hondo and Baba [32] asked prosumers to self-report changes in several pro-environmental behaviours since they adopted PV, concluding that a positive change had taken place. Stikvoort et al. [29] compared intentions and motivations to perform pro-environmental behaviours between prosumers and consumers, concluding that the former held higher intentions to perform pro-environmental behaviour as well as self-assessed electricity awareness. These are all examples of potential ripple effects of the adoption of PV, also known as a behavioural spillover effects, which are said to occur when the performance of one behaviour increases or decreases the likelihood of other behaviours [33,34].

### 1.4. Identified research gaps, aim and research questions

There are a number of issues with the previous studies that have ramifications for the validity and generalizability of their findings.

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1. Unless overcompensating feed-in tariffs are in place.

2. Exporting to the grid in Sweden does typically not reduce fossil fuel use because hydropower is used as balancing power [59]. Fossil fuels are only used to deal with exceptional peak demand situations that might occur a few times a year.
These issues, which stem from the methodological challenges involved in studying prosumers and the possible implications of a prosumer-dense future, have in turn created a number of knowledge gaps that deserve our attention.

1) The studied prosumers are self-selected

The first issue is that there is an inherent causality dilemma, which stems from the fact that prosumers are most often self-selected, i.e. they have chosen to become prosumers themselves. This means that there is an intervention selection bias present in most studies (also known as selection into treatment), which severely threatens their external validity (e.g. [8]). Findings from such studies suggesting that self-selected prosumers are different from electricity users can therefore be construed either as a cause for, or consequence of, PV investment. Moreover, since a sample of self-selected prosumers is not randomly drawn from, and thus not representative of, the larger population of households, it cannot be used to make causal inferences concerning how householders in general would react to becoming prosumers.

2) The studied prosumers are likely not representative of the future population of prosumers

As most of the studied prosumers are self-selected, most are also living in single-family homes. This is not yet a major issue, but as the uptake and deployment of PV is expanding to other types of housing, our current understanding of what prosumers do might become invalid.

The deployment of PV on multifamily residential buildings has already begun to gain momentum in some countries, as real estate companies, housing associations and the likes have recognized the untapped potential of rooftops and facades. As populations grow and urbanization continues, a majority of households will live in multifamily buildings. Installing PV on such buildings not only makes sense with regard to the urgency of a large-scale transition towards renewable energy systems and the increased geographical density of energy demand, but from a financial and technical perspective as well.

People living in single-family homes often differ from people living in apartments in ways that are likely to affect the outcomes we are interested in studying. Firstly, there are socio-economic and demographic differences, such as in income, family composition and occupation — factors that are likely to affect electricity use (see e.g. [35]). That self-selected prosumers are indeed different has been pointed out in several studies, for example with regards to income and education [22,26,36–38]. Secondly, there are differences when it comes to the financial incentives to care about one’s electricity use and the ability to affect one’s costs. Single-family homes require more electricity to run, and the electricity-related costs of those who have PV vary depending on the weather and level of self-consumption. This makes it difficult to discern whether prosumers living in single family homes, who engage in acts aimed at increasing their self-consumption, do so because of the financial incentive, or because of something else. The fact that single-family homeowners moreover have full autonomy over home investments also means that they often have greater possibility to affect their electricity use. Thirdly, as single-family homeowners were the first to become prosumers, the studied prosumers often belong to the early adopters — that is, individuals that have been strongly motivated to become prosumers, e.g. because of environmental reasons and/or a strong interest in technology and/or self-sufficiency and/or in signalling a certain social identity [21,22,26,27,31,39].

There are to our knowledge only three studies that have included apartment-living prosumers [21,23,27]. These suggest that such prosumers hardly engage with their PV and do not seem to use electricity any differently than non-prosumers, perhaps because they may not even be aware of the technology or what it does. However, none of these studies have been designed in a way that allows for causal inferences to be made.

3) A lack of quantitative evaluations

Another observation is that most studies of prosumers are based solely on self-reports, collected via interviews and/or surveys, and have not made use of electricity use data to explore how prosumers actually use their electricity. Doing so would not only allow for a better understanding of how different households’ electricity use patterns might look and change over time, but also for verification of any self-reported behavioural changes.

Furthermore, if the data are collected retrospectively, i.e. without the householders being aware at the time the data is recorded, subsequent electricity use analyses will not suffer from volunteer selection biases or Hawthorne effects, which studies based on self-reports can never get rid of [8,40]. In fact, a quasi-experimental design using retrospective data may be preferable to use over an experimental design when an experiment cannot be conducted double-blind, to avoid the risk of volunteer selection bias or Hawthorne effects [41].

4) A lack of intervention studies

Studies of how electricity users respond to demand-side interventions are common, but there are, to our knowledge, no studies of how prosumers respond to interventions aimed at inducing load-shifting. As more householders become prosumers, it is important to study how they might differ from electricity users in their response to such interventions. For example, if self-consumption is desirable from a societal point of view, but the inherent incentive to self-consume is too weak, it is important to look at how prosumers can be further incentivised to self-consume.

5) A lack of studies exploring soft-benefits/spillover effects

PV-ownership has been suggested to have the potential to yield ‘soft benefits’ beyond load-shifting, such as increased energy awareness, energy literacy and engagement in emission-reducing behaviours [42]. Few studies so far have however focused on the effects of adopting PV on actions beyond load-shifting and electricity use, and, to our knowledge, no such study has been equipped to make causal inferences. Thus, it is of importance to properly evaluate if the adoption of PV actually can elicit such effects among householders.

1.5. Closing the gap

To sum up, there is still much to learn about the social and societal effects of PV. This study seeks to address the above gaps by studying how apartment-living householders — who have become prosumers without self-selection — respond to an intervention consisting of information about that they have become prosumers, what that means for themelves and the collective they are part of, how to self-consume solar electricity and why they should do so.

Given the nature of the sample and the study design, we may address questions of causality and learn about how apartment-living householders might respond to becoming prosumers. As it is the collective rather than the individual household that benefit financially from increased self-consumption in the chosen empirical context, we can also assess whether householders may be willing to change their electricity use without being financially rewarded for doing so, to help disentangle the actual drivers of load-shifting behaviours. As all of the household’s major appliances had built-in-timers, the technical conditions for being able to engage in load-shifting were excellent. By measuring the householders’ use of electricity as well as their perceptions of opinions about and habits of engaging in a range of pro-environmental behaviours, both before and after the intervention, we also allow for a deeper understanding of their response and its causal link to the intervention.

We specifically seek to answer the following research questions:
1. Do non-self-selected apartment-living prosumers shift their electricity use to daytime in response to information about that they have become prosumers, what that means for themselves and the collective they are part of, how they can self-consume solar electricity and why they should do so?
2. If so, why do they respond and how is their response achieved? If not, why not?
3. Does the intervention change their perceptions of, opinions about, and habits of engaging in pro-environmental behaviours other than those addressed by the intervention?

2. Methods

2.1. Empirical context

The study was carried out in a multifamily residential building consisting of 54 condominiums (tenant-owned apartments) with a shared rooftop PV installation of 32.4 kWp, located in Uppsala, the fourth largest city in Sweden. The majority of the householders, who moved in at the time the building was finished in May 2016, had purchased their apartment up to 2 years earlier. As the plan to install PV was not marketed by the real estate agent, the decisions of those who purchased their apartments before the building was raised were supposedly independent of the fact that they would have PV on the roof. Furthermore, the building itself was just like any other multifamily building, i.e. it was not exceptionally priced, labelled as eco-friendly or located in an eco-oriented part of the city, meaning that the sample of householders was most likely representative of a larger population of condominium-living householders (with similar socio-economic characteristics).

