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Original research article

Do laundry when the sun shines: Factors that promote loadshifting in Dutch households with solar panels

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ABSTRACT

The installation of solar panels by residential households is vital for the energy transition. However, the rapid uptake of solar panels by households leads to congestion in the electricity grid. Specifically, when the sun shines, these solar panels simultaneously produce a lot of electricity that is fed into the grid, which is inefficient and can destabilize the grid. Consequently, it is better if self-produced solar energy is directly consumed when the sun is shining. Loadshifting involves shifting energy use (e.g., doing laundry) to periods in which energy is produced. This necessitates behavior change within the household, and it is not yet well understood why people struggle to loadshift. To assess the individualistic and contextual factors influencing laundry loadshifting behavior in the Netherlands, we conducted a survey among 283 Dutch households with solar panels. The survey builds on a framework that integrates aspects of the theory of planned behavior and social practice theory. The framework comprises eight factors (sufficiency attitude, user beliefs, know-how, monitoring skills, habits, hassle, practical knowledge provided, and feedback provision by system design), which are quantitatively measured and analyzed. We used multiple regression analysis to explore the collected responses. Results show the relevance of monitoring skills, strong habits, passive user beliefs and practical knowledge for laundry loadshifting behavior. Findings highlight that instead of asking people to adjust to technologies, technologies should support behavior change and understand its intricacies and connections to its broader context. Additionally, it is important to strengthen households' beliefs regarding their active role in the energy system.

1. Introduction

As is widely recognized today, greenhouse gas emissions must be reduced significantly due to their global warming potential contributing to climate change. Energy production and consumption are essential contributors to global warming, and greenhouse gas emissions from energy production and consumption continue to rise [1]. In the European Union, households are responsible for more than a quarter of final energy consumption, mainly relying on natural gas and electricity generated from fossil fuels [2]. For instance, electricity production in the Netherlands still relies mainly on natural gas (46.5 %) and coal (12 %) [3]. Burning these fossil fuels to meet household energy demand remains one of the key drivers of climate change, with energy use by households accounting for about 20 % of global carbon dioxide emissions [4,5].

Switching to renewable energy technologies such as photovoltaic solar panels is an effective way for households to reduce the emissions associated with their energy demand [4,6]. Solar panels provide households with the opportunity to substitute indirect consumption of (fossil) fuels from the electricity grid with direct self-consumption of self-produced solar energy. Self-consumption, referred to in this paper as *prosumption*, is defined as the share of total electricity produced by the household solar panels that is directly consumed by the residents [7,8]. Residents who consume their self-produced energy are referred to as *prosumers* [7–9]. To be specific, we follow the definition of prosumers of Inderberg and colleagues, who refer to “*small-scale end users, who, in addition to using electricity from the grid, generate power for their own use and export it back into the electricity system*” [10, p.258]. Prosumption not only helps to reduce emissions from household energy demand but also reduces the burden on the electricity grid. Primarily during peak daylight hours, the increasing saturation of solar panels offloading power onto the grid is known to cause congestion problems and energy losses through the curtailment of electricity produced by solar panels in many countries [11].

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Prosumption of solar energy could thus help alleviate grid congestion if prosumers use their self-produced energy during peak hours, reducing the power that is offloaded onto the grid during these hours. However, such effective prosumption requires a behavior change in the residents in the house. For example, they need to break routines and adapt their demand patterns to the variable supply of solar energy instead [12,13]. Stated simply, prosumers need to use appliances such as the dishwasher or laundry machine when the sun is shining. The demand for electricity is thus shifted to those periods when electricity is produced: from nighttime to daytime [8]. Throughout this paper, we use the term loadshifting for time-shifting the use of energy-intensive appliances to periods in which a household's solar panels produce solar energy. Ample loadshifting studies have focused on doing the laundry since this behavior examples well for understanding time-shifting to synchronize supply and demand patterns, being a flexible but resource-intensive household practice [14–16]. However, as of yet, a clear overview of what factors influence laundering time-shifting is lacking [17]. In this study, we first consulted solar energy experts about these factors, studied the literature on this topic and finally used the output for the design of a survey. We distributed the survey among 283 Dutch residential solar energy prosumers. The Netherlands makes for an exciting and timely case to study prosumption because so many people already have solar panels. In fact, the Netherlands is the European frontrunner regarding the installed capacity of solar energy per person [18], as >20 % of households and businesses possessed solar panels at the beginning of 2022 [19].

1.1. Background: the Dutch solar energy landscape

In the Netherlands, congestion of the electricity grid has become an especially prominent topic since the demand for electricity transport from both the electricity provider and the electricity consumer is far more extensive than the transport capacity of the grid. This demand for electricity transport through the grid will continue to rise as the number of installed solar panels continues to increase to record heights, with the total capacity of electricity generated by solar panels growing by 30 % over the past year [20]. This electricity is desperately needed, as the shift away from coal- and gas-based energy towards appliances running on (renewable) electricity (such as heat pumps or electric vehicles) means Dutch grid operators are struggling to satisfy the vast electricity demand of businesses and new residential areas [21]. Yet prosumers often do not use a large share of their self-produced solar energy, especially during peak production hours (e.g., during sunny summer days). Instead, the excess energy produced by the growing number of residential solar panels is injected into the grid, causing extensive and sudden peaks of solar energy inflow and further destabilizing the already congested electricity grid [20].

Specific policies may increase or decrease prosumption levels. For instance, the Dutch net-metering scheme[1] was initially employed to support decentralized energy production yet discourages solar energy prosumption [9]. Under net-metering, Dutch prosumers receive the same monetary compensation for the energy they inject into the grid as they pay for the energy withdrawn from the grid, which does not financially incentivize prosumers to prosume as grid-produced and self-produced energy have the same economic value [9]. To help alleviate grid congestion, several of the Netherlands' largest electricity grid operators have called to dismantle the net-metering scheme as soon as possible [19,22]. Heeding this call, the Dutch government is planning to phase out net-metering from 2025 onwards, dismantling it entirely by 2031 [23]. This decision is causing substantial political and public debate, as some are concerned the dismantling of net-metering will cause people to refrain from buying new solar panels [24].

The political developments described in the previous paragraph show the emphasis that is currently placed on financial factors influencing prosumption, with Dutch policymakers focusing on the implementation of monetary incentives alone. However, it is crucial to assess whether any other factors influencing loadshifting are at risk of being overlooked. Both Gautier et al. [17] and Braito et al. [25] state that prosumption policies should look beyond financial incentives and make sure any behavioral barriers or drivers for prosumption are understood and included beforehand. Similarly, Gohary et al. [26] have shown that the vast majority of people do not adequately process nor understand price signals policymakers are focusing on to balance supply and demand. Thus, research and policy should focus on alternative strategies for communication and engagement rather than maintaining a dominant focus on the magnitude of these price signals [26]. This study addresses this issue.

1.2. Increasing prosumption of solar energy

Despite the advantages regarding efficiency and electricity grid congestion, most studies estimate that prosumption levels of self-produced solar energy are no higher than 35 % in most European countries [7]. In the Netherlands, yearly prosumption levels are approximately 30 % of self-produced energy, although varying depending on, e.g. electricity prices [27]. Levels of prosumption are relatively low, mainly due to the disparity between solar power generation during the day and prosumer demand in the evening [28]. This disparity could be overcome through two main approaches intended to increase prosumption levels. The first approach is through battery storage systems, allowing prosumers to store solar energy produced during the day for later use [7,8]. Requiring no behavior change, the potential of such systems seems promising: Luthander et al. [7] found the use of batteries could increase prosumption of solar energy by 13–24 %. Still, battery storage systems remain rather costly for residential households [29].

The second option to increase solar prosumption is through behavioral measures such as loadshifting. Loadshifting means time-shifting the use of energy-intensive appliances to periods in which a household's solar panels produce solar energy. If desired, such behavior can be supported by technological devices offering (partial) automatization, such as laundry machines that provide a signal when solar panels are producing energy [30]. Unlike battery storage systems, loadshifting (with or without technological support) is an inexpensive measure to increase prosumption levels that can be implemented immediately. Thus, to increase prosumption levels quickly without extra costs for the prosumer, electricity grid operators state that loadshifting should be encouraged [20].

