Characterizing the Danish energy prosumer

Who buys solar PV systems and why do they buy them?

Hansen, Anders Rhiger; Jacobsen, Mette Hove; Gram-Hanssen, Kirsten

Published in:
Ecological Economics

DOI (link to publication from Publisher):
10.1016/j.ecolecon.2021.107333

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Ecological Economics 193 (2022) 107333

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Characterizing the Danish energy prosumer: Who buys solar PV systems and why do they buy them?

Anders Rhiger Hansen [a,*], Mette Hove Jacobsen [b], Kirsten Gram-Hanssen [a]

[a] *Department of the Built Environment, Aalborg University, Denmark*
[b] *Social- og Sundhedsskolen Syd, Denmark*

A R T I C L E I N F O

Keywords:
Solar photovoltaics
Energy prosumer
Residential solar
Renewable energy adoption
Technology adoption
Consumer behavior

A B S T R A C T

Lower costs and stop-go policy around 2012 created two distinct groups of households with solar photovoltaics (PVs) in Denmark – a large group of early adopters (annually metered), and a smaller group of later adopters (hourly/real-time metered).

This paper analyses these groups to characterize Danish PVs prosumer households and identify why they bought PVs.

A comparison of a full population of 73,974 Danish household PVs owners (registered as of 2015) with other households shows that adopters tended to have higher incomes, be older, live in rural areas, have newer houses, and use individual heating (e.g. heat pumps). Moreover, the registered owners of PVs tended to be technically educated men.

A 2018 survey of 2505 PVs owners indicates that later adopters were slightly more inspired by peers, whereas early adopters were more inspired by news articles and sales drives. Moreover, independence, financial gains, and displaying proenvironmental action are identified as motivations to adopt PVs.

This paper concludes that technically educated men seem to dominate the decisionmaking process and that Danish energy prosumers seem to share (more or less) the same characteristics and motivations as PVs adopters in other contexts despite the distinct diffusion pattern in Denmark.

1. Introduction

Expansion of the generation of electricity from solar photovoltaics (PVs) is expected to play an important role in the transition towards an energy system based on renewable energy (IEA, 2019) and thereby contribute to meeting the climate change mitigation scenario in which global temperature rise is kept within 1.5 degrees Celsius (IPCC, 2018). Although small-scale intermittent energy generation may challenge the electricity system (Mathiesen et al., 2017), PVs on private residential houses are set to play an important role in producing more electricity from renewable sources. These so-called energy prosumer households, which not only consume but also produce and sell electricity (Kotilainen, 2020), may also bring other benefits. For example, some studies indicate that prosumer households become more environmentally friendly after getting PVs (Hansen et al., 2019), and micro-generation of electricity seems to increase households' awareness of the energy system (Hansen and Hauge, 2017; Keirstead, 2007; Palm et al., 2018; Palm and Tengvard, 2011).

In any case, the number of prosumer households is increasing, and they will have an important impact on the future development of electricity systems, energy markets and energy practices. It is therefore important to learn more about the energy prosumer households in order to ensure that they contribute to a sustainable transition of the energy system.

This paper investigates two research questions. First, which types of households tend to buy PVs, and second, why do these households buy PVs? Using Denmark as a case study, the paper aims to characterize the Danish households that bought PVs before 2015. This characterization includes comparison with other households as well as identification of motivations and inspirations for buying PVs.

Previous research on PV adoption in Germany shows that households that adopt PVs differ from households that rely on traditional energy sources in a number of ways, including, for example, regarding the socio-economic parameters of occupants and the types of buildings they occupy (Oberst et al., 2019). Moreover, PV households have been described as environmentally concerned and technically interested (see

* Corresponding author.
E-mail addresses: arhansen@build.aau.dk (A.R. Hansen), kgh@build.aau.dk (K. Gram-Hanssen).

https://doi.org/10.1016/j.ecolecon.2021.107333
Received 9 June 2021; Received in revised form 17 November 2021; Accepted 26 December 2021
Available online 5 January 2022

e.g. Schelly, 2014). Significant factors that influence PVs adoption include market and policy conditions. These are related to three issues of motivation of adopting PVs, namely economic gains, environmental concern and self-sufficiency (for a review, see Balcombe et al., (2013)).

However, the context of Denmark appears to differ from contexts in previous studies, especially those conducted outside the Nordic countries. Although many countries have used a 'stop-go' policy approach (Mathiesen et al., 2017), it seems that PV adoption in Denmark is especially influenced by it. Prior to 2011, sales of PVs were very low in Denmark, but around 2012, sales of PVs to private households boomed. This was primarily because annual net metering and lower costs on PVs made it favorable for private households to buy PVs. At the end of 2012, annual net metering was changed to hourly or real-time net metering, and sales normalized at a much lower level from then onward. These market conditions and stop-go policy mean that the Danish PVs owner households fall into one of two groups: 1) a large group of around 73,000 *early adopters* that bought PVs until end of 2012 (before and during the boom) with annual net metering of production and consumption,[1] and 2) a much smaller group of less than 4000 *later adopters* that bought after 2012 (after the boom) with hourly or real-time net metering of production and consumption. Samples of these two groups are compared throughout the paper.

Building on previous studies, this paper contributes in the following three ways.

First, this paper contributes with new empirical findings on who buys PVs in the residential sector and why they do so, for example related to aspects of gender.

Second, this paper contributes by broadening the empirical description of energy prosumer households. As no previous study has directly investigated PV adoption in Denmark (to our knowledge), this contribution especially concerns the specific case Denmark represents regarding market and policy conditions.

Third, this paper contributes by demonstrating how register panel-data on a full population of PV owners can be used to more accurately characterize prosumer households in combination with survey data on a sample of Danish PV households. Most studies on PVs adoption lack longitudinal data and rely on surveys with small sample sizes. In this paper, appeals for studies with larger sample sizes and longitudinal data (Oberst et al., 2019) are addressed by analyzing two comprehensive datasets on Danish PVs owners. The first dataset consists of a full population of PVs owners, registered in the years 2000, 2005, and 2007 to 2015, which are compared with a full population of households for the same years using administrative register information. The second dataset consists of responses from a 2018 questionnaire survey of 2505 PVs owners, whom were selected randomly using stratified sampling among all addresses with installed PVs.

The paper starts by presenting previous studies on households that tend to buy PVs and why they do so. Then, data and methods are presented. The results are divided into two sections, one that describes who bought PVs and another that describes why these households did so. Finally, the discussion and conclusion summarize the results and suggest implications for energy policy.

2. Which households tend to buy PVs and why

Previous research shows that PVs prosumer households tend to share characteristics and differ significantly from households without PVs. In particular, six aspects have been highlighted.

First, *household resources* are an important factor for the adoption of PVs. Higher levels of household income correlate with higher levels of PVs adoption by those households (Ameli and Brandt, 2015; Best et al., 2019a; Sigrin et al., 2015; Welsch and Kühling, 2009). In addition, higher wealth is also found to correlate with higher likelihood of PVs adoption by households (Best et al., 2019a), and a Californian study finds that individuals with higher educational levels are more likely to buy PVs (Sigrin et al., 2015). However, the latter correlation contrasts with the findings of Ameli and Brandt (2015), who report that educational level does not have any impact households' adoption of PVs.