Measures to confirm the assumed absence of a volunteer selection bias were included in the pretreatment survey (Section 2.4.2). Two out of 32 respondents said they had known about the PV while also having been positively affected by it in their decision to buy their apartment. These two, possibly self-selected prosumers, were deemed not to be an issue for the validity of our study. Another prerequisite that we wanted to confirm was that the householders were not already engaged in the behaviours that the intervention aimed to induce. We knew that they had not been informed about how the PV system worked prior to the intervention, but the PV panels had been visible and active for more than a year before the intervention, which could in theory have affected their electricity-using practices. However, there were no signs of that the householders were engaged in, or had even thought about, the behaviours targeted by the intervention in the pretreatment survey responses (see Fig. 7).

Each household had Internet-connected electricity meters measuring their hourly use, as well as dishwashers, washing machines and tumble dryers with built-in timers. The building had a single connection to the grid, wherefore the electricity retail and distribution costs were paid for by the tenant-owners’ association (in accordance with the contracts signed on behalf of its members) and later on divided between households according to their individual monthly use. Although these costs varied over the day and season in accordance with the hourly production of solar electricity, the hourly retail price and the seasonally varying two-part distribution tariff, the households paid a flat volumetric charge of 1.22 SEK/kWh to the tenant-owners’ association.4 Thus, the individual households had no direct financial incentive to use, or refrain from using, electricity at certain times of the day. Electricity was used for everything in the apartments except for space heating and hot water which was provided by district heating (included in the monthly fee).

2.2. Intervention

We designed an information-based intervention, mainly consisting of four leaflets. The medium and the frequency of distribution were carefully chosen. The intervention needed to be financially and operationally realistic to adopt for tenant-owner’s associations and the likes, and the risk of introducing volunteer selection bias and Hawthorne effects had to be minimal. Advanced digital feedback systems do not fulfill these requirements. Furthermore, studies on the use of dynamic feedback often conclude that householders tend to lose interest in it over time [17–19]. Even very engaged householders have been found to rely on simple rules of thumb in their decisions to load-shift when faced with complex feedback [17].

The intervention had a two-fold aim. Firstly, it aimed to inform the householders of that they had become prosumers and what that meant for themselves and the collective of households that they were part of. Secondly, it aimed to inform them of how they could self-consume their solar electricity and different reasons for why they should do so. The signal to self-consume was formulated as a simple rule of thumb — use your appliances during daytime, aiming at 12.00 p.m. — followed by instructions on how to schedule their dishwasher, washing machine and tumble dryer using the built-in timers. The idea was to provide simple and concrete instructions on how to increase their self-consumption with minimal effort by: focusing on load-shifting practices that householders often engage in [12,14,15,17,20–22], informing about the technical means available that might facilitate such load-shifting [20,22,26,43] and by omitting the need to pay attention to the weather and/or solar electricity production as it requires more effort and as forecasts might be ignored if perceived as unreliable [17,18]. Although the production varies with the weather, most of the electricity will be produced at solar noon when the PV panels are facing south (which they were), which occurs around 12.00 p.m. in Uppsala.

The four leaflets were distributed by hand to each household’s mailbox, roughly once a quarter, starting in September 2017 and finishing in June 2018. The leaflets were distributed under the tenant-owners’ association’s auspice, making sure that the householders received the information from a well-known and trusted source.

The first leaflet informed the householders of their role as prosumers, that the electricity they generate is best used by them at the moment of production and how they could use the rule of thumb and their built-in timers to do so. Once all households had received the first leaflet, they were invited by the board of the tenant-owners’ association to an information meeting about fire procedures and the solar panels, where two of the authors of this study gave a brief talk to 24 attending households, essentially repeating the information in the first leaflet. The second leaflet repeated the information while emphasizing that solar

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3 Tenant-owned apartments are a common form of housing in Sweden, and the most common in Uppsala (36% in 2018). In Sweden, a tenant-owned apartment is an apartment located on a property owned by a tenant-owners’ association. The association is made up of the tenants (householders) themselves, who have become members by purchasing “their apartment” (a share of the association’s property) on the housing market. Each tenant disposes of the inside of its apartment within certain limits, but everything outside each apartment is shared property, owned and managed by the association. Thus, the PV installation is owned by all tenants and all costs/savings associated with it are shared among the households, although these are never specified to the individual tenant.

4 1.22 SEK = 0.13 EUR = 0.15 USD in September 2017. The charge was set before the householders moved in and represents the average net cost of the electricity used within the households, i.e. the total cost of grid-imported electricity divided by the number of kWh used by all households. Thus, the financial benefit of the PV installation is included in the price. The charge excludes electricity costs related to the running of the building itself. Such costs are instead included in the monthly fee that each household pays to the tenant-owners’ association, and is dictated by each household’s share of the tenant-owners’ association rather than their share of the collective use of electricity.

5 The instruction were specific to the very appliances they owned, as these were the same for all households and known by the tenant-owner's association.
electricity is generated during wintertime as well to encourage continued engagement and addressing some householders’ concerns that running appliances unsupervised may not be safe. This leaflet came with two magnets that could be stuck on appliances to remind householders to use the timers (see Appendix A). The third leaflet repeated the core information once more, while adding a discussion of the collective financial savings that could be and had been generated by the PV panels. The last leaflet was a one-page summary of the previous ones, a thank you to the householders for their attention and engagement and an encouragement for them to continue to shift their electricity use to daytime. They were also informed that the board had collaborated with Uppsala University to find out whether the collective use of solar electricity had changed over the past year. Lastly, the were asked to share their experiences and knowledge about how and why (or why not) they had changed their electricity use by filling in an accompanying survey (see Section 2.4.2). The original leaflets, as well as English translations, are available in Appendix A.

2.3. Study design and procedure

Due to the difficulty of finding a comparable group of prosumers (i.e. non-self-selected etc.) which could be used as a control, a stepped wedge design was used (see e.g. [44])—that is, a subset of households were used as control for another subset by randomly dividing them into groups and treating them (i.e. providing leaflets to them) at different times. This design naturally reduces unwanted differences between the treated and the control that could affect the outcomes of interest—such as in demographics, socio-economic factors, weather and climate—and by randomly dividing the households into groups that are treated at different times, such confounding factors are controlled for by design as well.

A stratified randomization procedure [45] was used to improve the efficiency of the design, in which the households were first divided into strata that were constructed based on their pretreatment electricity use data, taking into account the level and dynamics of their electricity use (see Section 2.5.1). To ensure balance in the measures of interest (specified in Section 2.5.1) before treatment, the sufficient statistics for these second order Taylor approximations of those measures were used as clustering variables. That is, the groups were balanced with regards to the parameters of interest pre treatment, rather than on covariates that might be important for their electricity use. The K-means clustering algorithm was used to find strata based on a subset of these statistics. Several indices suggested a three strata solution. Lastly, households from within each strata were randomly split into three groups, which were then treated at different times (Fig. 1). In this way, untreated households could act as controls for treated households, until all households were treated. For details about the stratified randomization procedure, see Appendix B.

2.4. Data collection

2.4.1. Electricity use data

Hourly household-level electricity use data were made available to us by the board of the tenant-owners’ association from the 10th of April 2017 and onwards. All data collected before each household received the first leaflet is henceforth referred to as pretreatment electricity use data and the rest as posttreatment electricity use data.

2.4.2. Survey

Two paper questionnaires were distributed by hand to each household’s mailbox: a pretreatment survey on the 20th of June 2017 (i.e. roughly two and a half months before the first group of householders received the first leaflet) and a posttreatment survey on the 4th of May 2018.