1.3. Understanding loadshifting behavior

The behavioral foundation of loadshifting has received limited attention in research and is thus not yet well understood [17]. Some previous studies have focused on the level or potential of prosumption, though the results are inconclusive. For example, Korsnes and Throndsen [31] studied the loadshifting behavior of prosumers in Norway using qualitative methods. They found that monetary incentives alone are not sufficient to achieve loadshifting, as energy-consuming behaviors are determined by daily circumstances (i.e. the need to wash children's clothes). Hansen and Hauge [32] investigated whether solar energy production impacts energy consumption practices and found that increased awareness of their surroundings (e.g., knowing when the sun is shining) helps prosumers adapt their energy consumption patterns to the availability of solar energy. The impact of loadshifting on daily routines is also outlined by Friis and Haunstrup Christensen [33]. Most

[1] The net-metering scheme is referred to as the "salderingsregeling" in Dutch. Households that generate power using solar panels but do not use all that power themselves feed that excess power back into the public grid. Households may subtract the energy they produce from the energy they take from the grid at another point in time. This subtraction is called net metering.

notably, they discuss how loadshifting impacts other household routines, such as getting out of bed earlier or shifting breakfast times in order to do the laundry in the morning [35]. Behavioral adaptations are though not a one-off occurrence, as energy consumption behaviors might have to follow not only daily but also annual fluctuations of energy production. For example, one might be able to charge an electric car within a couple of hours in summer but not in winter. To accommodate such fluctuations, prosumers might have to adopt seasonal mobility patterns [34].

A Dutch study about laundry loadshifting showed that smart appliances (e.g., smart laundry machines) help households shift the use of the laundry machine to periods in which the household's solar energy system produces energy. However, this quantitative study focused on the effect of technical appliances alone and did not include other factors that can influence loadshifting behavior [30]. Some studies using qualitative self-reporting measures suggest that prosumers often want to and can change the timing of their electricity use to synchronize production and consumption levels [17,37]. Yet, some quantitative studies find no evidence of such a shift. Moreover, although households with solar panels are found to unsurprisingly consume less electricity from the grid than those without solar panels, these differences diminish when solar energy production is low [4,37]. This finding seems to indicate that prosumers do not adapt their energy consumption according to the availability of self-produced energy. Similarly, Peters et al. [38] found that whilst many new prosumers intend to prosume as much as possible when getting their solar panels installed, most fail to realize this intention in the longer term. Prosumer behavior may even reflect a rebound effect, where households increase their energy consumption levels compared to before the installation of their solar panels [36]. Thus, prosumers may show a tendency to use more energy than necessary to not "lose" their self-produced energy [32]. Whilst beneficial for households confronted with energy poverty, an increase in energy consumption is generally not desirable [35].

Overall, it is not understood why even well-intentioned prosumers struggle with loadshifting. In order to establish strategies to support prosumers in their prosumption efforts, more understanding is needed of the reasons why prosumers do or do not loadshift. Niamir et al. [39] suggest that prosumers may lack knowledge of what prosumption is or why it matters, as respondents did not distinguish between energy produced for prosumption and overall energy produced. The relevance of knowledge on energy availability is also outlined in a study by Gram-Hanssen et al. [40]. Their quantitative analysis showed that the provision of more granular data about energy availability and use (hourly metering) was an essential factor impacting loadshifting in Danish households. In addition, Gill et al. [41] identified several factors affecting the efficient use of solar hot water systems in Australian households (e.g., shifting taking a shower from night to daytime). These include motivation, awareness through monitoring, social norms, everyday practices or habits, sources of advice or information, and household- and property characteristics [41]. Gautier et al. [17] studied factors impacting the prosumption of solar energy specifically, focusing mainly on institutional and contextual factors. These factors include the effects of net-metering and subsidies for storage, as well as socio-demographics [17]. Studies focusing on the *installation* of solar panels (rather than prosumption) are still more numerous, with Ebrahimigharehbaghi et al. [42] identifying household- and property characteristics, awareness, and hassle as important barriers.

However, to the best of our knowledge, none of these studies mentioned in the previous paragraphs provide a clear set of factors influencing loadshifting - and in particular time-shifting laundry practices - yet. Moreover, most of these studies focus on prosumption in general (not specific to solar energy) or solar prosumption without an explicit focus on (laundry) loadshifting. Still, these previous studies do imply that the reason why prosumers struggle to prosume relates to more than just individualistic characteristics: barriers may also refer to the context prosumer households operate in. Thus, to improve our understanding of laundry loadshifting, a broad range of factors influencing this practice need to be studied, considering both individualistic and contextual factors.

To understand contextual and individualistic factors influencing laundry loadshifting, we developed a survey, the design of which is based on a theoretical framework (see Section 2.3) and the results of expert interviews (see Section 3.1.1). In the subsequent section, we first introduce this theoretical framework. Our methods are discussed in Section 3. The results of our analyses are presented in Section 4, and we conclude with a discussion of these results in Section 5.

2. Theoretical framework

We have outlined that factors relating to the individual prosumer, as well as the context in which an individual operates, should be considered when studying laundry loadshifting behavior. Different behavioral theories and models include such individualistic and contextual factors [43–45]. Generally, a distinction can be made between theories focusing mainly on (1) the individual performing the behavior or (2) the context in which the individual performs said behavior [46].

2.1. The theory of planned behavior: focusing on individualistic behavior

A well-known theory in the first category is the theory of planned behavior [47]. It states that voluntary behavior is directly influenced by an individual's behavioral intention [48]. This intention is a function of attitudes, subjective norms and perceived behavioral control, which are all shaped by beliefs [49]. Thus, the theory of planned behavior is an influential psychological theory focusing heavily on cognition and voluntary, intentional behavior. Since its origin, the theory of planned behavior has been used in countless studies to assess many different kinds of individualistic behaviors.

However, the theory of planned behavior generally disregards *sub*-conscious influences on behavior, such as emotions or habits [49]. Furthermore, the theory of planned behavior neglects the importance of social relations, as well as contextual factors such as material infrastructures, which may enable or restrict certain behaviors (e.g., available technologies, devices, or other tools) [32]. These shortcomings affect the usability of the theory of planned behavior to study household energy consumption. This is because, when it comes to household energy consumption, many behaviors (including doing the laundry) are not guided by a deliberate intention but are routinized. This means that such behaviors reflect subconscious habits that are deeply embedded in everyday life [50,51] and which are strongly influenced by contextual factors (e.g., demand for clean laundry by other household members or social norms related to personal hygiene). The focus of the theory of planned behavior on voluntary, intentional, and purely individualistic behavior thus makes this theory unsuitable for covering the complexities of household energy consumption.

2.2. Social practice theory: focusing on collectively shared behavioral patterns

Following the line of reasoning of the previous paragraph, behavioral research focusing on household energy consumption has often made use of socio-psychological theories which explicitly include the context surrounding the individual. Such a theory is social practice theory, which places the focus on an everyday practice rather than on the individual performing said practice [50]. A practice is hereby defined as a socially shared convention or pattern of behavior, which has become routinized due to the interconnectedness with day-to-day routines and structural conditions [50,52]. As such, a practice is a behavioral pattern that is shared by a collective (i.e., a household). Unlike the individualistic behavior itself, being the main focus of the theory of planned behavior, social practice theory thus considers this collectively shared concept of "practice".

Shove et al. [53] developed a framework in which they divided such a social practice into three intertwined elements, which was extended by Hess et al. [50]: materials (physical infrastructures, tools, hardware), meanings (mental activities, emotions, motivation) and competence (know-how, background knowledge, specific skills). Specific competencies thus correspond to what people need to know to perform the practice ("doings"), meanings cover how people perceive the practice and what is culturally said about the practice ("sayings"), and materials refer to all physical parts required for performing the practice ("havings") [32]. Together, these three elements constitute the core of a practice and what people need to be able to perform said practice [32]. Klint et al. [54] used this framework to study the practice of doing the laundry by using fewer resources, and Frances and Stevenson [55] developed a similar framework to explore solar energy engagement. Similarly, Fox [35] studied solar entitlement and energy vulnerability in the context of prosumption. In the study by Fox [35], materials are considered to be the meters that help people understand when power is generated. Competencies refer to the knowledge of using solar energy efficiently, whereas meaning includes values and beliefs (e.g., solar panels are only for the rich, leading to aversion and reduced engagement). However, despite arguably striking a better balance between individualistic and contextual elements than the theory of planned behavior, one must be wary not to lose the individual out of sight completely when applying social practice theory. Insights into the more cognitive aspects of behavior change, provided through, e.g. the theory of planned behavior, remain valuable.

