"*That is what we can influence*": Exploring energy time-shifting using an always-on display in households with solar panels

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***Abstract*—Solar panels add a time component to the energy provision of households. Households equipped with solar systems will experience days and hours of abundance, during which they generate a surplus of electricity, as well as times when they need to purchase power from the grid. This creates opportunities for households to utilize more "free" energy when it is available by shifting activities in time, but while this may be possible for some activities, other practices may be seen as non-negotiable. We report on the deployment of an in-home display installed in nine households with solar panels in the south of Sweden. We conducted two sets of interviews: one before installing the display and another four months post-installation. Our results confirm that the negotiability of a certain energy practice may vary between different households. Washing, dishwashing and charging EV were seen as negotiable by everyone, whereas cooking and hot water use were seen as non-negotiable by most, but not all, the households. The in-home display worked as expected as a trigger and provided feedback for helping shifting the negotiable practices, but not for non-negotiable and it was appreciated by the users for its simplicity.**

***Index Terms*—Prosumers, always-on displays, photovoltaics (PV)**

I. Introduction

In the European Union, household energy consumption amounts to 27% of the final energy consumption, with electricity accounting for 24% [1]. The increased electrification of households and adoption of electric vehicles (EVs) are increasing the household share of electricity consumption on the grid. While combustible fuels, such as coal, natural gas and oil account for less than half the electricity produced in the EU, they are still the single largest contributor to electricity generation in the EU (41%) [2]. Solar energy is seen as an important component in reducing the dependence on combustible fuels and a necessary step in the transition to green energy. Falling costs, along with new incentives and opportunities afforded by photovoltaic (PV) panels are prompting more households to invest in the technology. The installation of solar panels in households has increased exponentially over recent years [3]. This adoption and growth of PV panels is changing the role of households in the electricity system, from passive consumers to 'producing consumers' (or 'prosumers') [4], [5]. Such a shift in role necessitates new technologies to help households to monitor and manage their electricity production and consumption.

Previous approaches to electricity-related technology in the household have been to visualise and materialize electricity consumption, to draw attention to its 'invisible' nature [6]–[8], to help households identify and reduce energy consuming behaviours through eco-feedback technologies [9], [10]. While the design of a significant number of these technologies follow behaviour change frameworks and patterns, by trying to provide the right incentives, motivations and knowledge to help people reduce energy consuming behaviors at home, they have also been criticised for the same. Social practice theory postulates that energy consumption behaviours in households are deeply embedded in routines and habits that are resilient to change. This makes it difficult for households to change the practices merely on the basis of rational thought and incentives [11], [12].

However, the adoption of PV panels, purchase of EVs and changing role of households in the electricity grid, have created new behaviours, incentives and infrastructures to change established routines. The growing weight of renewable energies is creating a more volatile energy market and bigger variability in electricity availability (and price). Solar energy technologies call for shifting of energy consuming behaviours to times of the day when energy production is high from PVs. The implementation of hourly tariffs provides additional incentives for shifting electricity use during different times and days to regulate changes in production and consumption.

Therefore, households equipped with solar panels present an interesting opportunity to explore this shifting role. Having proactively installed a solar system for economical and/or environmental reasons, these households are already more active in their energy use. Solar panels add variability to household electricity use patterns: sometimes there is a surplus of electricity and the household is selling to the grid, while at other times, the household may need to purchase electricity from the grid. Connected to dynamic electricity prices and smart meters, this variability complicates the optimization of electricity usage, whether from economic, environmental, or system perspectives. It goes beyond merely reducing the total kWh consumed; it evolves into a challenge of shifting consumption in time. Sometimes it makes sense to use a lot of electricity, while other times it is better to save as much as possible. From a sustainability perspective this adaptive behavior is a way of dealing with increased variability of electricity production due to renewable sources, instead of relying on technical solutions such as batteries or accumulators. But it also expects a lot from the households, both from their energy literacy needed for making informed decisions, and from their possibilities and willingness to change existing practices in their everyday life.

This 'perfect storm' of changing factors affords an opportunity to re-examine the impact of technologies and infrastructure in the household and to see how household practices are being affected.

This article aims to understand better how households with solar panels, already having variable patterns of production and consumption, have or have not changed their practices by shifting consumption to match production. We developed and installed an always-on display in nine households with solar panels in the south of Sweden and performed a qualitative study to explore the following questions:

- Which energy practices have they changed and which have remained unchanged after installing solar panels? What are the barriers?
- Does an always-on display help in triggering further time-shifting?