Second, *technological interest* is another important factor for the adoption of PVs. This is often related to individuals' technical competence and innovativeness. For example, affinity with technology is found to be an important driver for becoming a prosumer household (Leenheer et al., 2011), and in a qualitative study from Wisconsin, early adopters of PVs are described as enjoying technical aspects, tinkering with technological projects and interested in technological innovation (Schelly, 2014). Adoption of PVs can also be a way for an individual to signal that they are a technological frontrunner (Rai et al., 2016).

Third, several studies find that the tendency to buy PVs correlates with *pro-environmental values* (Best et al., 2019a; Jager, 2006; Welsch and Kühling, 2009; Wittenberg and Matthies, 2016), and a Dutch study finds that environmental concern is the most important driver for intentions to become an energy prosumer (Leenheer et al., 2011). In addition, Sigrin et al. (2015) find that early adopters of PVs often have environmental values, whereas later adopters do not differ from the rest of the population in terms of values.

Fourth, *demographic characteristics* also appear to be important for adoption of PVs. However, concerning the significance of age of household members, the evidence on and similarities across contexts are not entirely clear. A Dutch study finds that interest in buying PVs is stronger among younger households (Leenheer et al., 2011), which correspond to a British study finding that older households are less likely to invest in PVs, whereas Ameli and Brandt (2015), in a study on 12 countries, do not find any correlation with age. Another study based on a survey of 11 European countries and household acquisition of energy-efficient white appliances finds that households with younger children seem more likely to buy PVs (Mills and Schleich, 2012). In our review, only the study by Oberst et al., (2019) includes a gender control variable, which is estimated to be insignificant. Gender might nonetheless still be an important factor. For example, a Danish study on gender and energy improvement of houses finds that renovation, primarily related to technical interests, is dominated by men (Tjørring, 2016).

Fifth, *social relations* also play a role in PVs adoption. In a sense, some of the above factors include this: for example, adoption of PVs can be a way for a person to signal resources and values to other people, and thereby relate to them. More specifically though, social relations matter in form of so-called peer-effects, for example there is strong evidence suggesting that knowing someone who has PVs (e.g. friends, neighbors or family members) increases the likelihood of buying PVs (Mundaca and Samahita, 2020; Palm, 2016; Welsch and Kühling, 2009; Woersdorfer and Kaus, 2011). In keeping with this, there is evidence that higher diffusion in an area has a causal peer effect on PVs adoption (Bollinger and Gillingham, 2012) and that geographical proximity to households with PVs is of a great importance (Rai and Robinson, 2015; Rode and Weber, 2016). This suggests that it is not just about knowing someone (e.g. interacting), but also about being inspired by seeing installed PVs, for example in the neighborhood. Moreover, a Swedish study finds that peer effects mainly function as a confirmation that PVs work as intended (Palm, 2017).

Sixth, the market and political *context* can be decisive for PV adoption in a specific country or region. An Australian study by Roberts et al. (2019) points at the importance of 'regulatory context', which refers to governance of apartment buildings, energy market regulation and electricity tariff policies. Furthermore, several studies find that subsidies are important for the adoption of PVs (Best et al., 2019b; Mundaca and Samahita, 2020), and local organizations promoting PVs are also found to have importance in a Swedish study (Palm, 2016). Another Swedish study used qualitative interviews to investigate changes in barriers to and motives for PVs adoption from 2008 to 2016, and finds that

[1] This has recently changed so that they are also metered on an hourly basis, but still with certain tax benefits.

administrative burdens and difficulties in finding information seem to be increasingly significant barriers, while financial motives have grown in importance over the years, and environmental motives have had consistently high significance over the years (Palm, 2018). A Dutch study finds that information meetings had a strong positive effect on PVs adoption (Jager, 2006). However, regarding energy efficiency investments, Baldini et al. (2018) argue that information campaigns in Denmark have largely been ineffective in encouraging households to invest in energy efficiency, and instead they find that other factors such as increased urbanization and demographic developments tend to correlate with increased investment in energy efficiency by households.

In addition to the six highlighted factors, previous research points at three primary motivations for buying PVs (see also Balcombe et al. (2013) for a review). First, households are found to be motivated by *financial gains*, for example reducing energy expenditures or securing against rising prices (Rai et al., 2016), and a Swedish study shows how this motivation was primarily important in a 'second wave' of PV adoption (Palm, 2018). Second, *environmental concerns* and the symbolic value of producing electricity are also considered important motivational factors (Palm and Tengvard, 2011). Third, the opportunity to become (more) *self-sufficient* and independent of energy suppliers is found to motivate households (Rai et al., 2016).

The review of previous studies finds no one simple or clear answer to why people chose to buy PVs. Based on the above review, the acquisition process consists of *motivational* factors and *contextual* factors. Motivations are often operationalized as the households' own reasoning or justification for buying PVs, for example related to (stated) values, peer-effects and practices. By contrast, contextual factors often refer to more objective aspects that influence the adoption of PVs. Such contextual factors could relate to conditions *inside* the households, for example economic resources, or conditions *outside* the household, for example market conditions and (energy) policy.

In any case, the process of buying PVs is situated and entangled in ongoing household practices, for example in the form of practical considerations and negotiations within the household. This could relate to ongoing renovation or DIY projects as well as to hobbies and social relations (Gram-Hanssen et al., 2020), where lower prices and subsidies can be seen as conveyers of (new) meaning to household practices (Hansen, 2018; Strengers, 2012), for example when the PVs solution enters discussions about household projects due to favorable market conditions for PVs investments.

Compared to previous research, this study contributes in three ways. First, by focusing more on aspects of gender, the analysis provides new nuances to the empirical description of PV adoption. Second, by using the case of Denmark, the analysis broadens the evidence on who buys PVs and why they do so in a context where primarily stop-and-go policy has strongly affected diffusion of PVs. Third, by using panel data on a full population of PV households and other households in combination with survey data with a sample drawn from the full population, the findings in this paper are based on a very strong data material, which contribute to strengthening both the validity and reliability of the results.

3. Data and methods

The analysis was based on data combining responses from a survey of Danish PVs owners, household data from the Danish administrative registers provided by Statistics Denmark and information on PVs from the Danish transmission system operator (Energinet). Data were merged using unique address codes linked to unique personal identification codes, both of which were anonymized. Data were processed and analyzed via Statistics Denmark's servers and therefore cannot be shared.

3.1. Register data

Data from the Danish administrative registers were used to investigate which types of households tend to buy PVs. This data contains rich information on socio-demographic characteristics (income, education and age), housing characteristics (housing type and construction period) and location.

Using an anonymized address code, the register data were merged with information on PVs from Energinet.dk, which includes data on the net settlement scheme, the anonymized personal identification code of the registrant and the date of registration (but not date of installation).

3.2. Survey data

The second part of the analysis, which investigated why households bought PVs, was based on survey data. The survey was conducted during the fall of 2018 and carried out by Statistics Denmark on behalf Aalborg University, Denmark. Stratified random selection was used to select 4567 individual PVs owners from a full population of 72,967 Danish PVs households. Most PVs owners in Denmark acquired and registered their PVs before 2012 (defined as early adopters in this study), and therefore are registered for annual net metering, while a small number acquired and registered their PVs after 2012, and are therefore metered on hourly basis or real-time. However, to ensure that later adopters were also represented in the survey, respondents were sampled to ensure an equal distribution of annually metered and other metering schemes (hourly and real time). Moreover, the survey was intentionally targeted at an equal number of men and women. Thus, where a household consisted of a couple, we randomly chose one of them. We acknowledge that this approach is not ideal, but we still consider it the best solution, especially in this survey, which focused on the aspect of living with PVs. A total of 2505 people responded via a web link, a response rate of 54.9%. The number of observations is lower in the analysis, primarily due to removal of respondents who did not take part in the purchasing decision. Additionally, and to a lesser degree, non-response, removal of 'Do not know' responses, and missing information in the administrative data also reduced the number of respondents.