2.3. Our framework: combining the individualistic and contextual focus

To include not just the individualistic focus on the prosumer as is expected in the theory of planned behavior, nor only the contextual or collective focus of social practice theory, but *both* of these focus points, we combined elements of the two theories into a single framework. To do so, we explicitly integrated the individualistic elements of the theory of planned behavior (attitudes and beliefs) into the "meanings" element of social practice theory. Similar to the approach by Frances and Stevenson [55], we further divided the "competencies" element into internal (know-how, monitoring skills, habits, hassle) and external (practical knowledge provided) competencies. To be clear, we do not claim these competencies to be entirely independent of each other, but we aim to distinguish them based on where the competence originates from. Thus, in this paper, internal competence refers to abilities possessed by a prosumer, which will vary per individual due to, e.g., differing personalities or previous experiences. In this paper, external competence refers to the competence extended to a prosumer from an external source (e.g., the practical information provided to each prosumer by governmental bodies or the company installing the solar panels). Ultimately, we have selected eight factors for inclusion in our framework, divided over the three core elements of social practice theory as visualized by Shove et al. [53]. Our framework is displayed in Fig. 1.

2.3.1. The selection and definition of our eight factors

The selection of the eight factors included in our framework warrants further explanation, as well as detailed definitions. We based the selection of factors and their definitions on similar factors found to influence prosumption in previous studies, as described in the paragraphs above. For example, Frances and Stevenson [55] refer to "feedback provision" to encompass all design elements of the solar energy system, which provide visual, direct, and synchronous feedback regarding energy production and consumption (such as displays). Luthander et al. [7] refer to such feedback devices as a primary reason for increasing prosumption. Gill et al. [41] call this factor "material elements and operation", referring to examples such as the opaque functioning of the solar hot water system and minimal or hard-to-discern energy savings registered on bills and meters. We chose to group these design elements

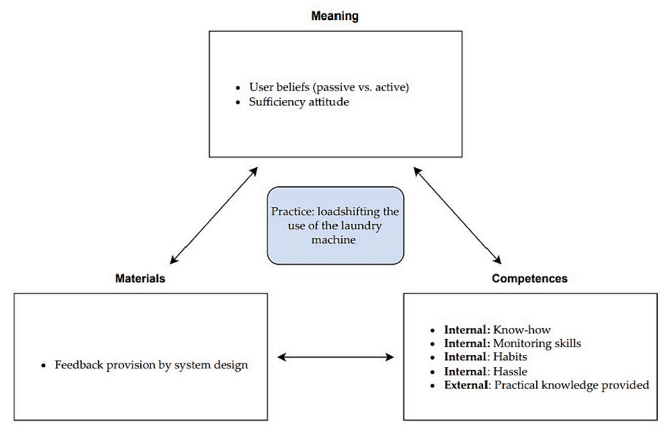

Fig. 1. Our newly constructed framework, with the eight selected factors as bullet points.

under the factor name "feedback provision by system design". Other factor names and definitions were taken directly from previous studies without needing such adaptation or integration. For example, "hassle", defined as the degree to which people anticipate a particular behavior to be a hassle which causes stress and avoidance of this behavior, was taken from a study by de Vries et al. [6]. An overview of all eight factors included in our study can be found in Table 1.

2.3.2. The limitations of our theoretical framework

Before continuing, we would like to briefly point out some of the conceptual limitations of our framework, combining the theory of planned behavior with social practice theory. We feel this information will help readers interpret the rest of this paper. Firstly, seamlessly combining these two theories is a rather complex task, not in the least because they focus on entirely different units of inquiry. As previously described, the theory of planned behavior focuses on the individual as the central unit of investigation. In contrast, a collective practice is the unit of inquiry at the centre of social practice theory. This leads to substantial differences in e.g. terminology, which can be challenging to integrate. For example, from a purely social practice theory perspective, the factor of "habits" (which we grouped under internal competencies) cannot influence the practice of time-shifting the laundry, as the concept of a practice *in itself* relies on habitual actions. Yet, from a theory of planned behavior perspective, this is entirely possible. Additionally, from a social practice theory perspective, it would be more logical to question an entire household on the practice of time-shifting the laundry (a collective). Yet, we examined individual prosumers as one would do when taking a theory of planned behavior approach (see the Methods chapter).

Secondly, regardless of being termed as individual behavior or as practice, it can be assumed that not all factors influencing time-shifting laundering can be taken into consideration in one single study. For example, we are not considering the effect of culture, although its influence on practices has been shown to guide sustainable transitions [56]. Similarly, the impact of motivation has been excluded despite its known effect on participation in demand response programs [57]. Jensen et al. [58] analyzed a thousand studies on sustainable energy consumption initiatives in 30 European countries, concluding that the insights provided by each study depend on the study framing (e.g., the type of behavior change that is assessed, the method to evaluate behavior change, the sample size, etc.). Accordingly, the insights of a single study cannot necessarily be generalized. This shortcoming also applies to the study presented in this paper.

Table 1
Overview of the eight factors from our framework.

Factor name	Definition	Framework element	Adapted from
Feedback provision by system design	Design elements of the solar energy system providing visual, direct, and synchronous feedback regarding energy production and consumption (on e.g., displays, energy bills)	Materials	[41,55]
Know-how	The ability prosumers have or acquire in terms of how to carry out the practice of (laundry) loadshifting	Internal competencies	[55]
Monitoring skills	Prosumers' ability to monitor their solar energy production and consumption regularly (e.g., by using an app or checking the weather ahead of time)	Internal competencies	[55]
Habits	Behaviors that are performed frequently and consistently in stable contexts	Internal competencies	[53,59]
Hassle	The degree to which prosumers anticipate (laundry) loadshifting to be a hassle, leading to stress and avoidance of this behavior	Internal competencies	[6]
Practical knowledge provided	Written or spoken advice, technical knowledge or documents regarding the use of the solar energy system which is provided to prosumers (by, e.g., governments, consultants, or technicians)	External competencies	[55]
User beliefs	Whether a prosumer believes to be an active or passive user of the energy grid and their own solar energy system (e.g., believing solar energy technology to be an active or passive tool to engage with, believing that their behavior makes a difference in the energy system)	Meanings	[32,41,55]
Sufficiency attitude	The degree to which prosumers aspire to live a sufficiency-oriented lifestyle, referring to a total reduction of resource consumption	Meanings	[60]

3. Methods

To assess the individualistic and contextual factors influencing laundry loadshifting behavior among Dutch residents living in households with solar panels, we conducted a survey in the Netherlands. Surveys are a commonly used method in social science to collect a large amount of primary data regarding respondents' opinions and feelings [61]. Currently, such empirical data from a prosumer's point of view is missing in the field of laundry loadshifting behavior. Designing an exploratory survey provides us with the opportunity to make generalizable statements about the experiences of a sample of respondents that is representative of Dutch homeowners and renters with solar panels. Further, it grants insights into the sample population's behavior and controls for the effects of confounding variables [48,61]. In this section, we describe the design and distribution of our survey.

3.1. Survey design

Considerable preliminary work went into our survey design, which was based mainly on the eight factors of our theoretical framework (see Fig. 1) and input from expert interviews to assess the suitability of this framework as the foundation of our survey (see Section 3.1.1). In this current section, we describe the process through which we designed our survey in more detail.

3.1.1. Expert interviews

Initially, we wished to use a survey to test the usability of our framework to study laundry loadshifting behavior in the Netherlands. However, we felt it would strengthen our survey if we could first incorporate a check of the potential and shortcomings of said framework *before* using it as the foundation for our survey design. We decided to do so by asking for expert input through interviews. Additionally, expert input could help us think of ways to operationalize the framework factors into measurable questions since there are no standardized questionnaires for the majority of these factors (see Section 3.1.2). We conducted six semi-structured interviews with solar energy experts. These interviews took place in February 2022. The selection of interviewees was mainly based on their profession or the role of the organization they represented. We interviewed two commercial consultants, two senior researchers from independent organizations, one senior researcher from a Dutch university, and one person working on the energy transition for the Dutch local government. Interviewing experts of different professions within the solar energy sector should provide a comprehensive view on the matter of prosumption and laundry loadshifting.

Although our framework was built on the theory of planned behavior and social practice theory, the questions included in the interview guide were purposefully left broad and open-ended rather than being based on any specific theory (see Appendix A [62] for the interview questions). This decision was made to ensure that interviewees were not steered in any particular direction regarding the factors they would or would not list. This involved experts simply being asked to what extent they feel solar prosumption and laundry loadshifting are a problem and which factors they think hinder prosumption of solar energy. In principle, we did not prompt factors ourselves or ask interviewees to confirm or deny any of our predefined factors since we were merely curious to see which factors came to mind. In the end, we wanted to see whether these listed factors showed any similarity with the factors included in our framework, as well as whether any crucial factors had been missed in our framework. As such, the qualitative findings of the interviews helped us assess the likelihood that the factors predefined in our framework were actually experienced by prosumers in practice and should thus be covered in the survey. Ultimately, all factors predefined in our framework were mentioned in some form by multiple interviewees, leading to the decision to include all eight factors in our survey. More information regarding the expert interviews can be found in the supplementary information (see Appendix A [62]).