II. Background and Related Work

A. Behaviors, Practices and Triggers

Influencing energy consumption behavior at home through interventions is a challenging but well studied domain [13]–[17]. Persuasive technologies and interventions, especially those based on the Fogg behavior change model [18] or the Behavior Change Wheel [19], seek to reduce energy consumption behaviors by affecting three factors [20], [21] -

1) providing the right motivations and awareness to conserve energy (motivations relating to *why* households should save energy).
2) identifying opportunities at which users should perform actions to conserve energy (triggers relating to *when* households should save energy).
3) improving capability and ability of users to save energy (abilities relating to *how* households can save energy).

However, such interventions are seen to effect marginal change in energy activities at home and have been criticised for the underlying assumption that users are rational beings who, with increased awareness and incentivisation, can easily alter their behaviors [22]. The conceptualization of the 'Resource Man' persona frequently serves as the archetype towards which interventions are tailored in the pursuit of reshaping energy-related behaviors [23]. Most energy consuming activities, actions and behaviors are a part of the fabric of everyday life, hidden in routines, activities and habits that are quite resilient to change [11], [12]. These everyday 'practices' are mediated by three factors [24], [25] -

1) Meanings and understanding about the practice.
2) Competence and knowledge required to perform the practice.
3) Materials and infrastructure necessary to perform the practice.

Within this theoretical framework, habits and routines are viewed as observable patterns of action that emerge from the repeated reproduction of stable practices. These practices are understood to structure habits and routines by limiting the range of possible alternatives, such as with regard to temporal aspects [26]. Certain practices necessitate significant coordination both temporally and socially for their satisfactory execution, thus forming collective or societal rhythms that further define and influence the shape of the practice. Peaks in electricity consumption, typically observed in the evenings, are seen as exemplifying these societal rhythms.

B. Energy behaviors and practices of PV households

The adoption of PV panels in households represents a tremendous shift in terms of the above ontologies. In terms of social practice theory, the installation of PV panels correspond to changes in infrastructure relating to energy practices. Infrastructure and practices are intertwined with the potential to shape and affect each other [27]. The ability to produce one's own electricity and the shift to a prosumer role, represents a change in the meaning of electricity in households in the sense that it is no longer a consumable commodity that households pay for, but it is now also a commodity capable of generating revenue. The transition to prosumers, in addition to the micro generation of electricity, also brings other benefits such as increased awareness about the energy system and energy literacy as well as increased pro-environmental behaviors [5], [28], [29]. To achieve energy sufficiency and capitalize on potential revenue from selling locally produced energy back to the main grid via PV panels, households need to reassess their skills related to energy consumption and their capability to either reduce or adapt their usage effectively. Given the dependence of electricity production from PV panels on variables beyond household control such as weather conditions and availability of sunlight, consumption (particularly of household appliances) emerges as the main factor, actionable by households, to remain demand flexible [30]. In terms of behavior change ontologies, maximising economic gains from selling produced electricity serve as new motivations and could be seen as a big driver in changing energy consumption behavior [30], while external factors such as weather, availability of sunlight, dynamic pricing schemes serve as new triggers to engage in active, demand side management of electricity consumption. When coupled with a potential revenue stream, households are incentivized to remain demand flexible, particularly during 'peak hours' of electricity consumption. This encourages PV households to 'time-shift' their energy consumption, which involves adjusting the timing of routine practices such as laundry, electric vehicle charging, and cooking. The co-adoption of PV panels and EVs are seen to have some impacts on electricity consumption in households, particularly with respect to EV charging behaviors [31]. The extent of this time-shifting behavior is closely linked to the metering scheme adopted by individual households [28].

Although, longitudinal studies have revealed that while significant variations exist among households, the predominant long-term changes observed in PV-equipped households manifest as minor adjustments rather than a substantial alteration in general behavior, with some practices seen as non-negotiable and non-amenable to time shifting [29]. The temporal demands imposed by certain practices restrict their reproductions to certain time slots. Consequently, this restriction are seen to constrains their potential for time shifting [26]. Additionally, certain households even exhibit an increase in consumption, rationalizing this behavior through the perception of accessing ostensibly 'free' energy, indicating misconceptions about the nature of PV electricity production [29].

However, the above-mentioned factors point to a changed context and landscape in which to revisit the earlier technological interfaces used in interventions relating to energy consumption behaviors.