The cover letter of the pretreatment survey stated that the tenant-owners’ association would conduct a project together with Uppsala University during the fall, aiming at “providing the association and society at large with knowledge that can contribute to a better living environment and a better world”. That is, we were careful not to inform them of the focus of our study as we wanted an unbiased picture of their pretreatment electricity use behaviours. We asked them to let the person who usually carries out the household chores (such as dishwashing and washing) to fill in the survey, or be of help during the filling, and to leave the completed survey in the mailbox of the board of the tenant-owner’s association, located in the building. The letter was signed by the chairman of the board and one of the authors of this study, representing Uppsala University.

The surveys captured three groups of variables: (1) basic socioeconomic variables; (2) timing of major household appliances; (3) their assessment on how eight behaviours (Table 1) affect the environment, to what extent they feel morally responsible to perform those, how often they perform them and how often they intend to perform them in the future.

The third group of variables was measured on a seven-point scale ranging from very negative impact to very positive impact for the belief concerning the impact of the pro-environmental behaviours on the environment; from no moral responsibility to very large moral responsibility for the extent to which they felt morally responsible to perform those behaviours; and from never to always for how often they perform those behaviours and how often they intend to perform those

![Fig. 1. A visual illustration of the stepped wedge design, including when leaflets were distributed and pre- and posttreatment data were collected.](image-url)
The specific time-window was chosen because it proved to be the least effect estimate of interest was defined as the households’ daily proportion of electricity use during daytime hours (defined as 9 a.m. to 15 p.m.), henceforth referred to as kWh. The households’ average daily electricity use, henceforth referred to as kWh, was another effect estimate of interest, included to accommodate for the possibility of spillover effects. Other potential measures, such as the actual amount of self-consumed solar electricity or electricity-related emissions of CO₂ were not included as these rather represent the context-specific outcomes of the targeted behaviour, rather than the behaviour itself.

The overall change in kWh, and kWh respectively, across the 54 households, was estimated using a panel regression model with fixed effects for household and time, given by

\[ kWh_{i,t(l)} = \gamma_i + \mu_i + r_{t(l)} + \epsilon_{i,t(l)} \]

where \( i \) corresponds to an individual household, \( t \) is the time period and \( \epsilon_{i,t} \) are the error terms — which were allowed to be heteroscedastic and serially correlated using robust standard errors [46]. The fixed time effects, \( \mu_i \), were included to ensure that any observed effect was not caused by natural variation over time. The fixed household effects, \( \gamma_i \), were included to ensure that any observed effect could not be attributable to differences between the groups pre treatment.

Table 1
The eight pro-environmental behaviours assessed by the surveys.

<table>
<thead>
<tr>
<th>Behaviour</th>
<th>(n)</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Eat more vegetarian food</td>
<td>32</td>
<td>43.3</td>
<td>17.9</td>
</tr>
<tr>
<td>2. Buy eco-labelled products</td>
<td>32</td>
<td>22.0</td>
<td>9.9</td>
</tr>
<tr>
<td>3. Sort and recycle waste</td>
<td>32</td>
<td>10.0</td>
<td>4.5</td>
</tr>
<tr>
<td>4. Choose another mode of transport than a car</td>
<td>32</td>
<td>2.1</td>
<td>0.9</td>
</tr>
<tr>
<td>5. Save electricity</td>
<td>32</td>
<td>59.6</td>
<td>5.87</td>
</tr>
<tr>
<td>6. Save water</td>
<td>32</td>
<td>6.86</td>
<td>3.82</td>
</tr>
<tr>
<td>7. Use electricity during the day instead of in the evening</td>
<td>32</td>
<td>0.25</td>
<td>0.04</td>
</tr>
<tr>
<td>8. Use electricity during the evening instead of in the day</td>
<td>32</td>
<td>6.96</td>
<td>3.28</td>
</tr>
</tbody>
</table>

Table 2
Descriptives of the survey respondents’ socio-economic variables as well as the respondents’ and non-respondents’ energy use parameters of interest (described in Section 2.5.1).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pretreatment respondents (n = 32)</th>
<th>Pretreatment non-respondents (n = 22)</th>
<th>Posttreatment respondents (n = 32)</th>
<th>Posttreatment non-respondents (n = 22)</th>
<th>Same householders (posttreatment) (n = 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of respondent</td>
<td>43.3</td>
<td>17.9</td>
<td>41.9</td>
<td>17.2</td>
<td>45.5</td>
</tr>
<tr>
<td>Female respondents</td>
<td>22</td>
<td>19</td>
<td>13</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Male respondents</td>
<td>10</td>
<td>13</td>
<td>8</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>Household members</td>
<td>2.1</td>
<td>2.1</td>
<td>0.8</td>
<td>2.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Household income (SEK/month)</td>
<td>59,650</td>
<td>25,530</td>
<td>56,830</td>
<td>26,050</td>
<td>65,000</td>
</tr>
<tr>
<td>kWh pre treatment</td>
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<td>0.25</td>
<td>0.04</td>
<td>0.04</td>
<td>0.26</td>
</tr>
<tr>
<td>kWh post treatment</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.26</td>
<td>0.03</td>
</tr>
<tr>
<td>kWh pre treatment</td>
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<td>3.82</td>
<td>5.87</td>
<td>2.45</td>
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<tr>
<td>kWh post treatment</td>
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<td>–</td>
<td>–</td>
<td>5.96</td>
<td>3.28</td>
</tr>
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</table>

The posttreatment survey was identical to the pretreatment survey, with the exception of three additional open-ended questions: (1) whether they had changed their electricity use in response to the information leaflets, and if yes, how; (2) what motives and/or incentives to adapt their electricity use to the availability of solar electricity they had experienced; and (3) what barriers and/or lack of incentives to adapt their electricity use to the availability of solar electricity they had experienced.

In total, 32 out of the 54 households responded to the pretreatment survey and 32 to the posttreatment survey, although they were not all the same households. Of the 32, there were 23 households that had responded to both the pre- and posttreatment survey, of which 20 were filled in by the same household. Table 2 provides a selection of descriptives for the different groups, including the respondents’ and non-respondents’ energy use parameters of interest pre and post treatment (described in Section 2.5.1) to illustrate that those who chose to respond to the surveys were not any different in their electricity use than those who chose not to respond. That is, the survey respondents constituted a representative sample of the 54 households with regards to the electricity use measures of interest. More detailed descriptives of the socio-economic variables are available in Appendix C.

2.5. Data analysis

2.5.1. Causal analysis of electricity use data and statistical power

As we wanted to see whether the households’ would shift their electricity use to daytime in response to the intervention, the main behaviours in future. Composite scores for each belief across the first six behaviours in Table 1 were calculated as proxies for ‘pro-environmental behaviours’ (the seventh behaviour was kept separate in the analyses because of its high importance and the eighth behaviour was omitted because the scores were entirely idiosyncratic). That is, one composite of its measures of interest. More detailed descriptives of those who chose not to respond. That is, the survey respondents constituted a representative sample of the 54 households with regards to the electricity use measures of interest. More detailed descriptives of the socio-economic variables are available in Appendix C.

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kWh, of 0.012, and approaches 100% for an average change of around 0.0225. Under the assumption that consumption patterns are similar in shape during the fall, this means that the probability of detecting a change in the daily average electricity use during daytime hours of 2.25% or higher is close to 100%. That is equivalent to a shift of 0.12 dishwasher runs to daytime hours per day (or 0.84 runs per week) on average per household.\footnote{Based on the energy consumption of the standard (eco) program of the dishwasher runs to daytime hours per day (or 0.84 runs per week) on average per household.} The corresponding power for kWh is 80% for 0.4 kWh and 100% for 0.6 kWh. In other words, even though the sample size of 54 households might seem small, especially considering that they are divided into subgroups that act as controls for each other, we deem the power of the design to be sufficient considering what we expect to be a reasonable response to the intervention. For more details about the power analysis, see Appendix B.