3.1.2. Final survey design

The interviews validated the framework depicted in Fig. 1 as the foundation of our survey. Therefore, the survey should include questions intended to measure the eight factors displayed in this framework. Each factor was measured using two questions phrased by us, except for sufficiency attitude (three questions, taken from a pre-existing survey by Verfuerth et al. [60]). Three statements measured time-shifting laundry behavior (i.e. loadshifting), the dependent variable. The wording of these three statements was derived from the expert interviews, as multiple interviewees mentioned these three operationalizations of laundry loadshifting as examples. These questions were (1) *When choosing a moment to do my laundry, I consider the electricity production of my solar energy system first*, (2) *I make use of an automated program/timer on my laundry machine so that it runs at a time when my solar energy system is producing energy*, (3) *By adjusting the use of the laundry machine to the energy production of my solar panels I try to utilize my own self-produced energy as much as possible*. The response options were: *never* (1), *rarely* (2), *sometimes* (3), *often* (4), and *always* (5). Thus, we did not differentiate between prosumers who loadshift with or without technological assistance of automated devices, the important thing being that prosumers self-report that they run their laundry machine when their solar panels are generating electricity. Furthermore, eight questions were included to measure demographics and control variables.

Ultimately, the survey consisted of 28 questions and was designed to take no >10 min to complete. This time restriction served to increase the completion rate. The survey was designed using Qualtrics, a web-based survey software, and distributed in the format of an online survey (see Section 3.2). The complete final survey design, as well as the division of questions per variable, can be found in the supplementary information (see Appendix B [62]).

3.2. Data collection

We contracted a commercial data platform (Dynata) to (1) distribute our survey among a sample representative of our targeted population and (2) to collect data. The population focused on in this study is defined as Dutch residents (homeowners and renters) living in a household with solar panels. Our sample should thus be representative of this specific population, not of the total Dutch population. To establish the required number of survey respondents, one should, therefore, first specify the size of this specific population in relation to the total Dutch population.

It is assumed that at least 20 % of households in the total Dutch population currently have solar panels installed [18]. As of early 2023, the Netherlands consists of 8.3 million households in total [63]. Twenty percent of 8.3 million equals a population size of 1.660.000 households in our study (1.66 million). With a confidence level of 95 % and a margin of error of 5 %, we would need 385 survey responses. Due to resource constraints, this was unfortunately not a feasible number of responses we could ask Dynata to collect, hence we decided to increase the margin of error slightly. With a confidence level of 95 % and a margin of error of 6 %, we would need 267 survey responses. As will be discussed in Section 3.3, we ended up collecting 316 responses, of which 283 were included in our analyses. The margin of error for this study thus lies between 5 % and 6 %, which reduces the internal validity of our findings in comparison to a 5 % margin of error but is deemed acceptable for non-clinical exploratory research such as ours [64,65].

Using our specific description of the targeted population (Dutch residents with solar panels), Dynata reached out to this population through their online respondent platform, ensuring our survey would swiftly reach respondents who met this description. Dynata had no insight into the survey or the results. Several conditions needed to be fulfilled for a response to be included in the final study sample. Firstly, participants were excluded if they had zero solar panels installed, which was one of the first questions of our survey. When filling in '0', these people were excluded automatically through a loop that led them out of the survey. Secondly, participants who took <60 s to complete the survey were excluded, as this time was deemed too short to read and answer all questions properly. Thirdly, participants were excluded in the case of missing data, i.e. if they did not complete the survey in its entirety. Fourthly, participants were excluded if we suspected them to have straightlined. Straightlining is a common phenomenon in survey research, occurring when respondents provide (nearly) identical answers to consequential questions using the same response scale [66]. In our study, we did not use a measurable criterion to decide whether a respondent straightlined, but relied on our own reasoning instead. According to our definition, straightlining occurs when multiple answers in a row (using the same response scale) are both repetitive and illogical. This seemed to have occurred in only one instance (see Section 3.3 below). To summarise, participants were included only if they lived in the Netherlands and had at least one solar panel already installed at their place of residence, if they took at least 1 min to fill in the survey completely, and if they did not appear to have straightlined according to our criteria.

Data was collected in two rounds. During the first round of data collection, the survey was distributed from March 25th (2022) until March 29th (2022), after which 216 responses had been collected. Dynata continued to run the survey for a second round until 316 responses were reached on April 1st (2022). Thus, Dynata collected all responses in a total time span of one week.

3.3. Study sample

Of the 316 responses collected in total, eighteen participants were excluded due to taking <60 s to complete the survey. Three additional participants had zero solar panels installed, and eleven other participants did not complete the survey. Lastly, one additional participant appeared to have straightlined according to our interpretation (entering "31" for the number of panels installed, the year of installation, as well as for household size). Hence, following the application of the in- and exclusion criteria, 283 responses were ultimately available for the analysis. The vast majority of included participants were homeowners (72.4 %), and just over half were male (53.7 %) (see Table 2). Included participants were distributed well across different age groups, ranging from 15.5 % of participants being between 25 and 34 years of age to 21.9 % being 65 years or older. The youngest age group (18–24 years) was clearly the minority (6.7 %). Additionally, 30 % of participants made use of energy storage.

4. Results

Due to the exploratory nature of this study, examining the influence of multiple factors simultaneously as based on the new framework, we chose to analyze our survey data mainly through a multiple regression analysis (MRA). An MRA can assess which factors included in the framework influence laundry loadshifting the most within our studied prosumer group. An exploratory factor analysis (EFA), reliability analysis, and bivariate correlation analysis were conducted to strengthen the MRA. All analyses were performed using IBM SPSS version 26.

4.1. Preliminary analyses

As mentioned in Section 3.1.2, the survey consisted of 28 questions, including those measuring socio-demographics and laundry loadshifting. With the exception of sufficiency attitude, the other seven factors were measured using a cluster of two survey questions each (see Appendix B [62]). To test if each cluster of questions corresponded with the predetermined factors we intended to measure (referred to as construct validity), we first conducted an exploratory factor analysis (EFA). Overall, the EFA showed statistical cohesion between survey questions

Table 2
Frequency table for the categorical characteristics of the included participants.

Variable	Frequency (n)	Percent (%)
Storage (n = 283)		
Yes	85	30.0
No	162	57.2
I don't know	36	12.7
Occupant status (n = 283)		
Homeowner	205	72.4
Renter	73	25.8
Other	5	1.8
Gender (n = 283)		
Female	131	46.3
Male	152	53.7
Other	0	0
Age (n = 283)		
18–24 years	19	6.7
25–34 years	44	15.5
35–44 years	56	19.8
45–54 years	45	15.9
55–64 years	57	20.1
65 years or older	62	21.9

and factors similar to what we expected based on our framework (see Appendix C [62]). Therefore, we decided to continue on to further analyses using our predefined factors, computing the stand-alone survey questions into nine separate variables of interest (our eight factors and laundry loadshifting as the dependent variable). Cronbach's alpha[2] showed the internal consistency of both three-question variables to be acceptable (*alpha* = *0.791* for the loadshifting variable and *alpha* = *0.687* for the sufficiency attitude factor). For the seven two-question factors, Spearman's rho[3] showed all correlations between questions intended to measure the same factor to be significant (see Appendix D [62]).

Next, a bivariate correlation analysis was conducted on our nine variables of interest to allow for further preliminary data inspection. The results of the correlation analysis are displayed in Table 3. Laundry loadshifting correlated significantly with all factors except hassle ($r = -0.104$, $p = 0.082$), although correlations mainly were weak to moderate ($r = 0.213$ to $r = 0.495$). Many correlations among the eight factors were statistically significant as well, although again, these correlations were primarily weak to moderate ($r = 0.003$ to $r = 0.467$). Only the correlations between hassle and know-how ($r = -0.511$, $p < 0.001$, or $p = 3{,}214\text{E-}20$ to be precise) as well as between hassle and habits ($r = 0.565$, $p < 0.001$, or $p = 2{,}8757\text{E-}25$ to be precise) were found to be strong. These correlations imply that prosumers who perceive a lot of hassle ($M = 2.98$, $SD = 0.95$) also report little know-how ($M = 3.54$, $SD = 0.78$), as well as strong habits ($M = 3.12$, $SD = 1.01$). Note that such correlations do not necessarily indicate causal relations and can be calculated only for two variables at a time (arguably not appropriately reflecting the complexity of behavior). The MRA, which follows in the next section, does allow for the consideration of multiple variables influencing behavior.