C. The Swedish Electricity context

Electricity generation in Sweden has mainly been met through hydroelectric (41%) and nuclear power (29%), resulting in high per capita consumption of electricity but low carbon emissions [32]. Thus, PV panel adoption has followed a different trajectory than in other European countries. In the Swedish context, PV panel adoption is still a small, but rapidly growing market with 147,690 panel installations totaling 374MW at the end of 2022. This represents a ten-fold increase from 2017 and it is expected to double during 2023-2024. A big majority of these PV installations (131,298) are smaller than 20 kW, mostly installed by private households [3]. The adoption of PV panels in residential contexts is underpinned by environmental, economic and social factors [33], [34]. A growing number of households are embracing the technology, spurred on by reduced costs of PV panels, escalating electricity expenses, purchases by peers and financial incentives or revenue opportunities stemming from the surplus electricity generated locally and supplied to the main grid [33], [35].

However, Sweden does not have feed-in-tariff (FIT) schemes, where the prosumers receive a predefined price per kWh regardless of the buyer and the time, instead they get paid the current hourly rate from the Nordpool power market which is decided a day in advance based on the offer and demand prognosis [1]. When there is surplus, the prosumers can choose to either increase their consumption to use up the energy they produce, or to sell it to the grid under a dynamic pricing scheme [36], [37].

[1]https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/ALL1/Hourly/

D. In-home displays

In-home displays are seen as an effective way to increase knowledge about resource consumption through eco-feedback and have been used in prior studies to help households improve their motivations and identify triggers for reduced electricity consumption through increased knowledge about consumption patterns, social implications [38], [39]. IHDs serve as an excellent medium to shed light on the 'invisible' nature of electricity [6]–[8] The heightened attention to consumption patterns and the 'repetition of attention' leading to increased information capacity about resource usage, that comes from having IHDs, is pointed to as a possible reason for the reduction in electricity consumption [10]. Alternative studies have pointed out that while IHDs do increase knowledge, reduction in consumption comes from the framing of the feedback provided by IHDs and not necessarily real-time feedback itself [40]. Contrary perspectives have been presented by other studies indicating that IHDs do not necessarily contribute to reduced electricity use and are often abandoned by users after a short period, due to factors such as lack of interest, difficulties understanding the display and technical issues [22], [41], [42]. Nevertheless, there is a general consensus among most studies regarding the efficacy of employing such systems to enhance knowledge and awareness concerning resource consumption. Additionally, these studies often put forth design recommendations for interfaces and visualizations associated with these systems [43]. Specifically, it is suggested that such interfaces should present information tailored to end-users through simple and conventional depictions, ideally in a portable format suitable for dissemination in public spaces [44]. Previous research has highlighted the challenges associated with collecting or accessing various types of information in the context of households with photovoltaic (PV) panels, including real-time data on consumption and generation, weather forecasts, and more [15]. Furthermore, the authors argue that providing households with contextualized information and subsequent control over their appliances, when a practice/activity is carried out is more engaging and aligns better with a households planning of activities than simply offering feedback.

Current approaches to energy consumption interfaces, particularly in households with PV panels, address the difficulties of data acquisition from different sources by providing a wealth of information including hour-by-hour consumption, forecasts, comparative data and economic measures, in the form of mobile apps or websites. In Sweden, such services provided directly by electricity companies such as Ellevio [2], Tibber [3], EON [4], etc, to name a few of the popular companies. Some providers even support additional services for connecting solar panels to the systems to visualize and even forecast electricity production data. The intended user of such systems fall in line quite clearly with the "Resource Man"

[2]https://www.ellevio.se/privat/solceller/solceller-kostnader/for-dig-som-installerat-solceller/

[3]https://tibber.com/se/tibber-appen

[4]https://www.eon.se/kundservice/vara-tjanster/app

persona [23]. Additionally, such interfaces also have gender and age specific styles of engagement with these technologies, with men typically taking the responsibility for managing the physical infrastructure and financial commitments [45]. Access to the apps and websites, and thereby the information provided by these, would also typically be in the hands of the men of the household. While IHDs are far from being neutral technologies; they allow all members in a household to view the information, thereby democratising access to the data. Due to their strategic placement within households,(IHDs) offer a more contextualized source of information than apps and websites, delivering information precisely when practices are being carried out. Other less data oriented forms of feedback have been explored in the context of energy consumption behaviors as well [46]. The aesthetic of the IHDs (or indeed any feedback device) is important to its communicative potential - if the device does not look good, it is hidden away and loses its potential to communicate [6]. Additionally, such interfaces are also seen as prompts to reflect upon the households energy practices and even in the development of new practices around energy. [47].

These factors point to IHDs, particularly in the form of a simplified ambient display, as a useful technology probe to investigate the evolving practices and changed context of the PV panel prosumer [48], [49].