2.5.2. Analysis of survey responses

Differences in the householders’ answers to the closed survey questions, between the pre- and posttreatment survey, were analysed using a combination of Bayesian model comparison (e.g.\cite{47}) and visual comparisons following the estimation approach proposed by Cumming\cite{48} (but with credible intervals instead of confidence intervals)\footnote{Classical (frequentist) null hypothesis testing has been heavily criticized for being non-intuitive, prone to misinterpretations and ingnorant to alternative hypotheses (e.g.\cite{60,61}). In response, Bayesian hypothesis testing has been proposed as an alternative, more intuitive approach, as it permits the expression of evidence in favor of one hypothesis compared to another (or many others) in a more nuanced fashion (e.g.\cite{62,63}). Bayesian hypothesis testing requires defining prior beliefs concerning the occurrence of the hypotheses, which, together with the likelihood of the observed data given the hypotheses, results in probability distributions of ‘Posterior beliefs’, i.e. the belief that the hypothesis fits the data. Instead of p-values, Bayes factors (BFs) may then be used to evaluate whether a treatment is likely to have had an effect or not. BFs indicate the likelihood of the hypotheses given the data on a continuous scale, testing for example whether the frequentist null hypothesis, or an alternative hypothesis, is more likely, given the data. BFs are reported either as BF\textsubscript{10} or BF\textsubscript{01}, where the first expresses the likelihood of the data under the hypothesis of there being a difference compared to the hypothesis of there not being a difference (e.g. between pre and posttreatment data), and the latter expresses the opposite. That is, BF\textsubscript{01} is the inverse of BF\textsubscript{10}.}. Since there are no prior experiments available to base parameter estimates on, priors were kept uninformative — that is, as zero-centred Cauchy distributions with a scale of 0.707, as provided by default in JASP version 0.9.2\cite{49} (the software used to perform the analyses). Robustness checks were run for all analyses to ensure that the choice of prior did not alter the results.

The householders’ answers to the open-ended questions were analysed by reading them through and inductively categorising them into themes describing the essence of the replies. The categorisation was revisited several times during the process and finally agreed upon by two of the authors of this study. The number of answers under each theme were then summarised and further analysed using bar charts.

The reason we chose to present their open-ended answers in a quantitative fashion rather than a qualitative fashion, was that their answers were quite short and heavily overlapping, thus allowing us to provide a digestible overview of the hundreds of answers we received, while retaining the relevant aspects of their replies with regards to our research questions and the literature.

3. Analysis

The analysis is divided into three sections, each addressing one of the research questions. Section 3.1 looks at whether the householders shifted their electricity use to daytime in response to the intervention by analysing how the share of electricity use during daytime as well as self-reported electricity-related behaviours and intentions changed over time. Section 3.2 zooms in on how and why any observed changes may have come about by looking at how the self-reported use of major appliances has changed and the stated reasons for using them at the specified times, as well as motives and barriers towards adapting to the availability of solar electricity. Section 3.3 looks at whether the householders’ have changed any behaviour or belief beyond those targeted by the intervention by analysing how their overall electricity use as well as their engagement with other pro-environmental behaviours and intentions towards such behaviours changed over time.

3.1. Did householders shift their electricity use to daytime?

The panel regression yielded an overall effect estimate of 0.003, with a standard error of 0.006 and an implied Wald confidence interval of $-0.008$ to 0.015. That is, the estimated mean change in the 54 households’ average daily proportion of electricity use during daytime hours (kWhr) in response to the first information leaflet was around zero.

As to their self-assessments of whether they were and/or would use electricity during the day instead of in the evening (behaviour and intention), their responses ($n = 20$) were 9.1 respectively 30 times more likely to occur under the hypothesis assuming a difference in means between the pre- and posttreatment survey, compared to the hypothesis...
assuming no difference \((M_{\text{pre behaviour}} = 3.00, SD = 2.10, 95\% \text{ CI} = [2.02, 3.98], M_{\text{post behaviour}} = 4.60, SD = 1.23, 95\% \text{ CI} = [4.02, 5.18], BF_{10} = 9.1; M_{\text{pre intention}} = 4.10, SD = 1.68, 95\% \text{ CI} = [3.31, 4.89], M_{\text{post intention}} = 5.75, SD = 0.91, 95\% \text{ CI} = [5.32, 6.18], BF_{10} = 30.0).\) Fig. 3 provides a visual comparison of the pre- and posttreatment survey scores.

As shown by Fig. 3, the credible intervals of pre- and posttreatment behaviour respectively intention do not overlap, suggesting a difference in means. The spread of responses is large, but overall, there is a dominance of an upward shift between pre- and posttreatment scores, both for behaviour and intention (as illustrated by the dotted lines)—suggesting that the mean upward shift from pre to post treatment is caused by a majority of householders shifting upward, rather than by a disproportionate shift by a select few.

Comparing self-reported to observed electricity use behaviour, we find no evidence of a correlation between the change in householders’ self-reported use of electricity during the day instead of in the evening and the change in kWh, (Kendall’s tau = −0.01, 95% CI = [−0.27, 0.25]). That is, those with a positive increase in self-reported behaviour were not necessarily the ones who exhibited a (substantial) increase in the average daily proportion of electricity use during daytime hours.

Householders were also asked to report if they had changed their electricity use in response to the information leaflets in the posttreatment survey (Yes or No), and if so, how (open-ended). The responses are visualised in Fig. 4.

Fig. 4 shows that the majority of the respondents reported that they had changed their electricity use in response to the intervention. Of those, the vast majority reported that they had done so by shifting electricity-using activities to daytime (yellow bar, henceforth called the **solar adapters**), while a few reported to have reduced their electricity use or to have increased their energy use awareness (green and blue bar respectively, henceforth called the **non-solar adapters**). To see if we could find any support for their claims in the electricity use data, we calculated the average daily proportion of electricity use during daytime hours (kWh) per household over a two-month period (one before and one after the intervention), and compared the solar adapters to those who said they had not changed their electricity use in response to the leaflets (henceforth called the **non-adapters**). The result is visualized in Fig. 5.

Fig. 5 shows that the sample distribution of the difference in the solar adapters’ average daily proportion of electricity use during daytime is somewhat upwards-shifted from that of the non-adapters. The difference in means being 2.5% units to be exact. The 95% credible
than not (Msolar adapters = 0.010, SD = 0.022, 95% CI = [−0.004, 0.024], Mnon-adapters = −0.015, SD = 0.042, 95% CI = [−0.040, 0.010], BF10 = 1.21).

The data were 1.2 times more likely under the hypothesis assuming a difference in means between the pre- and posttreatment survey, at the within-household level (n = 23). Positive numbers on the y-axis represent an increase in the number of respondents having chosen a given time-of-use alternative between the pre- and posttreatment survey. Negative and positive numbers add up for each appliance in each panel. The change in the actual number of respondents is shown by the numbers inside each bar.

Intervals do however overlap extensively, wherefore there is little evidence for a systematic difference between the groups. The data were 1.2 times more likely under the hypothesis assuming a difference in means than not (Msolar adapters = 0.010, SD = 0.022, 95% CI = [−0.004, 0.024], Mnon-adapters = −0.015, SD = 0.042, 95% CI = [−0.040, 0.010], BF10 = 1.21).

3.2. How did the householders respond to the intervention, why and why not?

3.2.1. Usage of major appliances

As the intervention addressed the usage of major appliances in particular, householders were asked to specify when during the day they normally use such appliances. The change in their responses, between the pre and posttreatment survey, is presented in Fig. 6.