4.2. Regression analysis

The MRA assessed the influence of user beliefs, sufficiency attitude, practical knowledge provided, know-how, monitoring skill, feedback provision by system design, habits and hassle on laundry loadshifting. The assumptions of normal distribution,[4] the absence of multicollinearity,[5] and homoscedasticity[6] were checked and not violated. Three regression models were run to account for different variations of potential covariates in the data. The first model contained only our eight factors as the *independent variables*. In the second model, age and gender were also added to these independent variables. In the third model, all remaining variables were added as covariates (occupant status, household size, intention, number of panels, year of panel installation, and storage). Due to the exploratory nature of the study, predictors were entered into the analysis simultaneously according to the enter method.

According to the first regression model, which was not adjusted for any covariates, there was a significant relationship between the eight factors as independent variables and the dependent variable of laundry loadshifting, $R^2 = 0.440$, $F(8, 274) = 26.934$, $p < 0.001$ (or $p = 1.1832\text{E-}30$ to be precise). Together, the eight factors thus explained 44 % of the variance in laundry loadshifting behavior, leaving 56 % of the variance unexplained. Although both age and gender appeared as covariates in the second model, the results persisted, $R^2 = 0.480$, $F(10, 272) = 25.154$, $p < 0.001$ (or $p = 1.7795\text{E-}33$ to be precise). This means that controlling for the effects of age and gender increases the variance that is explained by the eight factors *and* these demographics to 48 %. The results remained robust after adjusting for all covariates in the third model, $R^2 = 0.544$, $F(16, 266) = 19.796$, $p < 0.001$ (or $p = 1.3242\text{E-}36$ to be precise). The eight factors, together with all covariates, thus explained 54 % of the variance in laundry loadshifting behavior, leaving 46 % of the variance unexplained. However, only storage was a significant covariate in the third regression model.

The MRA also showed the effect on laundry loadshifting per predefined factor, the results of which are displayed per model in Table 4. The findings indicate that the four factors of user beliefs, practical knowledge provided, monitoring skills, and habits significantly influenced laundry loadshifting in all three regression models (thus, regardless of any covariates in the data). Additionally, sufficiency attitude emerged as a fifth factor influencing laundry loadshifting in the third model, in which only storage appeared as a significant covariate. Note that most values in Table 4 are indicated to be $p < 0.001$ since the exact p values cannot easily be rounded to three decimals (ranging from $p = 6.034\text{E-}8$ to $p = 0.000442$). The three factors of know-how, feedback provision by system design, and hassle remained insignificant in all three models.

5. Conclusion and discussion

5.1. Conclusion

In this study, we aimed to assess the individualistic and contextual factors influencing laundry loadshifting among Dutch residents living in households with solar panels (referred to as prosumers). Specifically, we investigated factors which influence the practice of time-shifting laundering to those moments when solar panels are producing solar energy. Through a survey, we tested the influence of eight factors included in our newly constructed framework, which was based on social practice theory with integrated elements from the theory of planned behavior. Preceding the survey, we conducted expert interviews to allow for preliminary validation of our framework as the foundation for survey design.

Overall, we have found that prosumers with low monitoring skills, strong habits, passive user beliefs and little practical knowledge struggle with loadshifting their laundering practice. That is, prosumers who struggle to loadshift are firstly found to have trouble monitoring the energy production of their solar panels and the energy consumption of their household. This finding is in line with other studies researching energy production and consumption monitoring, such as Gram-Hanssen et al. [40] and Gill et al. [41]. Secondly, the laundry practice of prosumers who struggle to loadshift is found to be strongly habitual. This finding resonates with the literature describing laundering as a practice: a socially shared pattern of behavior which has become routine due to the interconnectedness with day-to-day routines [50,52]. Although doing the laundry does not have to follow a strict pattern, such as preparing and having food, it is nevertheless an activity that people undertake in a routinized manner [67]. This has important implications for increasing prosumption levels, which will be discussed in Section 5.3. Thirdly, prosumers who struggle to loadshift their laundry practice have been found to feel like passive users of their solar energy system and the energy system overall. Lastly, these prosumers who struggle to loadshift laundering are found to have been provided with little information on the advantages of prosumption or ways to prosume. In other words, the quantitative survey findings indicate that four of our eight measured factors influence laundry loadshifting behavior in Dutch households with solar panels.

[2] Cronbach's alpha is a measure of internal consistency.

[3] Spearman's rho is a correlation coefficient assessing how well two items relate.

[4] The data seemed to be normally distributed based on a plot of the standardized residuals.

[5] The independent variables (the eight factors) did not appear to correlate too highly with each other based on the calculation of the variance inflation factors (VIF), with all VIF values being below 2.

[6] The variance of errors did not seem to differ at different values of the independent variables (the eight factors), based on a plot of the standardized predicted values.

Table 3
Correlations between laundry loadshifting and the eight computed factors.

Factor	Mean (SD)	Pearson's correlation coefficients								
		Loadshifting	Beliefs	Attitude	Knowledge	Know-how	Monitoring	Design	Habits	Hassle
Loadshifting	2.58 (1.12)	1	0.334**	0.304**	0.495**	0.213**	0.517**	0.324**	−0.253**	−0.104
Beliefs	2.42 (0.70)	0.334**	1	0.118*	0.229**	0.020	0.195**	0.038	0.024	0.003
Attitude	3.77 (0.68)	0.304**	0.118*	1	0.249**	0.467**	0.365**	0.250**	−0.169**	−0.233**
Knowledge	3.17 (0.97)	0.495**	0.229**	0.249**	1	0.146*	0.392**	0.411**	−0.048	−0.030
Know-how	3.54 (0.78)	0.213**	0.020	0.467**	0.146*	1	0.267**	0.127*	−0.452**	−0.511**
Monitoring	3.35 (0.97)	0.517**	0.195**	0.365**	0.392**	0.267**	1	0.431**	−0.227**	−0.118*
Design	3.55 (0.84)	0.324**	0.038	0.250**	0.411**	0.127*	0.431**	1	−0.049	−0.004
Habits	3.12 (1.01)	−0.253**	0.024	−0.169**	−0.048	−0.452**	−0.227**	−0.049	1	0.565**
Hassle	2.98 (0.95)	−0.104	0.003	−0.233**	−0.030	−0.511**	−0.118*	−0.004	0.565**	1

* Correlation is significant at the $p < 0.05$ level.
** Correlation is significant at the $p < 0.01$ level.

Table 4
MRA results on the relationship between the eight factors and laundry loadshifting.

Predictor	Beta	SE	t	*p*-value
User beliefs				
Model 1	0.207	0.075	4.391	<0.001**
Model 2***	0.194	0.073	4.217	<0.001**
Model 3****	0.146	0.071	3.267	0.001**
Sufficiency attitude				
Model 1	0.079	0.088	1.464	0.144
Model 2***	0.103	0.086	1.955	0.052
Model 3****	0.113	0.082	2.233	0.026*
Practical knowledge provided				
Model 1	0.293	0.060	5.571	<0.001**
Model 2***	0.258	0.059	5.002	<0.001**
Model 3****	0.179	0.059	3.488	0.001**
Know-how				
Model 1	−0.010	0.086	−0.166	0.868
Model 2***	0.015	0.083	0.251	0.802
Model 3****	0.015	0.080	0.262	0.793
Monitoring skill				
Model 1	0.275	0.064	4.952	<0.001**
Model 2***	0.273	0.062	5.083	<0.001**
Model 3****	0.208	0.062	3.896	<0.001**
Feedback provision by system design				
Model 1	0.048	0.070	0.915	0.361
Model 2***	0.035	0.068	0.685	0.494
Model 3****	0.015	0.065	0.297	0.767
Habits				
Model 1	−0.209	0.064	−3.651	<0.001**
Model 2***	−0.213	0.062	−3.837	<0.001**
Model 3****	−0.191	0.060	−3.558	<0.001**
Hassle				
Model 1	0.069	0.069	1.176	0.241
Model 2***	0.016	0.068	0.277	0.782
Model 3****	0.009	0.066	0.159	0.874

* Significant at the $p < 0.05$ level.
** Significant at the $p < 0.01$ level.
*** Model 2 is adjusted for age and gender.
**** Model 3 is adjusted for age, gender, occupant status, household size, intention, number of panels, year of installation and storage.