3.3. Methods

Two methods were used in the analysis: the generalized estimating equation (GEE) panel regression model was used (Szmaragd et al., 2013) to compare PVs adopters with other households and exploratory factor analysis was used to identify underlying forms of motivations. In addition, *t*-tests based on the two-tailed *p*-value were used to compare the means of the two groups.

3.3.1. Population-averaged logistic regression

The analysis of which types of households bought PVs is based on panel data from 2000, 2005, and 2007–2015, with a full population of PVs owner addresses and a full population of Danish households as a comparison group. Conducting a logistic regression analysis on pooled data would not account for serial correlation across years. To account for serial dependence, the average partial effects were estimated using the GEE approach, which adjusts the estimates of a logistic regression model and standard errors for autocorrelation (Szmaragd et al., 2013). This means that the response probabilities, here, buying PVs or not, are specified conditional only on the independent variables, as probabilities are based on a multivariate weighted nonlinear least squares (MWNLS) estimator (Wooldridge, 2010). In other words, the panel data model, compared to a pooled data model, ensured that households buying PVs were compared with other households not buying PVs in that particular year.

3.3.2. Exploratory factor analysis

Exploratory factor analysis (EFA) was used to explore whether a set of questions on motivations for buying PVs had similar patterns of response – in other words, whether they shared variance that could be interpreted as an underlying variable (here called factor) (Fabrigar and

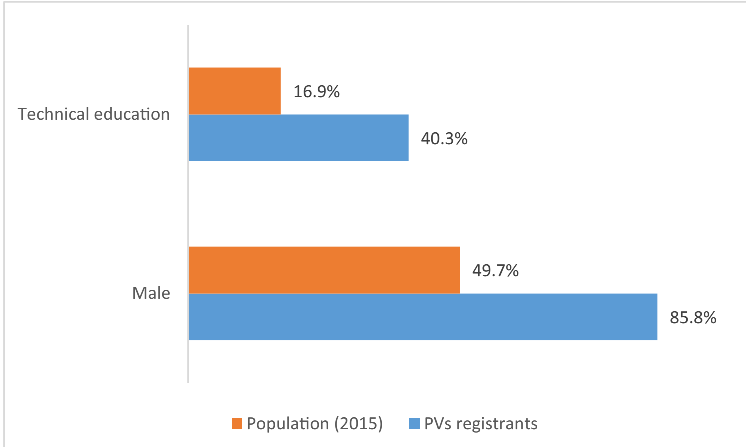

Fig. 1. Percentage of PVs registrants that are male and with technical education compared to population.

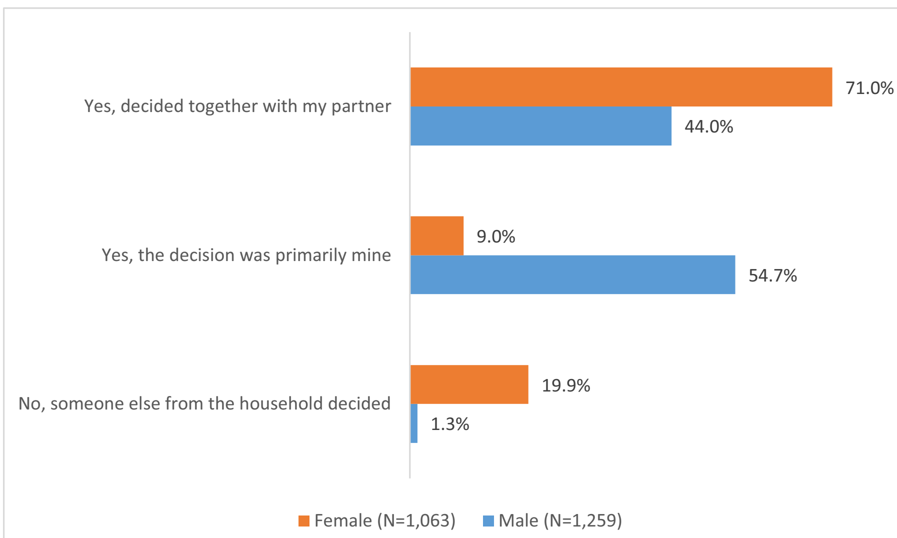

Fig. 2. Responses to the question "Were you involved in the decision on buying PVs?" across gender.

Wegener, 2011). The aim of factor analysis is to model the interrelationship among variables. Therefore, prior to the factor analysis, the strength of associations between the responses was investigated using Kendall's tau since the variable items have an ordinal distribution (Newson, 2002). The steps of the factor analysis are described in section 4.2, and through the analysis, three forms of motivations were detected using oblique rotation, which allows factors to correlate. Afterwards, Cronbach's Alpha test was used to measure the scale reliability of the three factors.

4. Analyzing PV adoption in Denmark

Our analysis consists of two parts. The first part uses register data to describe which types of households were more likely to buy PVs. The second part uses survey data to investigate why households acquired PVs, including an identification of three forms of motivation for buying PVs.

Both parts of the analysis compared early and later adopters of PVs. Early adopters were defined as individuals who had bought PVs on or before November 19, 2012 (although installation may have occurred later) and who were on annual net metering scheme. Later adopters were defined as individuals who had bought PVs after November 19, 2012 (and until end of 2015, where the data for this study ends) and who were on hourly or real-time net metering schemes. Before combining with other data, early adopters included 72,967 households and later adopters 3699 households.

4.1. Who bought PVs?

This first part of the analysis describes what characterizes the households that bought PVs in Denmark. Differences between early adopters (annual net metering) and later adopters (hourly or real-time net metering) are also investigated.

4.1.1. Technically educated men typically registered as owner

Although our analysis focuses on households, our data allowed us to identify the gender of the person who registered as the owner of the PVs system. Fig. 1 shows that those registered as owners were more often men (85.8%) and were most often technically educated (40.3%) compared to the general household population in 2015.

The overrepresentation of men among PVs registrants was also reflected in the survey questionnaire, where one question asked whether the decision to buy PVs was taken by one household member or together with a partner. Respondents were allowed to choose only one response. Fig. 2 indicates that gender is an important factor in the process of buying PVs. Only 9.0% of female respondents stated that the decision to

Table 1
Population-averaged logistic regression model coefficients of the likelihood of buying PVs.