III. Study

A. Method

The study follows an action research approach, balancing the implementation of problem-solving interventions with qualitative research [50], [51]. A technology probe was developed to make electricity production and consumption more prominent in households, using an always on display connected to the newer smart-meters being installed in the south of Sweden. Nine households in rural Sweden participated in the study and a smart-meter reader and an always-on screen were installed in prominent locations in their homes (in their kitchens or living-rooms). Qualitative semi-structured interviews were performed before installation during spring of 2023, and follow up interviews after four months during the fall of 2023. The first interviews were performed at home, the follow-up interviews were performed either at home or remote through video conference.

Themes explored during the Pre interviews (not exact questions to the households) included:

- Background: Basic data on the households and dwelling.
- Solar installation: Technical data and drivers for installation.
- Practices: Investigating if they have changed any electricity related practice after the installation of solar panels, and the existing drivers and barriers for shifting.
- Data: Investigating how they use existing available data, for example mobile applications from the utility company or from the solar installation.
- Literacy: Exploring how they understand quantitative electricity data, appliance's consumption and solar panel production.

Themes explored during the Post interviews (not exact questions to the households) included:

- Practices: Revisiting which practices were and were not shifted based on solar power availability, the barriers they experienced, and the integration of the display in their practices.
- Understanding: Exploring if the displayed production and consumption follow their expectations. Revisiting their energy literacy and their understanding of the displayed data.
- Technology: Asking for experienced problems and suggestions from a design/technology perspective, and their willingness to keep the display.

The interviews were recorded using an iPad and notes were taken by the researcher using Notability [5]. The audio was uploaded for speech-to-text processing at Sonix.ai [6] for transcription. The analysis was performed using the interview notes and the transcriptions using thematic analysis [52] . The material was analyzed and tagged for identifying relevant topics connected to the research questions.

B. Study Sample

The study was performed with nine households in a smaller village in the countryside in Sweden. The households were recruited by word of mouth and represent a majority of households with solar panels and updated smart meters in the area. Table I provides details of the respective households.

The following points are mentioned in the table -

- Houses: all houses were detached houses or farmhouses, from 120 m^2 up to 300 m^2. Six of the houses were more than hundred years old, two of them from the late 20th century, and one recently built.
- Heating: all houses had geothermal heat pumps, except one that had an air heat pump. Several households complemented it with wood stoves.
- Household size: four households were older couples with two adults (60–70), while the other five households were younger or middle-age couples (30–50) with one to three kids or young adults living with them.
- Demographics: the households were representative of a wide demographic group including for instance doctors, teachers, engineers, nurses, truck drivers, forest owners, retired metal workers.
- Cars: four households had EVs, two of them plug-in hybrids, two of them fully electric ones.
- Hourly tariff: four households had hourly tariff for buying electricity while the rest had monthly tariff.
- Solar panels: most households interviewed had recently installed their solar panels, except one household that had them already for several years. The size of the installation

[5] https://notability.com/
[6] https://sonix.ai/

Household	Adults + children	Age group adults	EV?	Hourly tariff?	Installed PV panel capacity	Installation Year	Yearly Consumption
A	2	70	No	Yes	8.6 kW	2021	10000 kWh
B	2+1	50	Yes	Yes	13 kW	2022	20000 kWh
C	2	70	No	No	10.5 kW	2021	5000 kWh
D	2	60	No	No	21.5 kW	2023	20000 kWh
E	2	60	No	No	15.5 kW	2022	18800 kWh
F	2+3	50	Yes	Yes	17 kW	2016	24000 kWh
G	2+2	40	Yes	No	9.6 kW	2022	16000 kWh
H	2+3	50	Yes	Yes	11 kW	2022	14000 kWh
I	2+2	30	No	No	20.5 kW	2023	20000 kWh

TABLE I

THE DEMOGRAPHICS OF THE HOUSEHOLDS INCLUDING THE NUMBER OF MEMBERS IN THE HOUSEHOLD, WHETHER THEY OWN AN ELECTRIC VEHICLE (EV), WHETHER THEY HAVE AN HOURLY TARIFF, INSTALLED SOLAR PANEL CAPACITY, INSTALLATION YEAR AND YEARLY CONSUMPTION.

varied from 8.6kW up to 21.5kW. One household (G) was unsure about their installed capacity.

- Yearly electricity consumption: household electricity use had a median of 18800 kWh per year which is similar to a Swedish average for detached houses of 20000 kWh. One household had a much lower electricity use due to wood heating. Everyone had an app from the energy network provider (Eon) with information about consumption and production. This information is not real time but it is updated every night with the day-before data.