5.2. Scientific contribution

In the introduction, we stated that there was a need to assess a clear set of factors that influence (laundry) loadshifting if its behavioral foundation is to be better understood. We addressed this knowledge gap by studying a multitude of factors simultaneously, based on a new framework that combined elements from the theory of planned behavior and social practice theory. Using this integrated framework as the basis for our survey allowed for the quantitative assessment of all three elements of social practice theory (materials, meaning, beliefs) and their influence on time-shifting the laundering practice in prosumer homes. Unlike previous studies, we focused specifically on time-shifting of laundry practices to increase solar prosumption, rather than on prosumption overall or on solar prosumption without a clear focus on laundry loadshifting [17,39,41]. Our study is strengthened by the fact that we used expert input during survey construction. By first conducting interviews with experts in the field of solar energy, we aimed to maximize the likelihood of our survey identifying those factors that prosumers genuinely struggle with in practice.

Although our approach to integrating the theory of planned behavior into social practice theory is imperfect, as was discussed in Section 2.3.2, acknowledging this difficulty is in itself an important contribution to the social sciences. We hope to have shown that there are significant challenges involved in trying to construct a framework covering the complexities of human behavior, when said behavior itself can be measured on different levels, to begin with (e.g., on an individual versus a collective level).

5.3. Implications and interventions

The findings of this study mainly imply that the factors influencing loadshifting are diverse and manifold, relating not only to user beliefs (meaning) or monitoring skills (competencies) but also to the practical knowledge that is provided by appliances and stakeholders (materials). It is, therefore, unlikely that there is one targeted solution to tackle all these factors. For instance, our results show that doing the laundry is indeed habitual, being a routinized pattern of behavior (a practice) in most households. Whilst in many purely psychological theories such as the theory of planned behavior a habit is a particular type of behavior, which can be addressed through an intervention, this is different in social practice theory (in which the habit itself is the unit of inquiry, as we have discussed). Here, the three elements (materials, meanings, competencies) are what affect the practice, which, in the case of laundering, is often strongly interwoven with other household chores [67]. This means that changing a practice can be difficult, especially if the three elements do not all support such a change. This is also shown in our findings. For example, if monitoring skills are missing, prosumers do not seem to loadshift their laundering. The same is true if prosumers do not have access to practical information on loadshifting (competencies). Additionally, perceiving oneself as an active or passive user of the energy system influences laundry loadshifting (meanings).

Because practices are difficult to change due to being embedded in daily routines, some degree of automation through technological interventions may be beneficial to increase time-shifting laundering. Examples include smart laundry machines alerting prosumers when the sun is shining (on the machine display or even in a mobile application). If such an intervention is desired, the home appliances sector can support prosumers by designing smart laundry machines that are able to display or send such alerts. Whilst the theory of planned behavior might suggest that a simple intervention will lead to behavior change, social practice theory shows that this might not be the case since changing one practice could cause ripple effects on many other practices. Smart technology could, therefore, be a work-around to help relieve prosumers of some of the complexities involved in increasing prosumption through changing energy-intensive household practices. However, as studies on automated washing appliances show, these should be integrated carefully and take into account the agency, clarity and reliability of control and feedback mechanisms [68]. Failing to do so will have negative consequences for the acceptance of such automated approaches to demand response and may stress household practices or cause inefficient energy use [68]. This matter is important, though it falls outside of the scope of the current paper.

Furthermore, we have shown that the habitual nature of laundry practices is not the only factor to take into account when studying laundry loadshifting behavior. The effects of monitoring skills, practical knowledge provided to prosumers, and user beliefs should not be disregarded. When it comes to tackling these factors, automation through technological interventions may fall short. Such interventions may even increase the negative influence of these factors if they deny prosumers the opportunity to become and feel like active, informed, and skilled users of our energy system. Herein lies a vital role for consultants, policymakers, and/or solar panel installers to actively distribute practical information to prosumers on the advantages of prosumption and ways to loadshift. Whilst the provision of information alone is known to be insufficient to change most habitual behavior [69], such a strategy could be effective when combined with other measures. For example, the provision of practical information at the time of panel installation could underscore the importance of prosumption and increase knowledge on which loadshifting practices matter most. To offer insight and guidance during the application of this knowledge, monitoring skills could be enhanced further through interventions such as intuitive, user-friendly mobile applications or visual displays hung in spaces prosumers pass by often [55]. In addition, automated alerts could help prosumers become aware of the times when their panels are producing enough energy to switch on the laundry machine, possibly replacing old habits with new ones.

5.4. Limitations

The shortcomings of our theoretical framework have already been discussed in Section 2.3.2. In addition to these shortcomings, it should be noted that the overall findings of the current study are specific to the case of the Netherlands (see also [58]). Limitations specific to our survey include the decision to measure factors using scales of only two questions. Arguably, more questions per scale might have led to better factor representation and more reliable scales [70]. Moreover, the way some questions were phrased may have been a limitation. For example, there could have been too much overlap in the questions intended to measure feedback provision by system design and monitoring skill, considering the EFA grouped these questions together (see Appendix C [62]). Considering that the vast majority of our questions were not standardized, such phrasing issues were perhaps unavoidable. Additionally, our data is correlational, meaning we cannot make statements regarding causal effects between the factors and laundry loadshifting. Our data is also self-reported, which is especially relevant to the dependent variable of laundry loadshifting: we do not know whether respondents truly do time-shift their laundering. Lastly, using an online respondent platform undoubtedly has its drawbacks. Despite guaranteeing a swift response rate, it is, for instance, difficult to assess the actual representativeness of the sample since we did not have insight into all characteristics of the users on Dynata's platform (in terms of, e.g., income, location, or education) [71]. In addition, responses are collected from participants who express interest in studies of a specific topic, meaning they “self-select” and are thus not entirely random [71].

5.5. Suggestions for further research

Further research could first assess whether there are any causal effects at play between our identified factors and laundry loadshifting. For this purpose, we suggest an experimental study design. For example, an experimental choice experiment could be used to test if prosumers who are aware of the difference between self-produced and grid-produced energy (know-how) are less restricted by e.g., habits and hassle when trying to loadshift their laundering. Similarly, more in-depth research could help clarify the nature of the relationship between habits, hassle and loadshifting, since the MRA did not detect any effect of hassle whilst the EFA combined both hassle and habits (see Appendix C [62]). General suggestions for future studies include the measurement of actual prosumption levels instead of relying solely on self-reports, as we did, which may provide more accurate insights regarding true (laundry) loadshifting. Additionally, one could question entire households instead of singular members, taking a collective approach that is more in line with social practice theory.

Lastly, we hope to have inspired other researchers to look at the interaction between technology and behavior even more closely and transdisciplinary than is currently the case when studying prosumption (e.g., regarding the purchase of smart appliances, residential batteries, smart grid integration, etc.). Although we have shown that there are difficulties involved in integrating different approaches and perspectives on human behavior, even within the social sciences, we believe this to be a worthwhile pursuit. Of course, the integration between technical and behavioral science extends far beyond topics such as prosumption and laundry loadshifting. Regardless of the topic under study, we believe our findings show the importance of developing technology which understands the intricacies of human behavior and the connections to its broader context rather than simply asking people to change.

Disclosure

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CRediT authorship contribution statement

Naomi D. Hubert: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Katharina Biely:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Linda M. Kamp:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Gerdien de Vries:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Naomi Hubert reports financial support was provided by TPM Energy Transition Lab. Co-author is the director of the TPM Energy Transition Lab - G.D.V.

Data availability

The authors do not have permission to share data.

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2024.103514.