Fig. 6 shows that a number of households have shifted their self-reported use of the dishwasher, washing machine and tumble dryer to around lunch or early afternoon. The biggest change is seen in the use of the dishwasher (especially during weekends), where there is a shift from all times of the day to around lunch or early afternoon. The time-of-use of the washing machine has not changed quite as much, and most of the change relates to weekday usage. The number of households who have shifted the use of the tumble dryer to around lunch or early afternoon is even less. However, the number of households reporting that they (almost) never use the tumble dryer has increased, which is also in line with the intervention as the first leaflet informed the householders to hang-dry their clothes instead.

To provide us with clues as to why the householders might be able and/or willing to shift the timing of their usage or not, they were also asked to explain why they used their appliances at the specified times (open-ended). The thematically categorised pre and posttreatment survey responses are visualised in Fig. 7.

Looking at the pretreatment responses in Fig. 7, the main reason that the householders gave as to why they chose to use their appliances at the times they had specified was daily rhythm/timing. That is, they stated that they run their appliances at times that are dictated by the temporal rhythm of their daily lives — such as work and other commitments that affect their possibilities of filling and emptying the appliances and the need to have things done by a certain time (e.g. to avoid stacks of dishes or not having clean cutlery or clothes). For the majority of householders, this meant running their appliances in the morning or evening. Another, but far less common reason, was their will to be home/awake when running their appliances. One of the four households who said this had a fear of water leakage and fire, while the others did not specify. The least common reason (given by one respondent) was noise, i.e. that running appliances in the evening was inappropriate due to the noise they produce.

As to the posttreatment responses in Fig. 7, daily rhythm/timing was still considered an important determinant of time-of-use. However, solar production now appeared as the second most commonly mentioned reason, Cost and environment were also mentioned. For example, one of the solar adapters explicitly said they adapted for environmental reasons and one of the non-adapters saved up the dishes to the evening because of the financial and environmental benefits of running a full machine.

3.2.2. Motivations/incentives to adapt one’s electricity use to the availability of solar

To provide us with clues as to what might have motivated the householders to respond to the intervention, they were asked to describe what motivations and/or incentives to adapt their electricity use to the availability of solar electricity they had experienced (open-ended). The thematically categorised posttreatment survey responses are visualised in Fig. 8.

As shown by Fig. 8, three types of motivations/incentives were
observed, of which the most commonly mentioned was cost. Of the ten who said so, one meant a personal financial incentive, two meant a collective financial incentive and the rest did not say. Environmental motivations were the next most commonly mentioned. Of the eight who said they wanted to use solar electricity for the sake of the environment, four also said cost was important. Three respondents expressed altruistic motives. That is, they seemed willing to adapt to the availability of solar simply because they could or because they found meaning in trying to make use of the solar electricity they had access to. Unfortunately, a majority of the respondents abstained from answering the question, or failed to specify their perceived motivations/incentives in a way that we could interpret.

In addition to the open-ended question, householders were asked to indicate how strongly they considered using electricity during the day instead of in the evening to have a positive impact on the environment (environmental impact belief), and whether they felt a moral responsibility to do so. Their responses were 6.2 respectively 40.6 times more likely to occur under the hypothesis assuming a difference in means between the pre- and posttreatment survey, compared to the hypothesis assuming no difference ($N_{\text{pre impact belief}} = 12$, $M_{\text{pre impact belief}} = 4.92$, $SD = 1.44$, $95\% CI = [4.00, 5.83]$, $N_{\text{post impact belief}} = 19$, $M_{\text{post impact belief}} = 6.00$, $SD = 0.94$, $95\% CI = [5.55, 6.45]$, $BF_{10} = 6.2$; $N_{\text{pre & post moral resp}} = 20$, $M_{\text{pre moral resp}} = 3.10$, $SD = 1.91$, $95\% CI = [2.16, 3.94]$, $M_{\text{post moral resp}} = 4.65$, $SD = 1.53$, $95\% CI = [3.93, 5.37]$, $BF_{10} = 40.6$). Fig. 9 provides a visual comparison of the pre- and posttreatment survey scores.

As shown by Fig. 9, the credible intervals of pre- and posttreatment scores overlap to some extent for the environmental impact belief and almost nothing for moral responsibility. The spread of responses is large, but overall, there is a dominance of an upward shift between pre- and posttreatment scores, both for the environmental impact belief and sense of moral responsibility (as illustrated by the dotted lines)—suggesting that the mean upward shift from pre to post treatment is caused by a majority of householders shifting upward, rather than by a disproportionate shift by a select few.

A comparison of the householders’ self-reported use of electricity during the day instead of in the evening (Fig. 4) and their beliefs about the environmental impact of such behaviour (Fig. 9) revealed a positive correlation between the two (Kendall’s $\tau = 0.34$, $95\% CI = [0.06, 0.54]$). A comparison of their self-reported behaviour and their sense of moral responsibility for engaging in such behaviour also revealed a positive correlation (Kendall’s $\tau = 0.64$, $95\% CI = [0.35, 0.79]$). We found similar results for the relationship between their intentions to engage in the behaviour of using of electricity during the day instead of in the evening (Fig. 4) and their environmental impact beliefs / sense of moral responsibility (Fig. 9). That is, both those who believed that shifting electricity use to daytime hours would benefit the environment and those who felt a moral responsibility to do so, also reported engaging in such behaviour to a greater extent as well as wanting to do so to a greater extent in the future. This tentatively suggests that environmental and moral motivations may be important determinants of the householders’ willingness to shift their electricity to daytime hours, which is also in line with their open-ended answers (Fig. 8).

### 3.2.3. Barriers/lack of incentives to adapt one’s electricity use to the availability of solar

The householders were also asked what barriers and/or lack of incentives to adapt their electricity use to the availability of solar electricity they had experienced (open-ended). The thematically categorised posttreatment responses are visualised in Fig. 10.

As shown by Fig. 10, three types of barriers were observed, of which the most commonly mentioned one was the daily rhythm of the householders’ lives, such as having difficulty doing the laundry during working hours or to cook dinner before the sun set during wintertime. The two other barriers that were mentioned were a difficulty to learn/remember new routines, such as using the built-in timers, and a lack of feedback of one’s use of solar, which was perceived as problematic and/or discouraging. Unfortunately, a majority of the respondents abstained from answering the question, or failed to specify their perceived barriers/lack of incentives.
perceived barriers and/or lack of incentives to adapt their electricity use to the availability of solar, categorised by themes representing the essence of their replies (x-axis) and grouped in accordance with their self-reported response to the intervention (described in conjunction with Fig. 4). The ‘non-solar-adapters’ are those who said they adapted but not by shifting activities to daytime. The number of respondents is represented by the height of each bar (y-axis) and the numbers inside them.

3.3. Did the intervention affect the householders’ perceptions of, opinions about and habits of engaging in pro-environmental behaviours?

The panel regression on the households’ average daily electricity use (kWh) yielded an overall effect estimate of 0.00866, with a standard error of 0.007 and an implied Wald confidence interval of $-0.0057$ to 0.023. That is, the estimated mean change in the 54 households’ average daily electricity use in response to the first information leaflet was around zero.

To see whether changes in their electricity use could have taken a longer time to emerge, for example, as a result of more reminders (leaflet 2–4 and the information meeting), we compared the average daily electricity use over a two-month period before the first leaflet had been sent out (April–June 2017) to a two-month period after the fourth leaflet had been sent out (April–June 2018)—of all households, the solar adapters and the non-adapters. Fig. 11 visualises the results.