Fig. 1. Solar panels of participating households

C. *Always-On In-Home Display*

The technical probe (see Fig 2) was developed to show real-time electricity consumption and production, using the following components:

Smart meter reader - A ESP32 based smart-meter reader which connected to the HAN port available on newer electricity readers being installed in Sweden. These devices were purchased from an independent developer [7]. These devices read the data from the electricity meter (updated every four seconds) including current consumption and production surplus in kW and push it to a server using MQTT. The production surplus is the net amount of kW the household pushes to the grid, in other words the current gross production minus

[7]https://energyintelligence.se/shop/

Fig. 2. Always-On Display showing a total consumption of 0.354 kW in a household. The red background indicates that the house is consuming/buying electricity from the grid

Fig. 3. Always-On Display showing a total consumption of 4.733 kW in a household. The green background indicates that the house has surplus energy and is selling electricity to the grid

the current household electricity usage. This information is different to what most users had available:

- The utility company's application displayed hourly consumption data in kWh. However, this data was not provided in real-time; instead, it was updated daily with the previous day's figures.
- Information from the solar inverter (real time gross production).

Display Two different setups were created due to supply chain shortages of Raspberry Pi Zero during development:

- Raspberry Pi Zero W with a 3.5inch screen. These were programmed using Python and had the possibility for using touch-screen and displaying other information like electricity hourly rate.
- Raspberry Pi Pico with a 3.5inch screen. These were programmed using C in the Arduino IDE and did not have the possibility for touch.

The program listens to the MQTT server and updates the display with new information. To facilitate easy understanding of production and consumption data and to incorporate a form of nudging we used a 'traffic light' feedback scheme - If the household has a surplus the display background is green, if the household is buying electricity the display background is red. The Zero version uses between 1.2 – 1.4 W, while the Pico version uses around 1 W. The code is available open source on GitHub [8].

D. Installing the Displays

The installation of displays was carried out by the first author and strategically positioned in conspicuous or prominent areas within each household. Notably, the kitchen was selected as a primary installation site, owing to its status as a frequented space where nearly all members of a household routinely congregate. In cases of open floor-plans and house layouts where the kitchen opens to the living room or dining room, these contiguous spaces were also designated as installation sites for the displays. The selection of these locations was guided by the aim of ensuring optimal visibility and engagement with the displays among household members.

E. Considerations

This study was conducted in 2023 after a time in which households experienced unusually high electricity costs in Sweden. This had made electricity saving a more relevant topic and affected how participants acted on electricity consumption.

IV. Results

The predominant themes from our data analysis predominantly center on the dynamics of how households engaged in the performance or reevaluation of their established practices, following the heightened visibility of energy production and consumption facilitated by the Always-On Display. Our findings are presented through quotes "..." (Household, Pre/Post interview) to illustrate the impact of this enhanced visibility on key household practices and the household responses in relation to the display itself. The ensuing analysis provides insights into the nuanced ways in which the introduction of the display instigated shifts in behavior and decision-making within the household context.

[8]https://github.com/zapico/SpotPico

A. Shifting Practices

The participants answered about which energy practices they may have changed since installing solar panels in their households, both before and after the display intervention. The main topics that came up were: a) dishwasher and washer machine, b) charging electric vehicles, c) cooking and baking d) heating. Together these represent a majority of electricity use in a household [1]

*1) **Washing machine and dishwasher**:* The participants consistently identified use of the dishwasher and washing machine, as practices that were deemed readily 'shiftable'. This consensus is evident in responses of the participants (with the exception of Household (I) which had recently installed their PV panels) as mentioned already in the Pre-interviews by all participants:

> "*I don't know if we do differently, but I usually say: Now it's a good time for washing when we have free electricity ... Run a washing machine or dishwasher and do not wait until it gets darker.*" (C Pre)
> "*If we are at home and it's sunny then we do the washing.*" (D Pre)
> "*Now it is like: the sun is shining, I put on the washing machine.*" (F Pre)
> "*The washing machine, we have thought a bit more that one can run it during the daytime when the sun is shining." "Not the dishwasher, that I haven't thought about.*" (G Pre)

This does not mean that the households enacted a time shift regarding these activities, and there were sometimes tensions within household dynamics:

> "*We have different views about this. I think we can try to shift more but* [my partner] *thinks it* [washing and drying] *should be done whenever there is time*". (B Post)

*2) **Charging electric vehicle**:* Charging an Electric Vehicle (EV) emerged as another energy practice that exhibited time shifting, with the four households possessing EVs demonstrating varying degrees of adjustment. The extent of the time shift and reasoning behind it also varied among households:

> "*Yes, we have bought a plug-in hybrid, with a charger that can be controlled to charge only with solar power.*" (F Pre)
> "*.. we check a bit for the car too.*" (H Pre)
> "*If we are at home we charge the cars during the day when the sun is shining.*" (H Post)
> "*.. charge the car too, now the screen is green: charge the car.*"(G Post)
> "[For the most part] *We use this app, it charges when the prices are lowest, then I do not need to think about it.*". "[But sometimes we charge the car with solar] *specially when the prices have been as low as they were last summer.*"(B Post)

A notable limitation pertaining to working households that arose for shifting EV charging was that these households that were not at home during the day and this necessitated the charging of cars in the evening/night for subsequent availability the next day. While there was occasional flexibility in rescheduling EV charging activities between different days, dependent upon factors such as battery capacity or commute distance, certain instances rendered EV charging non-negotiable for these households. Practical constraints imposed by work related practices thus affects the negotiability of EV charging practices.