Household income	
Q1	−1.384*** (0.023)
Q2	−0.554*** (0.015)
Q3	Ref.
Q4	0.390*** (0.011)
Q5	0.512*** (0.011)
Highest attained education in household (Ref. "Primary")	Ref.
Secondary	0.257*** (0.017)
BA/MA	0.496*** (0.017)
Technically educated in household	0.330*** (0.008)
Average age of household (Ref. "40 or lower")	Ref.
41 to 50	0.160*** (0.010)
51 to 60	0.319*** (0.012)
Over 60	0.345*** (0.013)
Young child (under 13) in household	0.030*** (0.010)
Teenager (13 to 19) in household	0.469*** (0.010)
Location (Ref. "Large cities and suburbs")	Ref.
Urban areas outside large cities	0.398*** (0.012)
Rural areas closer to large city	0.549*** (0.103)
Rural areas further away from large cities	0.658*** (0.010)
Construction period (Ref. "before 1961")	Ref.
1961–1978	0.188*** (0.009)
1979–1998	0.329*** (0.011)
After 1998	0.819*** (0.012)
Housing type (Ref. "Single-family")	Ref.
Townhouse	−1.271*** (0.018)
Farmhouse	0.607*** (0.011)
Heating form (ref. "District heating")	Ref.
Central heating (oil, natural gas or other fuel)	0.226*** (0.009)
Other heating supply, incl. Electricity and heat pump	0.826*** (0.009)
Constant	−6.616*** (0.012)
Number of PVs households	73,974
Number of observations	13,878,571
Number of households	1,574,675

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, standard error in parentheses.

buy PVs was theirs alone. 54.7% of male respondents reported that the decision was theirs alone. Still, it seems that most households decided in collaboration, at least based on the responses of women, which may reflect gender differences in perceptions of energy renovation projects or involvement in (technical) decisions when building a new house.

4.1.2. *Wealthy households living in rural areas tend to buy PVs*

A population-averaged logistic regression model (also known as the GEE approach) was used to estimate the likelihood of buying PVs based on the characteristics of a full population of PVs households across years compared to a full population of other households. This model was chosen because it allows comparison of households that buy PVs with households that do not buy PVs in a given year. The estimates should nonetheless be interpreted as in cross-sectional regression analysis. Table 1 shows the results of the model, where specific groups appear significantly overrepresented and thereby more or less likely to buy PVs. Starting with socio-economic characteristics, households with higher income, and with members who had higher education levels or a technical education were significantly overrepresented. Regarding socio-demographic characteristics, households with an average age of >40 were overrepresented, especially the group with an average household age of >50. It is also worth noting that households with a teenager aged 13 to 19 are strongly overrepresented. However, this might simply reflect the importance of stages of family life, where teenage households might be at a stage with sufficient money, time and (mental) energy for household projects like buying and installing PVs.

Buying households tended to be located outside large cities, and this tendency was strongest furthest away from large cities. Finally, those living in newer houses, especially those built after 1998, were much more likely to buy PVs, as were people living in houses with heating forms other than central heating (e.g. heat pumps or other electrical heating).

Table 2
Logistic regression model coefficients of the likelihood of being later adopter (hourly/real-time metering) compared to being earlier adopter (annual net metering).

Male registrant (1 = Yes)	−0.258*** (0.050)
Registrant with technical education (1 = Yes)	0.054 (0.073)
Household income	
Q1	0.139 (0.093)
Q2	0.017 (0.066)
Q3	Ref.
Q4	−0.156*** (0.052)
Q5	0.037 (0.053)
Highest attained education in household (Ref. "Primary")	
Secondary	−0.144* (0.074)
BA/MA	−0.175** (0.074)
Technically educated in household	−0.175 (0.069)
Average age of household (Ref. "40 or lower")	
41 to 50	−0.049 (0.048)
51 to 60	−0.047 (0.058)
Over 60	−0.055 (0.062)
Young child (under 13) in household	−0.105** (0.048)
Teenager (13 to 19) in household	−0.240*** (0.045)
Location (Ref. "Large cities and suburbs")	
Urban areas outside large cities	−0.315*** (0.058)
Rural areas closer to large city	−0.108** (0.048)
Rural areas further away from large cities	−0.324*** (0.049)
Construction period (Ref. "before 1961")	
1961–1978	−0.249*** (0.045)
1979–1998	−0.298*** (0.056)
After 1998	−0.016 (0.055)
Housing type (Ref. "Single-family")	
Townhouse	0.683*** (0.065)
Farmhouse	−0.284*** (0.058)
Heating form (ref. "District heating")	
Central heating (oil, natural gas or other fuel)	−0.002 (0.043)
Other heating supply, incl. Electricity and heat pump	0.007 (0.053)
Constant	−2.211*** (0.107)
Number of observations	73,557

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, standard error in parentheses.

4.1.3. *Comparing PVs adopters across net metering schemes*

As stated earlier, we identified two groups of PVs adopters in Denmark. We therefore wished to see if these groups also have different characteristics. Table 2 shows the results of a logistic regression on having bought PVs later (hourly/real-time metering) compared with earlier (annual net metering). The results show several differences. First, male registrants seem to be less likely to be later adopters, which indicate that the earliest group of PV buyers in Denmark was dominated more by men than the group of later PV buyers was. However, in terms of technical education, we found no differences between early and later adopters.

The 4th income quintile group is the only income group that is significantly different from the reference group. This suggests that early adopters attracted one particular income group (4th quintile), slightly above the median. Moreover, households with BA/MA as the highest attained education were less likely to be later adopters, with a significance level of 95%, and households with secondary school as highest attained education also tended to be less likely to be later adopters, although only at a 90% significance level. Regarding housing characteristics, the results suggest that households outside larger cities were less likely to be later adopters.

4.2. *Why did households buy PVs?*

Based on survey data, this section focusses on three aspects of households' reasons for buying PVs – first, how PVs can be combined with other house projects; second, inspiration for buying (e.g. peers and news); and third, motivations for buying. Although, inspiration and motivations relate to similar processes, we still find it relevant to distinguish between *what* might have attracted their attention (inspiration) and *how* they justify their decision (motivation).

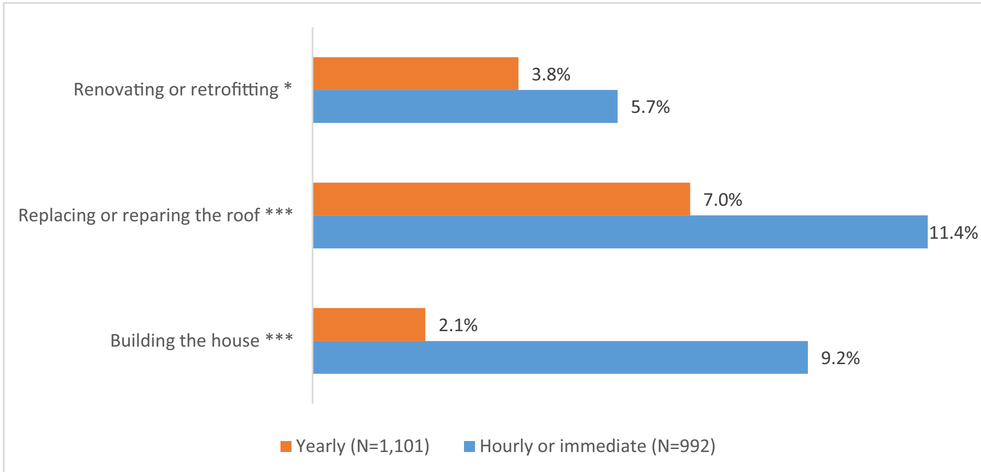

Fig. 3. Responses to the question"Were the PVs bought in combination with…?" across net settlement scheme. *t*-test indicates significance of differences; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