References

[1] IPCC, Synthesis Report of the IPCC Sixth Assessment Report (AR6): Longer Report. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf, 2023.
[2] Energy use in households in 2020, Eurostat, 2022, June 17 https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220617-1#:~:text=In%202020%2C%20households%20accounted%20for%2027.0%25%20of%20final,and%20petroleum%20products%20%2812.3%25%29%20and%20derived%20heat%20%288.2%25%29.
[3] Elektriciteit En Warmte; Productie En Inzet Naar Energiedrager, Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/cijfers/detail/80030ned, 2022, December 15.
[4] N. Bhushan, L. Steg, L. Jans, C. Albers, Does installing photovoltaic panels affect daily electricity usage patterns? A generalized additive model approach, Energy and Climate Change 2 (2021), https://doi.org/10.1016/j.egycc.2021.100052.
[5] Z. Hu, M. Wang, Z. Cheng, Mapping the knowledge development and trend of household energy consumption, Environ. Dev. Sustain. 24 (5) (2022) 6053–6071, https://doi.org/10.1007/s10668-021-01727-z.
[6] G. de Vries, M. Rietkerk, R. Kooger, The hassle factor as a psychological barrier to a green home, J. Consum. Policy 43 (2) (2020) 345–352, https://doi.org/10.1007/s10603-019-09410-7.
[7] R. Luthander, J. Widén, D. Nilsson, J. Palm, Photovoltaic self-consumption in buildings: a review, Appl. Energy 142 (2015) 80–94, https://doi.org/10.1016/j.apenergy.2014.12.028.
[8] I. Wittenberg, E. Matthies, Solar policy and practice in Germany: how do residential households with solar panels use electricity? Energy Res. Soc. Sci. 21 (2016) 199–211, https://doi.org/10.1016/j.erss.2016.07.008.
[9] A. Gautier, J. Jacqmin, J.-C. Poudou, The prosumers and the grid, J. Regul. Econ. 53 (1) (2018) 100–126, https://doi.org/10.1007/s11149-018-9350-5.
[10] T.H.J. Inderberg, K. Tews, B. Turner, Is there a prosumer pathway? Exploring household solar energy development in Germany, Norway, and the United Kingdom, Energy Res. Soc. Sci. 42 (2018) 258–269, https://doi.org/10.1016/j.erss.2018.04.006.
[11] J.M. Roldan-Fernandez, M. Burgos-Payan, J.M. Riquelme-Santos, Assessing the decarbonisation effect of household photovoltaic self-consumption, J. Clean. Prod. 318 (2021) 128501, https://doi.org/10.1016/j.jclepro.2021.128501.
[12] M. Wolsink, Framing in renewable energy policies: a glossary, Energies 13 (11) (2020) 2871, https://doi.org/10.3390/en13112871.
[13] G. Walker, The dynamics of energy demand: change, rhythm and synchronicity, Energy Res. Soc. Sci. 1 (2014) 49–55, https://doi.org/10.1016/j.erss.2014.03.012.
[14] B. Anderson, Laundry, energy and time: insights from 20 years of time-use diary data in the United Kingdom, Energy Res. Soc. Sci. 22 (2016) 125–136, https://doi.org/10.1016/j.erss.2016.09.004.
[15] R. Khalid, T.H. Christensen, K. Gram-Hanssen, F. Friis, Time-shifting laundry practices in a smart grid perspective: a cross-cultural analysis of Pakistani and Danish middle-class households, Energ. Effic. 12 (2019) 1691–1706, https://doi.org/10.1007/s12053-018-9769-7.
[16] J. Mylan, D. Southerton, The social ordering of an everyday practice: the case of laundry, Sociology 52 (6) (2018) 1134–1151, https://doi.org/10.1177/0038038517722932.
[17] A. Gautier, B. Hoet, J. Jacqmin, S. Van Driessche, Self-consumption choice of residential PV owners under net-metering, Energy Policy 128 (2019) 648–653, https://doi.org/10.1016/j.enpol.2019.01.055.
[18] NOS, Nederland Europees koploper zonnepanelen, maar hoe kan het beter. https://nos.nl/artikel/2439211-nederland-europees-koploper-zonnepanelen-maar-hoe-kan-het-beter, 2022, August 3.
[19] NOS, Netbeheerder: Stroomnet te vol, stop met gunstige regeling zonnepanelen. https://nos.nl/artikel/2413476-netbeheerder-stroomnet-te-vol-stop-met-gunstige-regeling-zonnepanelen, 2022, January 17.
[20] NOS, Historische groei zonnepanelen op woningdaken. https://nos.nl/artikel/2461430-historische-groei-zonnepanelen-op-woningdaken, 2023, January 27.
[21] NOS, Overbelast stroomnet raakt bedrijven en woningbouw. https://nos.nl/nieuwsuur/artikel/2427174-overbelast-stroomnet-raakt-bedrijven-en-woningbouw, 2022, May 1.
[22] NOS, Vraagtekens bij subsidie zonnepanelen:'Mensen zonder panelen zijn het bokje.'. https://nos.nl/artikel/2452301-vraagtekens-bij-subsidie-zonnepanelen-mensen-zonder-panelen-zijn-het-bokje, 2022, November 13.
[23] Milieu Centraal. (n.d.). *Salderingsregeling voor zonnepanelen.* Retrieved May 23, 2023, from https://www.milieucentraal.nl/energie-besparen/zonnepanelen/salderingsregeling-voor-zonnepanelen/#:~:text=Milieu%20Centraal%20rekent%20met%206%20cent%20per%20kWh.,mag%20je%20elk%20jaar%209%20procent%20minder%20salderen.
[24] NOS, Steun voor plan om subsidie op zonnepanelen af te bouwen onzeker. https://nos.nl/artikel/2460240-steun-voor-plan-om-subsidie-op-zonnepanelen-af-te-bouwen-onzeker, 2023, January 18.
[25] M. Braito, C. Flint, A. Muhar, M. Penker, S. Vogel, Individual and collective socio-psychological patterns of photovoltaic investment under diverging policy regimes of Austria and Italy, Energy Policy 109 (2017) 141–153, https://doi.org/10.1016/j.enpol.2017.06.063.
[26] F.E. Gohary, M. Nordin, P. Juslin, C. Bartusch, Getting the signal - do electricity users meet the preconditions for making informed decisions on demand response? Energy Res. Soc. Sci. 100 (2023) 103119 https://doi.org/10.1016/j.erss.2023.103119.
[27] W. van Sark, W. Schram, PV Prosument Richtlijnen. Universiteit Utrecht. https://www.pvp4grid.eu/wp-content/uploads/2019/08/1907_PVP4Grid_Bericht_Niederlande_RZ_web_BSW.pdf, 2019.
[28] J. Dehler, D. Keles, T. Telsnig, B. Fleischer, M. Baumann, D. Fraboulet, A. Faure-Schuyer, W. Fichtner, Self-Consumption of Electricity from Renewable Sources, 2017, pp. 225–236, https://doi.org/10.1016/b978-0-12-809806-6.00027-4.
[29] T. Kemmler, B. Thomas, Design of heat-pump systems for single- and multi-family houses using a heuristic scheduling for the optimization of PV self-consumption, Energies 13 (5) (2020) 1118, https://doi.org/10.3390/en13051118.
[30] C.B.A. Kobus, E.A.M. Klaassen, R. Mugge, J.P.L. Schoormans, A real-life assessment on the effect of smart appliances for shifting households' electricity demand, Appl. Energy 147 (2015) 335–343, https://doi.org/10.1016/j.apenergy.2015.01.073.
[31] M. Korsnes, W. Throndsen, Smart energy prosumers in Norway: critical reflections on implications for participation and everyday life, J. Clean. Prod. 306 (2) (2021) 127273, https://doi.org/10.1016/j.jclepro.2021.127273.
[32] M. Hansen, B. Hauge, Prosumers and smart grid technologies in Denmark: developing user competencies in smart grid households, Energ. Effic. 10 (5) (2017) 1215–1234, https://doi.org/10.1007/s12053-017-9514-7.
[33] F. Friis, T. Haunstrup Christensen, The challenge of time shifting energy demand practices: insights from Denmark, Energy Res. Soc. Sci. 19 (2016) 124–133, https://doi.org/10.1016/j.erss.2016.05.017.
[34] R. Galvin, I'll follow the sun: geo-sociotechnical constraints on prosumer households in Germany, Energy Res. Soc. Sci. 65 (2020) 101455, https://doi.org/10.1016/j.erss.2020.101455.
[35] N. Fox, Increasing solar entitlement and decreasing energy vulnerability in a low-income community by adopting the prosuming project, Nat. Energy 8 (1) (2023) 74–83, https://doi.org/10.1038/s41560-022-01169-5.
[36] R. Galvin, J. Schuler, A.T. Atasoy, H. Schmitz, M. Pfaff, J. Kegel, A health research interdisciplinary approach for energy studies: confirming substantial rebound effects among solar photovoltaic households in Germany, Energy Res. Soc. Sci. 86 (2022) 102429, https://doi.org/10.1016/j.erss.2021.102429.
[37] I. Öhrlund, B. Stikvoort, M. Schultzberg, C. Bartusch, Rising with the sun? Encouraging solar electricity self-consumption among apartment owners in Sweden, Energy Res. Soc. Sci. 64 (2020) 101424, https://doi.org/10.1016/j.erss.2020.101424.
[38] A.M. Peters, E. van der Werff, L. Steg, Mind the gap: the implications of not acting in line with your planned actions after installing solar photovoltaics, Front. Psychol. 10 (2019), https://doi.org/10.3389/fpsyg.2019.01423.
[39] L. Niamir, O. Ivanova, T. Filatova, A. Voinov, H. Bressers, Demand-side solutions for climate mitigation: bottom-up drivers of household energy behavior change in the Netherlands and Spain, Energy Res. Soc. Sci. 62 (2020) 101356, https://doi.org/10.1016/j.erss.2019.101356.
[40] K. Gram-Hanssen, A.R. Hansen, M. Mechlenborg, Danish PV prosumers' time-shifting of energy-consuming everyday practices, Sustainability 12 (10) (2020) 4121, https://doi.org/10.3390/su12104121.
[41] N. Gill, P. Osman, L. Head, M. Voyer, T. Harada, G. Waitt, C. Gibson, Looking beyond installation: why households struggle to make the most of solar hot water systems, Energy Policy 87 (2015) 83–94, https://doi.org/10.1016/j.enpol.2015.08.038.
[42] S. Ebrahimigharehbaghi, Q.K. Qian, G. de Vries, H.J. Visscher, Identification of the behavioural factors in the decision-making processes of the energy efficiency renovations: Dutch homeowners, Building Research & Information 50 (4) (2022) 369–393, https://doi.org/10.1080/09613218.2021.1929808.
[43] K. Biely, The Behavioral Perspective: Working Paper 1, Delft University of Technology, TPM Energy Transition Lab, 2022, https://doi.org/10.4233/uuid:0f0a5234-ec1f-44b1-88d5-49d703814c2c.
[44] A. Darnton, Reference report: an overview of behaviour change models and their uses, GSR (2008) 1–70. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/498065/Behaviour_change_reference_report_tcm6-9697.pdf.
[45] T. Jackson, Motivating sustainable consumption: a review of evidence on consumer behaviour and behavioural change, Sustainable Development Research Network 15 (2005) 1–132. https://coolclimate.berkeley.edu/files/coolclimate/Jackson+_2005_+-+Motivating+sustainable+consumption.pdf.
[46] K. Biely, Guidance through the jungle of behavioral science theories, models, and concepts for non-behavioral scientists, Urban, Planning and Transport Research 10 (1) (2022), https://doi.org/10.1080/21650020.2022.2145350.
[47] I. Ajzen, The theory of planned behaviour: reactions and reflections, Psychol. Health 26 (9) (2011) 1113–1127, https://doi.org/10.1080/08870446.2011.613995.
[48] D. Liu, S. Qi, T. Xu, Visual observation or oral communication? The effect of social learning on solar photovoltaic adoption intention in rural China, Energy Res. Soc. Sci. 97 (2023) 102950, https://doi.org/10.1016/j.erss.2023.102950.