An additional problem mentioned in one household was that the charging demand imposed by newer EVs exceeded peak solar production:

> "*It sounds dramatic, but because my car consumes so much when it's charging, I haven't thought as much about it* [compared to the partner which has a different EV, see quote above]. *If it was only a bit green I would not run to connect the car because it takes so much when charging. Look, now I have my car on, it* [the screen] *says 11,760kW.*" (G Post)

*3) **Cooking and baking**:* Cooking and baking practices emerged as major sources of electricity consumption in households. Some households were aware of this aspect and others had not previously reflected upon the substantial energy demand associated with these activities. Notably, despite the awareness of the energy-intensive nature of cooking and baking, many households expressed a perception of these practices as non-negotiable in terms of timing ,as mentioned in the interviews:

> "*We prepare food at the time when we want food*" (A Pre)
> "*I cannot say that it affects how we use the kitchen*" (B Pre)
> "*I cannot say that I have reflected about that* [kitchen energy use]". "*Does the stove use so much energy?*" (G Pre)
> "*"It is about having time, that one doesn't have the possibility to shift cooking in time too much*" (H Pre)
> "*"If one bakes a lot and the oven is on, that's an energy thief [...] but no, we must have food*"(C Pre)
> "*"We cook when we need food, in my opinion it is the one* [energy activity] *we can influence the least about when and how we do it.*" (B Post)

Despite these though, a noteworthy observation was made in certain households where some cooking practices were indeed time-shifted subsequent to the installation of the display screen:

> *"Washing machine, dishwasher, oven and stove. I have baked and cooked at the same time* [when there is solar power]" (E Post)
> "*Now I take advantage* [of solar power] *for cooking and baking or to prep things*"(G Post)
> "*I had not realized that the kitchen used as much as it actually does. It was an eye opener that the kitchen uses that much electricity, with the oven and the stove". " I've cooked during the day because it is sunny.*" (I Post)

While cooking is more time-dependent, baking was identified as a practice that could be relatively more amenable to time shifting. Participants highlighted that baking, in comparison to regular cooking or meal preparation, could be more easily shifted to align with optimal energy production periods:

> "*... baking something, making homemade muesli or similar, that otherwise I would make during the evening, but then I do it during the day instead if possible. That I have done.*" (G Post)

*4) **Heat and hot water**:* Heat and hot water emerge as the main electricity use, especially for the interviewed households living in detached houses or farmhouses .Eight households utilized geothermal heat-pumps, while one household employed an air heat-pump. Additionally, several households supplemented their heat-pump systems with wood stoves. While the households were aware of the significant energy consumption associated with heating and hot water, the consensus was that this particular energy-intensive practice was not easily amenable to time shifts:

> "*Hot water would be a thing, but we cannot control it* [...] *and the heat-pump, it lives its own life, so nothing else we can control.*" (A Pre)

As with respect to the other practices, there was variety here as well with one household who mentioned working proactively shifting or modifying heating practices:

> "*Sometimes it is so during the winter if the sun is shining, turn up the heat a bit, and then turn it back down when the sun is gone. Then the house gets extra heated during the sunny hours.*" (F Pre).

However, such situations are not an uncommon occurrence, particularly during typical Swedish winters.

While time-shifting heating can be difficult, hot water usage, particularly for activities such as showering, might be more amenable to time shifting. , However, some households explicitly identified showering as a notably strong and non-negotiable practice:

> "*No, to shower in the middle of the day? Oh, no!*" (E Pre)
> "*I do not use more hot water when the sun is shining, that I do not do. It is a bit more connected to electricity prices being higher. So I think a bit more about how much hot water I use. But I cannot say I go in the shower during the day when the sun is shining.*" (G Post)

One household opted for a more technical approach as an alternative to time-shifting daily practices:

> "*I configured the boiler so it ran only during the night* [because cheaper price during winter]).*Now* (ed. in spring) *I change it so it only runs during the day* (ed. when there is solar power)." (H Pre)

*5) **Other Barriers and limitations**:* A shared perspective emerged among some households, exemplified by comments from Household A, Household C, and Household B, suggesting a consensus on the limited scope of activities that can be feasibly shifted.For example both Household A and Household C mention after talking about washing machine and dishwasher that *"that is what we can influence"*. And Household B includes the EV *"It is what we can influence: dishwasher, washing machine, and the car"*.