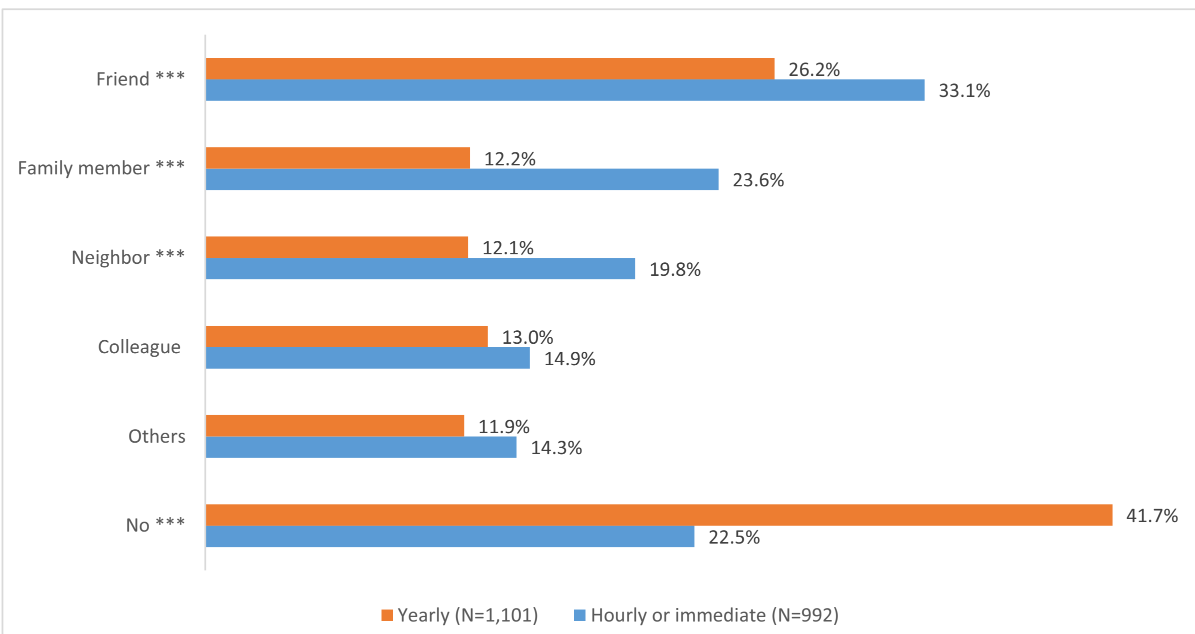

Fig. 4. Responses to the question "Did you know others with PVs prior to buying PVs yourself?". *t*-test indicates significance of differences; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The percentages do not sum to 100% as the question was multiple choice.

4.2.1. Part of ongoing household projects

As previous studies have shown, installing PVs might be part of ongoing household renovation or retrofitting projects. However, in our survey, there were relatively few PVs owners that stated that they bought PVs in combination with ongoing projects. Fig. 3 shows that, for those who did buy PVs in combination with ongoing projects, the most popular combination was to acquire PVs in combination with replacing or repairing a roof, for early adopters and especially for the later adopters. The second most-stated combination for later adopters was an acquisition of PVs in combination with building their house, whereas the second most-stated combination for early adopters was in combination with renovating their house.

4.2.2. Inspiration for buying PVs

To elucidate the role of social relations in the adoption of PVs, we asked the respondents whether they knew other people with PVs prior to buying PVs themselves. Many of the PVs owners answered that they did. Fig. 4 shows the difference in percentage of different social relations split by net metering scheme. 'Friend' was the most frequent response with 29.4% for all PVs owners. However, Fig. 4 shows significant differences between the PVs owner groups. Most notably, the percentage of early adopters responding 'No' was almost double that of later adopters. It makes sense that earlier adopters had fewer opportunities to know someone with PVs, since few had been installed at that time. Almost half of the early adopters responded that they did not know anyone with PVs prior to buying PVs themselves. The later adopters were much more likely to state that they knew a family member (23.6% compared to 12.2%) or a neighbor (19.8% compared to 12.1%).

The 'sources of inspiration' also seemed to differ significantly between early and later adopters. Fig. 5 indicates that talking to an acquaintance and reading newspapers, especially for early adopters, were the most important sources of inspiration. However, an interesting

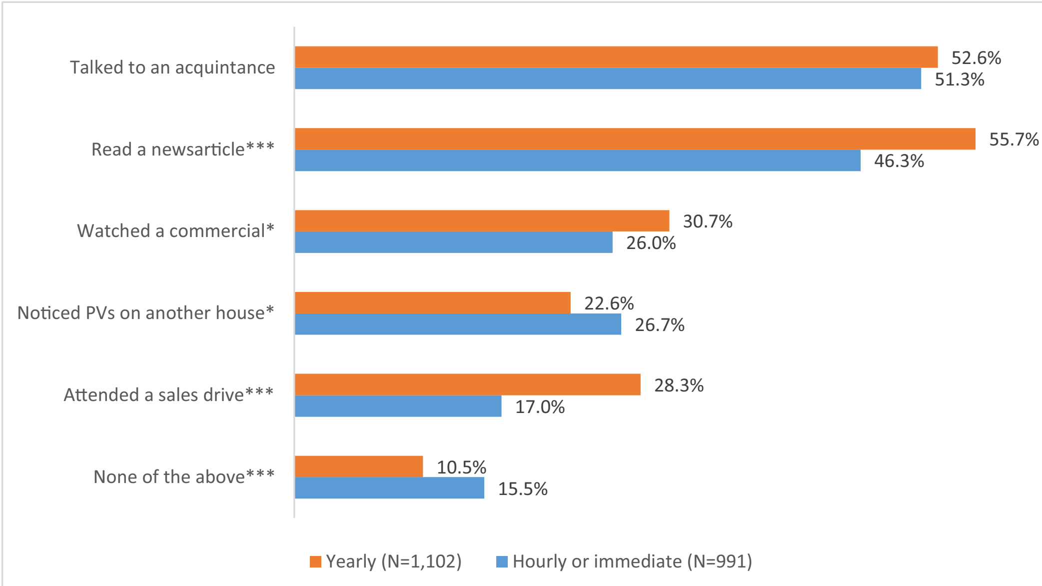

Fig. 5. Responses to the question "Did you do any of the following related to PVs prior to buying?". t-test indicates significance of differences; *** p < 0.01, ** p < 0.05, * p < 0.1.

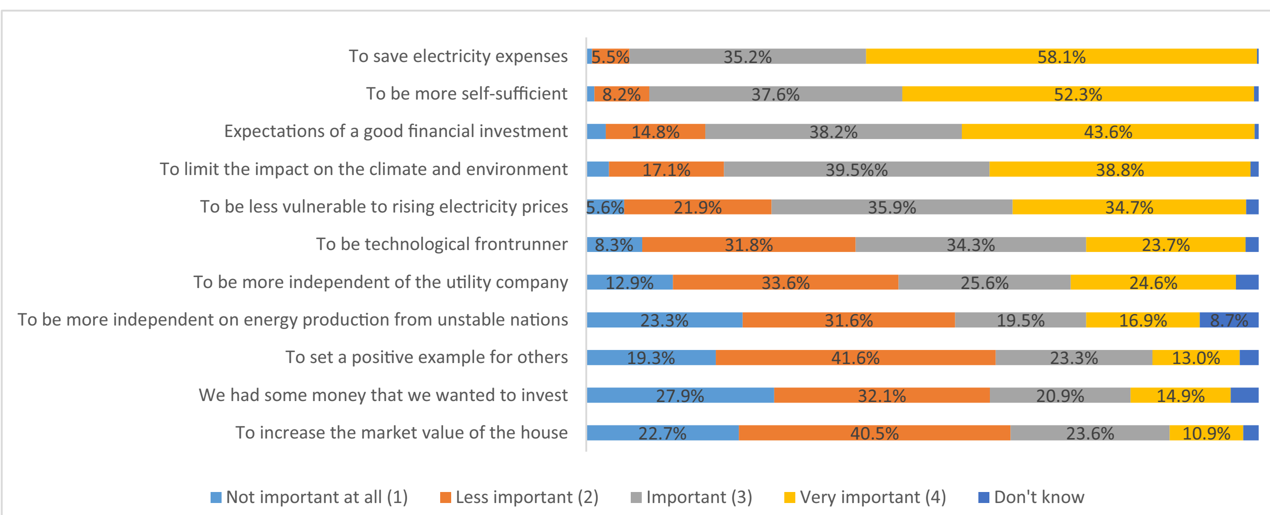

Fig. 6. Responses to the question "How important were the following reasons for your purchase of PVs?". Percentages lower than 5% are not displayed, see instead Appendix B (N = 2094). The statements are ranked according to highest percentage stating 'Important' or 'Very important'.