Fig. 11 shows that the sample distribution of the difference in all households’ average daily electricity use between May–June 2017 and May–June 2018 is centred around zero. That is, there is no evidence for that changes had happened after the full intervention period either. The data for all households were 4.6 times more likely under the hypothesis assuming no difference between pre and posttreatment means compared to that assuming a difference ($M_{all \, households} = -0.22$, $SD = 1.84$, 95% CI = $[-0.72, 0.28]$, BF$_{01} = 4.6$ (i.e. BF$_{10} = 0.22$)). The mean of the difference was close to zero for the non-adapters as well ($M_{non-adapters} = 0.09$, 95% CI = $[-0.66, 0.83]$), while it was a bit below zero for the solar-adapters ($M_{solar \, adapters} = -0.88$, 95% CI = $[-1.83, 0.09]$). This tendency of a downward shift is however not large enough to suggest a systematic shift in electricity use, as the 95% credible interval encompasses zero and overlaps that of the non-adapters quite extensively.

As to the householders’ self-assessments of the six pro-environmental behaviours and intentions included in the composites (Table 1, Appendix C), their responses ($n = 20$) were 3.5 respectively 2.7 times more likely under the hypothesis assuming no difference in means between the pre- and posttreatment survey, compared to the hypothesis assuming a difference ($M_{pre \, behavioural \, composite} = 4.76$, $SD = 0.83$, 95% CI = $[4.35, 5.17]$, $M_{post \, behavioural \, composite} = 4.78$, $SD = 0.97$, 95% CI = $[4.32, 5.23]$, BF$_{10} = 3.5$ (i.e. BF$_{01} = 0.28$); $M_{pre \, intention \, composite} = 5.63$, $SD = 0.76$, 95% CI = $[5.25, 6.01]$, $M_{post \, intention \, composite} = 5.37$, $SD = 0.75$, 95% CI = $[4.99, 5.76]$, BF$_{10} = 2.7$ (i.e. BF$_{01} = 0.36$)). The mean of the intention composite was, however, high in both surveys, so potential changes could have been masked by ceiling effects. That is, the householders reported very high intentions to engage in pro-environmental behaviours in the pretreatment survey, and as such, there was little room to increase their scores in between surveys. As shown by Fig. 12, which visualises the self-reported occurrence of each of the pro-environmental behaviours separately, there is nothing to suggest a change in any of the behaviours in response to the intervention except use electricity during the day instead of in the evening.

It could be that spillover effects resulting from an intervention like this take longer time to develop. If so, any indication of that could be visible in their behavioural motivations. To test this, we explored whether there were any differences in the composites of the two measured motivations (i.e. the environmental composite and the moral composite, Table 1, Appendix C) between the pre- and posttreatment surveys. In line with the absence of a shift in intention and self-reported behaviour, the data ($n = 20$) were 3.1 respectively 4.2 times more likely to occur under the hypothesis assuming no difference in means between the post- and posttreatment survey, compared to the hypothesis assuming a difference ($M_{pre \, environmental \, composite} = 5.94$, $SD = 0.67$, 95% CI = $[5.58, 6.30]$, $M_{post \, environmental \, composite} = 6.08$, $SD = 0.56$, 95% CI = $[5.81, 6.35]$, BF$_{10} = 3.1$ (i.e. BF$_{01} = 0.32$); $M_{pre \, moral \, composite} = 4.85$, $SD = 1.21$, 95% CI = $[4.27, 5.44]$, $M_{post \, moral \, composite} = 4.88$, $SD = 1.06$, 95% CI = $[4.38, 5.37]$, BF$_{10} = 4.2$ (i.e. BF$_{01} = 0.24$)).

4. Discussion

This section presents an in-depth discussion of the above presented results, with emphasis on (1) the discrepancy between observed and self-reported response to the intervention, (2) how and why prosumers responded to the intervention (or not) and (3) interpretations of the spillover analysis.
4.1. The discrepancy between observed electricity use and self-reported response

The first research question underlying this study was whether the non-self-selected apartment-living prosumers under study would shift their electricity use to daytime in response to information about that they have become prosumers, what that means for themselves and the collective they are part of, how they can self-consume solar electricity and why they should do so. While the survey responses indicated a shift, the analysis of the change in electricity use did not. That is, there is a discrepancy between self-reported and observed response. There are several possible explanations for such a discrepancy.

One possibility is that the householders did respond to the intervention as claimed, but that the changes they made were too small to be captured by our measure of choice (kWh). For example, it could be that shifting major appliances to daytime hours does not affect the households’ ratio of daily electricity use during daytime hours to an extent sufficient to be detected by the study design at hand. However, this is unlikely given that we have (close to) 100% probability of detecting a change to the ratio of 0.0225 points or higher, which is equivalent to a shift of 0.12 dishwasher runs todaytime hours per day (or 0.84 runs per week) on average per household (see Section 2.5.1). This means that if each household would have time-shifted one dishwasher run (or a washing machine or tumble dryer run) per week during the first three weeks of the intervention, we would have detected it. Of course, if some households would not have shifted, the remaining households would have had to shift more appliance runs for us to be able to detect it. For example, some households may already have been using their appliances during daytime hours, and would thus be unable to shift these. Although we would have expected respondents to have mentioned this as a barrier (which they did not), we wanted to find out whether our design could cope with such attrition. To do so, we made a conservative estimate of their ability to shift the use of major appliances to daytime hours, by looking only at their dishwasher time-of-use pretreatment (i.e. pretending that no other appliances can be time-shifted). 15 of the 32 responding households had the possibility to shift their dishwasher from late afternoon/evening to daytime hours during both weekdays and weekends. Assuming that survey response and time-of-use are independent (which we find no reason to doubt given the bias-check provided in Table 2), a conservative estimate is thus that half of the 54 households had the possibility to time-shift their dishwashers. That is, if half of the households would have shifted 5 dishwasher runs (i.e. no other appliances) per household over the course of the first three weeks (1.7 runs per week), we would have detected it.

A complicating factor is that the ratio of electricity use during daytime hours depends on the absolute amount of electricity use. Thus, if the solar adapters and/or those who had the ability to shift were above average in their electricity use, shifting one appliance-run would not affect their ratio as much. To find out whether our design was robust against such a possibility, we analysed how a shift of different appliance-runs were expected to affect the ratio across different households. It turned out that the ratio was affected to the same extent on average across the different groups of interest (shown by the overlapping distributions in Fig. 5, Appendix B), i.e. there is nothing to suggest that the solar adapters or those who had the ability to shift the time-of-use pre treatment would have needed to shift more appliance-runs in order to have an effect on the overall ratio of electricity use during daytime hours.

Another possible explanation for the observed discrepancy between observed and self-reported response lies in the dissimilar time-periods of measurement between the panel regression analysis of the change in ratio (kWh) and the surveys. The period included in the panel regression covered the distribution of the first leaflet, whereas the survey data encompassed a period of nearly one year, thus covering all four

Fig. 12. Self-reported occurrence of seven pro-environmental behaviours in the pre and posttreatment survey on a scale ranging from 0 (never) to 7 (always). Individual data-points are represented as circles with a 5% vertical jitter to visualise density. Red crosses represent means and the error bars represent 95% credible intervals. ‘Use electricity during the day instead of in the evening’ (far right) was already reported Fig. 3, but is included here to allow for a comparison across all behaviours.
leaflets and the information meeting. It is possible that a change in behaviour took place after the time-period covered by the regression analysis. However, if this was the case, we should have observed a shift in the average difference between the pre- and posttreatment ratio of daily electricity use during daytime hours, as measured over a period of two months before and after the intervention (Fig. 5). The fact that no apparent shift was observed strengthens our belief that a behavioural effect did not occur later.