Additionally, for households within the working-age demographic, a notable barrier was identified - the misalignment between the times when solar panels produce energy and the times when household members are at home:

> "*We are away during the daytime.*" (D Pre).

This misalignment introduces a practical challenge in leveraging solar energy optimally, given that individuals may not be present during peak solar production periods, limiting their ability to directly influence or shift certain energy practices.

In contrast, other households exhibit a relatively more flexible outlook to adjusting their activities and practices:

> "*We don't have any kids or so, so we can adjust.*" (E Pre)
> "*I am at home, so I can prepare dinner during the day* [when sunny] *as I am in any case preparing lunch for the baby.*" (I Post)

In one household, a perceived barrier to change in energy practices was attributed to the pricing model (or the mental model of how prices function):

> "*We have not done anything different, we have a monthly tariff, if we had hourly tariff it would have been different and we would adapt after the sun a bit more, but now it all adds up to an average in any case*" (D Post)

In one household where the presence of solar panels was associated with an unintended consequence – an increase in electricity usage, which they self-identified as bad:

> "*When there is electricity it is simpler. But if I'm honest I'm scared that it becomes easier to use electricity, and I am aware that it shouldn't be so. It's not so bad, but I see a tendency in myself* [to use more electricity when available] *so I know that other people probably think the same.*" (F Pre)

B. Always-On Display

The introduction of the Always-On Display was met with positive reception among the households, as it was generally perceived as a more accessible and user-friendly tool compared to mobile applications. The explicit mention of the display being easier to check than apps indicates a preference for a tangible and constantly visible interface:

> *"A surprise has been* [...] *that often we consume more than the solar panels give. We could see the sun shining and we expect to have a lot of effect from them. But it* (ed. the display) *says that we consume, so maybe the cars are charging or something like that"* (H Post)
> *"Yes, what I check is that it would not go down all the way to red. That's what I thought. I don't usually check exactly how much specific things consumed, I check the colors."* (E Post)
> *"It is a bit fun to watch sometimes, for example if it is really sunny weather or so, you can really see the difference"* (C Post)
> *"We have changed quite a bit actually* [After getting the display]" (E Post)
> *"You go by and look, and they you get a reminder all the time about electricity consumption"* (D Post)

An additional positive outcome of the Always-On Display was noted in some households, where the presence of the screen fostered engagement among members who were not initially active participants in electricity management. This observation underscores the display's role in extending awareness and involvement beyond the primary user, creating a more inclusive environment for all household members -

> *"Yes, my wife had never been a bit interested about these questions, but suddenly we can have a dialogue about it."* (H Post)
> *"Yes and our ten year old also points out that the screen is green or so. He notices, maybe he does not act upon it, but he notices and understands the point of it."* (H Post)
> "*The colors were good for the kids. They do not know how much a thousand or two thousand means, but they understood the colors.*" (F Post)

The very positive sentiment among the interviewed households was reflected in the fact that almost all of them opted to retain the Always-On Display. The consensus among participants, stating that they would miss the display if it were not available, underscores the perceived value and impact of the intervention on their daily lives -

> "*I would miss it if it disappeared.*"(G Post)
> "*I look at it often. Before I looked at the mobile phone,*[...] *but now it has been a long time I haven't used the apps." "The display is easier, one goes by it all the time*"(A Post)

V. Discussion and Conclusion

The Always-on In-Home Display (IHD) in itself was appreciated as a reminder and trigger. The simple design and interface was a positive aspect for the users and it substituted checking specific apps. Combining behavior change concepts of nudging (through the traffic light feedback scheme) and triggers [18] with the design implications laid out in practice theory literature [6], [22], resulted in the creation of a minimal but well-appreciated and functional display. Our approach in taking a minimalist approach to information visualisation and distilling the data to its essentials occupies a middle ground between the non-numerical approaches to energy visualisation [8], [46] and the conventional data-centric, visualisation heavy approaches adopted by apps and websites [20]. The fact that almost all the households chose to keep the display could indicate that it has become part of their household practices (the relatively short time period of around 5 – 6 months makes it hard to validate this). Another positive aspect of the IHD was seen in one household where more members of the family got involved with energy practices. In most households interviewed it was only the most active member that had access to the phone apps connecting to the PV and energy company, an in-house display can increase inclusiveness to other members, as observed in some of the interviewed households..