finding is the significant difference for 'Attended a sales drive' and 'None of the above'. Around 2012, when most of the early adopters bought their PVs, there were many campaigns and sales drives for PVs, which might explain the difference found here.

4.2.3. *Motivation for buying PVs*

In this study, motivation to buy PVs is defined as the reason(s) that households themselves define as important. Therefore, the PVs owners were presented 11 statements that reflected motives to buy (see 3.4 Methods section for further details). Fig. 6 presents the responses to these statements on a scale from 'Not important at all' to 'Very important' with the option 'Don't know'.

Fig. 6 shows that the prospects of saving future electricity expenses and of being more self-sufficient were stated as the most important reasons, with more than half of the respondents stating these were 'Very important'. Although the expectation of making a good financial investment also appears to be an important motivation, financial aspects do not seem to refer to increasing the market value of the house, nor do they seem to be based on some available money the household wished to invest, as these two factors appear to be the least important.

To investigate the interrelationship among the statements, a factor analysis was performed to detect similar patterns of responses and reduce the number of motivations. In other words, the factor analysis explores whether the observed responses reflect underlying factors representing different forms of motivations (Fabrigar and Wegener, 2011). Besides the thematic resemblance of the statements, a test of sphericity clearly rejected the hypothesis that variables were not intercorrelated, and both a Kaiser-Meyer-Olkin test and correlations between the responses to the statements supported the use of factor analysis (See Appendix C).

Before the factor analysis was conducted, the 'Don't know' responses were removed, as these did not follow the ordinal ordering of categories. After removing the 'do not know' responses, the question items had four response categories: 1. "Not important at all", 2 "Less important", 3

Table 3
Factor loadings after oblique promax rotation ($N = 2094$). Factor correlations in Appendix D. Items with factor loadings higher than 0.300 are marked as bold.

How important were the following reasons for your decision to buy PVs?	Independence	Financial interests	Pro-environmental action
To limit the impact on the climate and environment	−0.008	−0.066	**0.600**
To set a positive example for others	0.014	−0.047	**0.690**
To be a technological frontrunner	0.041	0.185	**0.541**
Expectations of a good economic investment	−0.033	**0.652**	0.004
We had some money that we wanted to invest	0.041	**0.675**	−0.010
To be less vulnerable to rising electricity prices	**0.487**	**0.376**	−0.023
To be more independent of the utility company	**0.786**	0.048	−0.039
To be less dependent on energy production from 'unstable' nations	**0.701**	−0.082	0.130
Proportion of variance accounted for after rotation	*0.709*	*0.542*	*0.527*
Variance	*2.199*	*1.683*	*1.636*

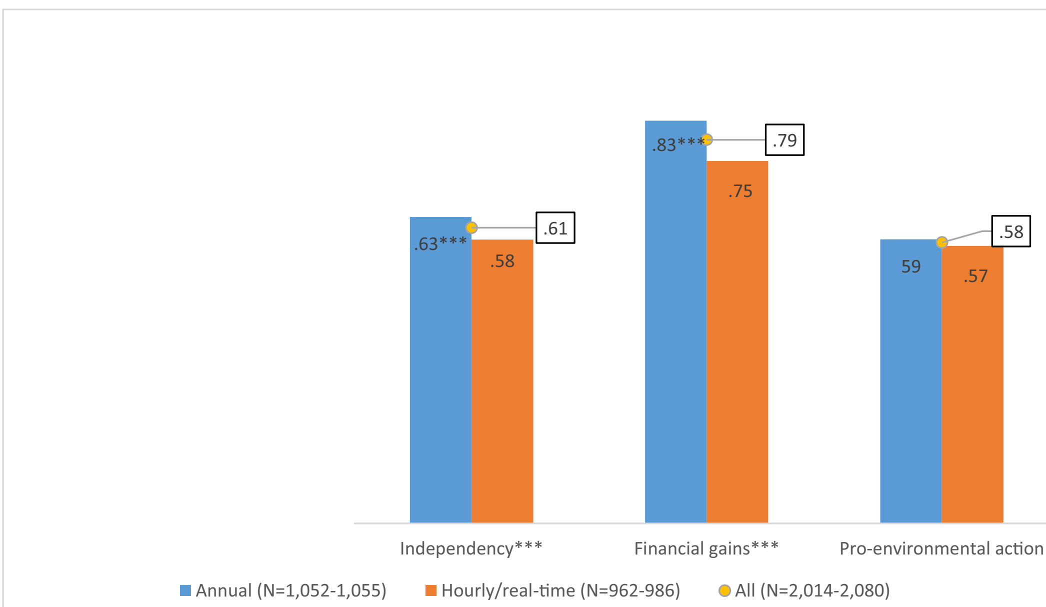

Fig. 7. Comparison of average scores of factors (normalized scales from 0 to 1) across net metering with two-sided t-test with *** $p < 0.01$.

"Important", and 4 "Very important".

A factor analysis on the remaining statements showed that two question items[2] had clearly lower shared variation with the other statements (uniqueness higher than 0.7) and that their factor loadings were weak (less than 0.35). Therefore, these items were removed. Running the factor analysis again showed that 'To be more self-sufficient' loaded equally, and relatively low (less than 0.33), on two factors. This statement was therefore also removed.

The final factor analysis showed the first factor with an eigenvalue of 2.027 (explaining 85.1%), the second with 0.828 (explaining 34.8%) and the third with 0.212 (8.9%). The first factor clearly met the criterion of being much higher than 1, the second is close to 1, which is acceptable as it is interpreted as meaningful, but the third factor showed a low eigenvalue. Although the scree plot also supported only two factors, the third was nonetheless included as well because the interrelationship of the three statements was meaningful and had high factor loadings.

Because the axes were rotated using oblique promax rotation, the factors were allowed to correlate, which means that they should not be seen as independent of each other (Vaus, 2002). This was chosen because households' motives for buying are not necessarily represented by just one form of motivation, but are most often a combination of different (interacting) forms of motivations that reflect various ways of reasoning or justifying the acquisition.

Although factor 1 and 2 correlated strongly (0.634) and the above-mentioned conditions had to be taken into account, three factors were identified. Removing four statements unfortunately meant that the number of variables was not reduced as much as was hoped. However, the three final factors could be meaningfully interpreted in relation to previous literature and according to factor loadings. Table 3 presents the factors with names and factor loadings.