A third possible explanation may be that the intervention did not reach everyone. Although the leaflets were delivered directly to each households’ mailbox without envelopes, it is possible that some householders did not pay attention to them to a sufficient extent. However, given that the majority of householders took the time to respond to the surveys, it seems reasonable that most householders also read the leaflets. Even if we assume that only the solar adapters would have shifted, they would only have had to shift 3.24 dishwasher runs per week and household during the first three weeks on average for us to be able to detect it.

A fourth possible explanation for the discrepancy could be that the survey responses were biased or overconfident, for instance due to perceived expectations from us as researchers and/or the tenant-owners’ association, imperfect memory of the frequency of the behaviours we asked for or inability to report on the entire household’s behaviour. A meta-analysis by Kormos and Gifford [50] found that the association between observed and self-reported pro-environmental behaviour was about $r = 0.46$, a moderate effect size, while in this study, we found no correlation between the difference in pre and posttreatment survey responses and the pre vs. post treatment difference in the average daily proportion of electricity use during daytime hours (Section 3.1). Unfortunately, we cannot tell whether this is a result of socially desirable answers, imperfect memory or inability to report on one’s household’s behaviour accurately.

To sum up, the ambiguity between observed and self-reported response to the intervention begs clarification via replication of the current study, preferably with more informative measures of observed and self-reported electricity use as well as a bigger sample to make sure that even minor changes by a minority of households do not go unnoticed. For example, time-of-use diaries could be used to capture frequencies of and daily variations in the time-of-use, and water use data could be used to produce a better understanding of when major appliances are used during the day. Moreover, measures for socially desirable answers could be incorporated, as well as questions on respondents’ self-assessed confidence in the perceived accuracy of their answers.

4.2. The how, why and why not

The second research question underlying this study sought to address the nature of their response to the intervention, i.e. why did they, or did they not, shift their electricity use to daytime hours and how was their response achieved? The survey gave multiple insights to the answers to these questions. Firstly, we saw that a fair share of the respondents claimed having changed the time-of-use of one or several major appliances, mainly from late afternoon or early evening to around lunch or early afternoon (Fig. 6). Given that the majority work during daytime and have no other apparent reason to start shifting their electricity use to daytime hours, they must have been using (or meaning to use) the built-in timers with the aim of increasing their self-consumption of solar electricity.

It is not surprising that the daily rhythm of people’s lives came up as the main reason for why they used their appliances the times they did (Fig. 7), as well as the main barrier towards changing one’s time-of-use (Fig. 10), as it has done so in many other studies [14,15,17–19]. However, it is interesting to see that the share of householders stating that their time-of-use was determined by daily rhythms is lower in the posttreatment survey, while at the same time, there was a large increase in the number of respondents mentioning the availability of solar electricity as a determinant of time-of-use. Assuming that the daily rhythms of their lives had not changed, this suggests that the householders re-evaluated the importance of the daily rhythm of their lives in response to the intervention. That is, the introduction of a new reason to care about the time-of-use (possibly facilitated by the access to and information about built-in-timers) revealed a time-of-use flexibility that was not visible pre treatment. Worth noting however, is that the daily rhythm of people’s lives is still considered to be the main determinant of time-of-use post treatment, suggesting that the access to solar electricity and built-in timers is not enough to motivate most householders to shift their electricity use to daytime.

What then were the reasons to adapt to the availability of solar electricity? Cost came out on top in this open-ended question (Fig. 8), both overall and among the solar adapters, which is surprising given that there was no individual financial incentive to increase one’s self-consumption (explained in Section 2.1). The householders were informed of the collective financial savings generated by the PV panels in the third leaflet, but not of the actual or potential savings incurred by an increased self-consumption (neither personal nor collective). We can see three, possibly overlapping, interpretations of these results: (1) they were motivated by the fact that the tenant-owner’s association would save money if they shifted their personal electricity use to daytime; (2) they overestimated or misunderstood their ability to incur personal financial savings by shifting their electricity use to daytime; (3) the mental association between electricity use and costs is so strong that householders mentioned it without deeper reflection.

The first interpretation could mean that they exhibit a genuine care for the wellbeing of the collective itself, in which case their motive could be described as altruistic rather than financial. Altruistic motives to engage in load-shifting, such as a perceived civic or moral responsibility, have been observed by others (e.g. [13,19]). If their motive would be altruism in disguise, it would imply that altruistic motives actually dominate (seeing that the other two motives, environment and altruism, are also altruistic in nature), which to our knowledge has not been observed before. On the other hand, non-price interventions aiming at inducing load-shifting are not very common. Our focus on non-price ‘collective good’ arguments in the leaflets could perhaps explain the high prevalence of such motives. Whether we believe in the hypothesis that their “cost motive” was altruistic or not, the analysis of the closed questions do suggest that the intervention has increased the householders’ perceived moral responsibility to shift their electricity use to daytime, as well as their belief about the environmental impact of doing so (Fig. 9)—indicating that altruistic motives exist and have been reinforced on a group level.

Caring for the financial wellbeing of the collective could also be an expression of a care for the financial wellbeing of oneself, as the two are connected. However, long-term changes to the personal financial situation resulting from changes to the collective financial situation (such as a change in the average electricity price) would be extremely difficult to connect to personal acts since individually incurred gains from an increased self-consumption of solar are averaged out across the collective. Thus, if their motive was actually personal financial gain, whether disguised as a care for the collective or not, it would mean that they felt motivated by a conviction that was never confirmed. If personal financial gains were truly important, we would not expect householders to be willing to adapt without knowing how much they would save, while one would expect the absence of personal financial feedback to be a barrier towards adapting. However, 7 of the 10 households who gave cost as a reason to adapt belonged to the solar adapters (Fig. 8), and only two of those mentioned the lack of feedback when asked about barriers (Fig. 10).

The willingness to engage in load-shifting (for financial reasons), even when the financial consequences of doing so are unknown, has been observed before. Inspired by Stengers [12], Öhrlund et al. [17] hypothesized that a possible explanation for this phenomenon might be that time-varying price signals convey meanings about electricity (other
than price levels) which may lead householders to engage in (self-reported) load-shifting — as long as doing so does not cause them any inconvenience. They also pointed out that householders might not be interested in feedback if they already consider themselves to have done what they are willing and/or able to do, which could explain the low number of households perceiving the lack of feedback as a barrier towards load-shifting (Fig. 10).

As we observed the same kind of self-reported behavioural change as Öhrlund et al. [17], even though there was no price attached to “the signal” in our study, our observations provide additional support for the hypothesis that meanings (conveyed by some form of signal) may play a role in inducing (at least self-reported) load-shifting. Furthermore, it seems that (at least some of) the practices that householders have been shown to load-shift from daytime to evening (such as dishwashing and washing), are actually considered possible to shift in the other direction as well.

Considering that the majority of householders mentioned cost as having been an incentive to adapt one’s electricity use, expectations of making a profit might however have existed. This begs the question of whether such expectations might play a role in motivating householders to engage in load-shifting. What if householders who claim to be motivated by money are only willing to act upon that belief (even though it is never confirmed) as long as that belief is not disconfirmed? Öhrlund et al. [17] asked the same question, but unfortunately, neither they nor we included measures that could be used to answer that question. Given that others have found that financial messages can turn people off when asked to save energy [51,52], this hypothesis deserves further investigation, and so does the potential consequences of adding a price to a self-consumption signal given to non-self-selected prosumers, as it would help to unravel the role of money in inducing load-shifting and answer whether price-based incentives would be more effective as we seek to find ways of incentivizing self-consumption.