The in-house display prototype helped in:

- Triggering: reminding the households to shift, signaling the availability of solar energy.
- Feedback: controlling that the amount that was being used did not exceed production. In many cases PV system are dimensioned such that it was difficult for users to use all the energy produced during a sunny summer day, but in other cases, with less sunny weather or activities with a higher effect such as EV charging, it was possible to exceed the amount being produced.

This triggering and feedback effect did not happen in all the households, but it was as expected dependent on the household's possibilities of shifting and availability of practices that they identified as negotiable (ability). While our results corroborate findings about the non-negotiability of certain practices [22], [47], the negotiability of a practice was household-dependent. What was negotiable varied from household to household, stemming from a combination of partly the technology but mostly of existing familial and social practices. The always-on IHD thus serves as a tool aiding prosumers in renegotiating their ability to time shift existing practices.:

- Dishwashing, washing and charging EVs were seen as negotiable by most households. This does not mean that they were always shifted to match electricity production from the PV panels, but that they were seen as possible to shift. The extent to which these activities were effectively shifted exhibited variability across households. Some households tried to shift as much as possible, while scheduling and convenience created barriers for others.
- Cooking was seen as mostly non-negotiable. Many households did not change any kitchen practice based on electricity production from PV panels and expressed strongly that it was not even in their thoughts. Other households did shift kitchen practices, for example baking and oven usage and even time-shifting kitchen prep-work. This shows how the negotiability of a practice is variable and possible to influence, under the right combination of triggers and motivations.
- Heating was difficult to shift in time because: a) seasonal disconnect between PV production and heating needs in Sweden; and b) technological difficult to time shift in many heating systems such as heat-pumps unless specific controls are installed.
- Showering and hot water should be an easy target to time-shift but it was seen as non-negotiable.

Our results also suggest a diversity in perspectives across different demographic groups. The older prosumer households, in contrast to their younger, working counterparts, seemed to embrace a greater sense of adaptability or openness to adjusting their energy practices over time. Understanding such variations in flexibility is crucial for comprehending the multifaceted nature of responses to changing energy dynamics and highlights the importance of tailoring interventions and strategies based on diverse household characteristics and demographics. This study therefore, sheds light on realistic expectations regarding the time-shifting of household practices, even in the context of prosumer households where electricity consumption carries additional meanings and necessitates the development of new competencies due to local electricity production.

The designed IHD consumes approximately 1 W,which, when operational continuously throughout the year, accumulates to 8.7 kWh. This energy consumption must be considered, however the participating households had an average yearly consumption of more than 16000 kWh, rendering the IHD's consumption a relatively minor proportion of their total energy use. But this would be context dependent, in households with low energy use, the extra wattage can offset possible small gains. Exploring possible breaking points between IHD consumption and shifting benefits would be an interesting topic for further exploration.

Additionally, we contend that IHDs function not merely as traditional instruments for behavior change, but rather as facilitative tools aiding prosumer households in discerning which facets of their energy-related activities can be can be shifted. By working as a trigger or a catalyst to help prosumers improve their ability to time-shift, it leads to the development of new competences in practices where electricity has new meanings.

The evolving landscape of energy systems, characterized by the proliferation of PV installations, EVs, dynamic electricity pricing, and smarter grids, pushes for a more proactive role for households within this paradigm. With PV installations, energy use is not only about the "how much" but also about the "when", given the periodic surplus of electricity experienced on certain days and hours. The adaptability of households to these surpluses is dependent upon the negotiability of energy practices, which, in turn, is constrained by existing practices and technology. This time-shifting is relevant as the electricity system becomes more time sensitive with the growing amount of renewables, the push towards hourly tariffs and the need to reduce peak effect problems. Taken from a different perspective, if time-shifting were seen as a distinct practice in and of itself, then IHDs assume a role as precondition or infrastructure facilitating the execution of this practice. From one perspective, this study was carried out after a period (Winter 2022 – 2023) when electricity had different meanings and value (particularly in Europe owing to prevailing political tensions stemming from the Ukraine-Russian conflict). This serves to highlight the volatility of energy systems and how they are prone to influence from external factors. Thus, it would not be unreasonable to envision futures where time-shifting of established households practices could become more necessary.

Our study contributes noteworthy insights, revealing the diverse perspectives among households regarding the negotiability of energy practices and the extent to which certain practices are amenable to time-shifting. The identification of certain practices as non-negotiable by some households contrasts with the proactive stance adopted by others, shedding light on the variability in attitudes toward time-shifting. In this regard, in-home displays (IHDs) emerge as pivotal tools that facilitate informed decision-making and contribute to the ongoing discourse on the dynamic role of households within the evolving energy landscape.

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