The first factor was interpreted as indicating energy independence. This factor seemed to reflect a wish to be independent of others concerning electricity production in combination with the insecurity caused by rising electricity prices. Perhaps this factor actually reflects a lack of confidence in utilities companies, and that self-sufficiency could be a way to cope with that.

The second factor was interpreted as indicating that households were motivated by financial gains. This factor seemed to reflect that PVs could be seen as a reasonable investment. Financial investment appeared as the most important aspect of the factor, and saving expenses on future electricity consumption also seemed to be an important aspect.

The most influential item of the third factor was 'to set a positive example for others'. This was followed by a specification of what example to set ('to limit the impact on the climate and environment') and how to set the example ('by being a technological frontrunner'). These three statements can be combined to reflect motivation by displaying pro-environmental action through technological adoption.

To look at differences between the early adopters and the later adopters, the three factors were constructed into summative scales where the responses were simply added up. This was supported by

[2] These were 'We had some money that we wanted to invest' and 'To increase the market value of the house'.

Cronbach's Alpha tests showing coefficients higher than 0.67 (Appendix C).[3] To enable comparison, the scales were normalized to a scale from 0 to 1. Other methods for scales (e.g. Bartlett) were tested and gave similar results. Fig. 7 presents the comparison of the average scores of the (normalized) factor scales split across net metering schemes. This shows that financial gains were the most important motivation, followed by independence and pro-environmental action. Using a *t*-test to compare across net metering schemes, Fig. 7 shows that financial gains and independence seemed more important for early adopters with annual metering. However, despite the significant difference, it is worth noticing that the actual difference is quite small.

5. Discussion: Which Danish households bought PVs and why?

This study has investigated Danish households with PVs, including their characteristics compared to other households and their motivation and inspiration for becoming PV owners, and thereby, energy prosumers. Based on extensive data material, including survey and register data, the findings contribute with new insights on who and why households invest in PVs, and also demonstrate how this can be investigated using various methods.

Using extensive panel register data with a full population of Danish PVs households and other households, this study found similar results to previous studies. Danish PVs households were found to live in rural areas and to have higher income levels, higher levels of education and technical qualifications. Moreover, farmhouses and houses with individual heating (e.g. electric heating) are overrepresented among the PVs adopters. The household members registered as the owners of the PVs were predominantly male and technically educated. Comparing early and later adopters, the results showed that males and households living outside larger cities were more likely to be early adopters than late adopters. These findings add new nuances to previous findings, especially by showing how technical educated men were clearly in the majority among PV registrants. Moreover, based on a full population of Danish households (with or without PVs), this study strengthens the reliability of similar previous findings.

Previous studies on (self-stated) motivations for buying PVs mainly point at three forms of motivation. These are: 1) financial gains (Rai et al., 2016), 2) environmental concern (Palm and Tengvard, 2011), and 3) self-sufficiency or energy independence (Rai et al., 2016). Based on a survey of a sample of almost 2500 Danish PVs households, this study identified three similar forms of motivations that provide nuance to the description and understanding of motivations for buying PVs. First, 'independence' primarily reflected motivation for being independent of energy production. Second, 'financial interests' primarily reflected PVs as an investment that will give expected financial gains. Third, '(displaying) pro-environmental action' reflected the motivation to reduce the impact on the climate and environment by setting an example as a technological frontrunner. However, financial gains and self-sufficiency were the most important motivations, especially for the early adopters on annual net metering.

The results also showed notable differences among the PVs owners. Whereas early adopters on annual net metering tended to have attended sales drives and read newspaper articles about PVs before buying, the later adopters tended to express that they knew friends, family members or neighbors with PVs prior to buying.

Although it is difficult to compare across different contexts, it seems that Danish prosumers rank self-sufficiency higher than prosumers in other countries do (that is with the same importance as financial interests). Moreover, whereas previous studies identify pro-environmental values as an important motivation, we interpret this slightly differently. Instead of focusing on a self-stated value, we wish to emphasize the desire of households to display pro-environmental action in relation to others. In doing so, we hope to move the focus from the correlation between (self-stated) values and PVs adoption to the way in which households display pro-environmental action via PVs ownership.

6. Conclusion: How to understand future PV adoption

This study highlights two important questions for understanding future PV adoption. First, what is the role of gender in the decision-making process? This study suggests that technically educated men played the predominant role in the decision to buy PVs, especially among early adopters, who tended to be more motivated by financial gains and independence. The acquisition of PVs is a process that starts much earlier than the actual decision to buy, and because being a prosumer has a profound impact on th everyday practices of the household (Gram-Hanssen et al., 2020), further research could look into the role of gender before, during and after the decision to buy PVs. Second, what does it mean for future PV adoption that households with technical competences and economic resources continue to be overrepresented? In line with previous studies, this study finds that in Denmark, resourceful households are more likely to buy PVs. This is despite the rapid changes in market and policy conditions in Denmark the latest decade. However, this might change in the future, for example if it gets cheaper to buy and install PVs, if electricity prices increase, or if PVs become a more common choice when building a new house or renovating it. The findings of this study indicate that changes in market and policy conditions, including going from annual net metering to hourly or real-time metering, do not seem to influence which types of households buy PVs. Another aspect of this is whether more households should have better opportunities to buy PVs or become energy prosumers.

Finally, this study has demonstrated how panel data and full samples of PVs households and comparison groups can contribute to more reliable comparisons of PVs households with other households. Further research could aim at improving the data basis and methodological design further in order to bring out more nuances and offer more detailed information on who buys PVs and why they do so.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by ForskEL grant number 2016-1-12504. We would like to thank the partners in the project.

Appendix A. Supplemen tary data

Supplementary material to this article can be found online at https://doi.org/10.1016/j.ecolecon.2021.107333.

References

Ameli, N., Brandt, N., 2015. Determinants of households' investment in energy efficiency and renewables: evidence from the OECD survey on household environmental behaviour and attitudes. Environ. Res. Lett. 10, 044015 https://doi.org/10.1088/1748-9326/10/4/044015.

Balcombe, P., Rigby, D., Azapagic, A., 2013. Motivations and barriers associated with adopting microgeneration energy technologies in the UK. Renew. Sust. Energ. Rev. 22, 655–666. https://doi.org/10.1016/j.rser.2013.02.012.

Baldini, M., Trivella, A., Wente, J.W., 2018. The impact of socioeconomic and behavioural factors for purchasing energy efficient household appliances: a case study for Denmark. Energy Policy 120, 503–513. https://doi.org/10.1016/j.enpol.2018.05.048.

[3] The *t*-tests were also performed on scales conducted using the Bartlett method, which gave similar results, and the simpler summative scale was chosen.