[49] F.F. Sniehotta, J. Presseau, V. Araújo-Soares, Time to retire the theory of planned behaviour, Health Psychol. Rev. 8 (1) (2014) 1–7, https://doi.org/10.1080/17437199.2013.869710.
[50] A.-K. Hess, R. Samuel, P. Burger, Informing a social practice theory framework with social-psychological factors for analyzing routinized energy consumption: a multivariate analysis of three practices, Energy Res. Soc. Sci. 46 (2018) 183–193, https://doi.org/10.1016/j.erss.2018.06.012.
[51] T. Kurz, B. Gardner, B. Verplanken, C. Abraham, Habitual behaviors or patterns of practice? Explaining and changing repetitive climate-relevant actions, WIREs Clim Change 6 (1) (2015) 113–128, https://doi.org/10.1002/wcc.327.
[52] E. Shove, Converging conventions of comfort, cleanliness and convenience, J. Consum. Policy 26 (4) (2003) 395–418, https://doi.org/10.1023/a:1026362829781.
[53] E. Shove, M. Pantzar, M. Wattson, The Dynamics of Social Practice: Everyday Life and How it Changes, 2012, https://doi.org/10.4135/9781446250655.n1.
[54] E. Klint, L.-O. Johansson, G. Peters, No stain, no pain – a multidisciplinary review of factors underlying domestic laundering, Energy Res. Soc. Sci. 84 (2022) 102442, https://doi.org/10.1016/j.erss.2021.102442.
[55] Z. Frances, F. Stevenson, A relational approach to understanding inhabitants' engagement with photovoltaic (PV) technology in homes, Archit. Sci. Rev. 63 (3–4) (2020) 303–315, https://doi.org/10.1080/00038628.2019.1682962.
[56] B.K. Sovacool, S. Griffiths, Culture and low-carbon energy transitions, Nat Sustain 3 (9) (2020) 685–693, https://doi.org/10.1038/s41893-020-0519-4.
[57] D. Sloot, N. Lehmann, A. Ardone, Explaining and promoting participation in demand response programs: the role of rational and moral motivations among German energy consumers, Energy Res. Soc. Sci. 84 (2022) 102431, https://doi.org/10.1016/j.erss.2021.102431.
[58] C.L. Jensen, G. Goggins, F. Fahy, E. Grealis, E. Vadovics, A. Genus, H. Rau, Towards a practice-theoretical classification of sustainable energy consumption initiatives: insights from social scientific energy research in 30 European countries, Energy Res. Soc. Sci. 45 (2018) 297–306, https://doi.org/10.1016/j.erss.2018.06.025.
[59] K. Maréchal, L. Holzemer, Unravelling the 'ingredients' of energy consumption: exploring home-related practices in Belgium, Energy Res. Soc. Sci. 39 (2018) 19–28, https://doi.org/10.1016/j.erss.2017.10.025.
[60] C. Verfuerth, L. Henn, S. Becker, Is it up to them? Individual leverages for sufficiency, GAIA - Ecological Perspectives for Science and Society 28 (4) (2019) 374–380, https://doi.org/10.14512/gaia.28.4.9.
[61] D. Muijs. Doing quantitative research in education with SPSS, 2nd edition, SAGE Publications, Ltd, London, 2011, pp. 1–11, https://doi.org/10.4135/9781446287989.
[62] N.D. Hubert, K. Biely, L. Kamp, G. de Vries, Dutch loadshifting study: supplementary information, Zenodo (2023), https://doi.org/10.5281/zenodo.7995271.
[63] Huishoudens nu, Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/woonsituatie/huishoudens-nu, 2023.
[64] D.E. James, G. Schraw, F. Kuch, Using the sampling margin of error to assess the interpretative validity of student evaluations of teaching, Assess. Eval. High. Educ. 40 (8) (2015) 1123–1141, https://doi.org/10.1080/02602938.2014.972338.
[65] B.K. Sovacool, J. Axsen, S. Sorrell, Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design, Energy Res. Soc. Sci. 45 (2018) 12–42, https://doi.org/10.1016/j.erss.2018.07.007.
[66] Y. Kim, J. Dykema, J. Stevenson, P. Black, D.P. Moberg, Straightlining: overview of measurement, comparison of indicators, and effects in mail–web mixed-mode surveys, Soc. Sci. Comput. Rev. 37 (2) (2019) 214–233, https://doi.org/10.1177/0894439317752406.
[67] G. Powells, H. Bulkeley, S. Bell, E. Judson, Peak electricity demand and the flexibility of everyday life, Geoforum 55 (2014) 43–52, https://doi.org/10.1016/j.geoforum.2014.04.014.
[68] E. Naghiyev, R. Shipman, M. Goulden, M. Gillott, A. Spence, Cost, context, or convenience? Exploring the social acceptance of demand response in the United Kingdom, Energy Res. Soc. Sci. 87 (2022) 102469, https://doi.org/10.1016/j.erss.2021.102469.
[69] T.A. Kyriazos, Applied psychometrics: sample size and sample power considerations in factor analysis (EFA, CFA) and SEM in general, PSYCH 09 (08) (2018) 2207–2230, https://doi.org/10.4236/psych.2018.98126.
[70] R. Eisinga, M. te Grotenhuis, B. Pelzer, The reliability of a two-item scale: Pearson, Cronbach, or Spearman-Brown? Int. J. Public Health 58 (4) (2013) 637–642, https://doi.org/10.1007/s00038-012-0416-3.
[71] A. Newman, Y.L. Bavik, M. Mount, B. Shao, Data collection via online platforms: challenges and recommendations for future research, Appl. Psychol. 70 (3) (2021) 1380–1402, https://doi.org/10.1111/apps.12302.