4.3. Spillover effects

The third research question underlying this study was whether the non-self-selected apartment-living prosumers under study would change their perceptions of, opinions about, and habits of engaging in pro-environmental behaviours in response to the intervention, as prior studies of self-selected prosumers suggest that spillover effects do (or might) exist [20,22,28,29,32].

This study, however, found no indication of behavioural spillover effects resulting from the intervention, i.e. of becoming (aware of one’s status as) a prosumer and gaining knowledge about what that means, how to self-consume and why one should do so. More specifically, the householders had not lowered (or increased) their electricity use during the intervention period, neither after the first information leaflet nor after the full intervention period (Section 3.3). Neither did their self-reported performance of, or intentions to perform, any other of the assessed pro-environmental behaviours change between the pre and posttreatment survey (Fig. 12).

Possible explanations for the absence of spillover effects could be: (1) there was too little time for the householders to incorporate the changes we encouraged into their daily routines, (2) the wrong behaviours were probed, i.e. spillover effects might have occurred in other behaviours, and/or (3) there simply were no spillover effects.

As regards to the first possible explanation, many pro-environmental behaviours require a certain amount of change of habits and daily routines. Given that behavioural changes in response to demand-side interventions may take time to emerge (e.g. [41,53]), it is likely that non-targeted behaviours take time to emerge as well. For example, the open-ended questions revealed that many householders found it difficult to shift electricity use to daytime due to the rhythms of their daily lives (Fig. 10). This barrier could be equally valid for the other pro-environmental behaviours. A fair share of the householders did however consider themselves able to perform the target behaviour, implying that spillover effects should have been able to emerge as well.

As regards to the second possible explanation, prior studies have suggested that pro-environmental behaviours occur in clusters or subgroups, i.e. that some behaviours are more related to one another than others (e.g. [54–57]). Assuming that two behaviours will spill over because they share a set of motivations that drives people to perform them, it is likely that behaviours that are more related to one another also spill over more easily. We selected six pro-environmental behaviours that were not targeted by the intervention to cover a wide range of potential spillovers. None of these behaviours increased over the intervention period, but we cannot exclude the possibility that other pro-environmental behaviours, not captured by this study, may have changed.

It is also possible that we missed a spillover effect on householders’ energy/electricity awareness (i.e. increase in one’s awareness of one’s energy consumption and how to reduce it, which has been observed among self-selected prosumers [20–22,27–29,42]), as we did not measure energy awareness thoroughly. If prosumers become more energy aware, this may, possibly on a longer term, result in behavioural changes beyond those behaviours related directly to the access to solar electricity.

As regards to the third possible explanation, it might be that “becoming a prosumer” does not induce behavioural spillover effects, at least not among those who are not self-selected and therefore perhaps lack intrinsic motivation to adjust their beliefs and behavioural motivations. Although we cannot draw conclusions beyond the population of non-self-selected apartment-living prosumers, we must conclude that, at least among the set of pro-environmental behaviours probed in this study, there is no support for the hypothesis that becoming a prosumer has soft benefits. As householders who actively decide to invest in PV may be more inclined to engage in pro-environmental behaviours from the start (compared to householders who do not invest), we cannot tell whether becoming a prosumer leads to behavioural spillover effects by studying such prosumers using cross-sectional designs. However, following self-selected prosumers over time, and comparing their trends in pro-environmental behaviours to non-prosumers over time, might be an alternative approach to discern selection effects from spillover effects. If such longitudinal studies were also to include non-self-selected prosumers, and measure factors like energy awareness, intrinsic motivation, environmental self-identity (as was suggested by [58] as a moderating factor to spillovers between pro-environmental behaviours) and awareness of one’s role as prosumer, we could continue to unravel whether spillover effects are entirely absent, or whether they may emerge under certain circumstances.

5. Conclusions

This study aimed at addressing a number of methodological issues and research gaps in the current literature on whether and how householders might change their behaviour in response to becoming prosumers. We did so by studying how non-self-selected prosumers living in apartments, who lack a direct financial incentive to self-consume their solar electricity, respond to information about that they have become prosumers, what that means and how they can, and why they should, make use of their self-produced electricity. To our knowledge, this is the first attempt to disentangle the causality dilemma surrounding prosumers.

As part of fulfilling the aim, this study set out to explore three research questions—the first being whether the non-self-selected apartment-living prosumers under study would shift their electricity use to daytime in response to information about that they have become prosumers, what that means for themselves and the collective they are part of, how they can self-consume solar electricity and why they should do so. The answer is two-fold: we did not detect any shift in the 54 householders’ average daily ratio of electricity use during daytime hours, but a group of householders reported that they had shifted their
electricity use, and felt able and motivated to do so when asked about nine months after the start of the intervention. This ambiguity highlights the need to use multiple methods and measures to assess behavioural change and begs clarification via replication of the current study—if possible, with more informative measures of observed and self-reported electricity use. For example, time-of-use diaries could be used to capture daily variations in the self-reported measures, and higher resolution and/or appliance specific electricity use data and/or water use data could be used to provide a better understanding of when major appliances are actually used during the day. Moreover, measures for socially desirable answers could be incorporated in a survey, as well as questions on respondents’ self-assessed confidence in the accuracy of their answers.

The second research question sought to address the nature of the householders’ potential response. More specifically: why did they, or did they not, respond to the intervention, and how was their potential response achieved? A fair share of the survey respondents reported using major appliances more during daytime after the intervention. The main determinant of their time-of-use was reported to be the daily rhythms of their lives before the intervention, while the availability of solar electricity scored almost as high after. The access to built-in timers likely facilitated their response, but was not enough to overcome the temporal limits of daily life for the majority of households. Even though there was no personal financial incentive to change the timing of one’s electricity use, cost had been perceived as the main incentive to increase one’s self-consumption, followed by environmental and altruistic motives. We discussed several possible explanations for why cost was mentioned, all of which suggest that financial rewards are second to the feeling of doing the right thing. However, as expectations of financial savings seemed to exist, further research is needed to find out whether householders who claim to be motivated by money are only willing to act upon that belief as long as that belief is not disconfirmed, and whether the response to a price-based intervention would be any different.

The third research question sought to address possible spillover effects. More specifically: did the non-self-selected apartment-living prosumers under study change their perceptions of, opinions about, and habits of engaging in pro-environmental behaviours (other than those targeted by the intervention) in response to the intervention? The answer is no. We found no indication of behavioural spillover effects resulting from the intervention. More specifically, householders did not lower (or increase) their electricity use, neither in the short or long-term. Neither did their self-reported performance of, or intentions to perform, a range of pro-environmental behaviours change. We discussed a number of possible explanations for why we did not observe any spillovers while others have suggested that there are or might be: (1) there was too little time for spillovers to occur, (2) spillovers occurred, but not to the observed behaviours, and (3) there were no spillover effects simply because they do not exist among non-self-selected prosumers. Experimental intervention studies like the one presented here, that also expand the scope of investigated variables to include concepts like energy awareness, intrinsic motivation, environmental self-identity, ownership of the decision to invest in solar panels and locus of control, will help to answer the question of whether spillovers are induced by PV-ownership or not.

In summary, this study has made a valuable contribution to our limited understanding of how householders might change their behaviour in response to becoming prosumers, and hopefully, to the research community’s awareness and understanding of the methodological challenges involved in studying this topic and how these may be addressed. Our findings suggests that merely having PV and being encouraged to self-consume solar electricity (without being financially rewarded in person for doing so) does not have a major impact on one’s daytime electricity use pattern, at least not among apartment owners. It does however induce self-reported behavioural changes. Further studies are needed to uncover whether non-self-selected prosumers might change their behaviours in response to other “stronger” or more “intense” interventions, such as price-based interventions and/or detailed and personalised dynamic feedback.

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None.

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Supplementary materials

References