Best, R., Burke, P.J., Nishitateno, S., 2019a. Understanding the determinants of rooftop solar installation: evidence from household surveys in Australia. Aust. J. Agric. Resour. Econ. 63, 922–939. https://doi.org/10.1111/1467-8489.12319.
Best, R., Burke, P.J., Nishitateno, S., 2019b. Evaluating the effectiveness of Australia's small-scale renewable energy scheme for rooftop solar. Energy Econ. 84, 104475 https://doi.org/10.1016/j.eneco.2019.104475.
Bollinger, B., Gillingham, K., 2012. Peer effects in the diffusion of solar photovoltaic panels. Mark. Sci. 31, 900–912. https://doi.org/10.1287/mksc.1120.0727.
Fabrigar, L.R., Wegener, D.T., 2011. Exploratory Factor Analysis. Oxford University Press, Incorporated, Cary, UNITED STATES.
Gram-Hanssen, K., Hansen, A.R., Mechlenborg, M., 2020. Danish PV Prosumers' time-shifting of energy-consuming everyday practices. Sustainability 12, 4121.
Hansen, A.R., 2018. Heating homes: understanding the impact of prices. Energy Policy 121, 138–151. https://doi.org/10.1016/j.enpol.2018.06.021.
Hansen, M., Hauge, B., 2017. Prosumers and smart grid technologies in Denmark: developing user competences in smart grid households. Energy Efficiency 10, 1215–1234. https://doi.org/10.1007/s12053-017-9514-7.
Hansen, A.R., Friis, F., Jacobsen, M.H., Gram-Hanssen, K., 2019. Three forms of energy prosumer engagement and their impact on time-shifting electricity consumption. In: ECEEE 2019 Summer Study Proceedings. Presented at the ECEEE Summer Study.
IEA, 2019. World Energy Outlook, p. 2019.
IPCC, 2018. Global Warming of 1.5 oC. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
Jager, W., 2006. Stimulating the diffusion of photovoltaic systems: a behavioural perspective. Energy Policy 34, 1935–1943. https://doi.org/10.1016/j.enpol.2004.12.022.
Keirstead, J., 2007. Behavioural responses to photovoltaic systems in the UK domestic sector. Energy Policy 35, 4128–4141. https://doi.org/10.1016/j.enpol.2007.02.019.
Kotilainen, K., 2020. Energy Prosumers' Role in the Sustainable Energy System. https://doi.org/10.1007/978-3-319-71057-0_11-1.
Leenheer, J., de Nooij, M., Sheikh, O., 2011. Own power: motives of having electricity without the energy company. Energy Policy 39, 5621–5629. https://doi.org/10.1016/j.enpol.2011.04.037.
Mathiesen, B.V., David, A., Petersen, S., Sperling, K., Hansen, K., Nielsen, S., Lund, H., Neves, J.B., 2017. The Role of Photovoltaics towards 100% Renewable Energy Systems: Based on International Market Developments and Danish Analysis. Department of Development and Planning, Aalborg University.
Mills, B., Schleich, J., 2012. Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: an analysis of European countries. Energy policy, special section: fuel poverty comes of age. Commemorating 21 Years of Research and Policy 49, 616–628. https://doi.org/10.1016/j.enpol.2012.07.008.
Mundaca, L., Samahita, M., 2020. What drives home solar PV uptake? Subsidies, peer effects and visibility in Sweden. Energy Res. Soc. Sci. 60, 101319 https://doi.org/10.1016/j.erss.2019.101319.
Newson, R., 2002. Parameters behind "nonparametric" statistics: Kendall's tau, Somers' D and median differences. Stata J. 2, 45–64. https://doi.org/10.1177/1536867X0200200103.
Oberst, C.A., Schmitz, H., Madlener, R., 2019. Are prosumer households that much different? Evidence from stated residential energy consumption in Germany. Ecol. Econ. 158, 101–115. https://doi.org/10.1016/j.ecolecon.2018.12.014.
Palm, A., 2016. Local factors driving the diffusion of solar photovoltaics in Sweden: a case study of five municipalities in an early market. Energy Res. Soc. Sci. 14, 1–12. https://doi.org/10.1016/j.erss.2015.12.027.
Palm, A., 2017. Peer effects in residential solar photovoltaics adoption—a mixed methods study of Swedish users. Energy Res. Soc. Sci. 26, 1–10. https://doi.org/10.1016/j.erss.2017.01.008.
Palm, J., 2018. Household installation of solar panels – motives and barriers in a 10-year perspective. Energy Policy 113, 1–8. https://doi.org/10.1016/j.enpol.2017.10.047.
Palm, J., Tengvard, M., 2011. Motives for and barriers to household adoption of small-scale production of electricity: examples from Sweden. Sustainability: Science, Practice, & Policy 7.
Palm, J., Eidenskog, M., Luthander, R., 2018. Sufficiency, change, and flexibility: critically examining the energy consumption profiles of solar PV prosumers in Sweden. Energy Res. Soc. Sci. 39, 12–18. https://doi.org/10.1016/j.erss.2017.10.006.
Rai, V., Robinson, S.A., 2015. Agent-based modeling of energy technology adoption: empirical integration of social, behavioral, economic, and environmental factors. Environ. Model Softw. 70, 163–177. https://doi.org/10.1016/j.envsoft.2015.04.014.
Rai, V., Reeves, D.C., Margolis, R., 2016. Overcoming barriers and uncertainties in the adoption of residential solar PV. Renew. Energy 89, 498–505. https://doi.org/10.1016/j.renene.2015.11.080.
Roberts, M.B., Bruce, A., MacGill, I., 2019. Opportunities and barriers for photovoltaics on multi-unit residential buildings: reviewing the Australian experience. Renew. Sust. Energ. Rev. 104, 95–110. https://doi.org/10.1016/j.rser.2018.12.013.
Rode, J., Weber, A., 2016. Does localized imitation drive technology adoption? A case study on rooftop photovoltaic systems in Germany. J. Environ. Econ. Manag. 78, 38–48. https://doi.org/10.1016/j.jeem.2016.02.001.
Schelly, C., 2014. Residential solar electricity adoption: what motivates, and what matters? A case study of early adopters. Energy Res. Soc. Sci. 2, 183–191. https://doi.org/10.1016/j.erss.2014.01.001.
Sigrin, B., Pless, J., Drury, E., 2015. Diffusion into new markets: evolving customer segments in the solar photovoltaics market. Environ. Res. Lett. 10, 084001 https://doi.org/10.1088/1748-9326/10/8/084001.
Strengers, Y., 2012. Peak electricity demand and social practice theories: reframing the role of change agents in the energy sector. Energy Policy 44, 226–234. https://doi.org/10.1016/j.enpol.2012.01.046.
Szmaragd, C., Clarke, P., Steele, F., 2013. Subject specific and population average models for binary longitudinal data: a tutorial. Longitudinal and life course studies 4, 147–165.
Tjørring, L., 2016. We forgot half of the population! The significance of gender in Danish energy renovation projects. Energy Res. Soc. Sci. 22, 115–124. https://doi.org/10.1016/j.erss.2016.08.008.
Vaus, D., 2002. Surveys in Social Research, 5th ed. Routledge, London and New York.
Welsch, H., Kühling, J., 2009. Determinants of pro-environmental consumption: the role of reference groups and routine behavior. In: Ecological Economics, The DPSIR framework for Biodiversity Assessment, 69, pp. 166–176. https://doi.org/10.1016/j.ecolecon.2009.08.009.
Wittenberg, I., Matthies, E., 2016. Solar policy and practice in Germany: how do residential households with solar panels use electricity? Energy Res. Soc. Sci. 21, 199–211. https://doi.org/10.1016/j.erss.2016.07.008.
Woersdorfer, J.S., Kaus, W., 2011. Will nonowners follow pioneer consumers in the adoption of solar thermal systems? Empirical evidence for northwestern Germany. Ecol. Econ. 70, 2282–2291. https://doi.org/10.1016/j.ecolecon.2011.04.005.
Wooldridge, J.M., 2010. Econometric Analysis of Cross Section and Panel Data, Second, edition. ed. MIT Press, Cambridge, Massachusetts and London, England.