Smart energy technologies for the collective

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Smart energy technologies for the collective: Time-shifting, demand reduction and household practices in a Positive Energy Neighbourhood in Norway

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ABSTRACT

The climate and energy crises are hastening the implementation of Positive Energy Districts/Neighbourhoods (PEDs/PENs) in European cities in line with the goal of net zero emissions by 2050. Demand-side energy reduction and flexibility are crucial to meeting this target by matching demand with local renewable energy production; however, it has not yet been empirically investigated in PEDs/PENs. Addressing this gap, we aimed to investigate households' energy practices in a Positive Energy Neighbourhood in Norway, focusing on the role of smart technologies for demand-side reduction and flexibility. A mixed methods approach was applied, combining in-depth and semi-structured interviews, house tours, actual energy consumption, and simulated solar energy production presented as narratives. The results indicated the need to rethink smart energy technologies to address the collective nature of PEDs/PENs by showing that (i) different ways of interpreting and domesticating these technologies impact demand reduction and flexibility of households with implications at the neighbourhood level, (ii) the individualistic design approach of smart energy technologies does not afford community interaction in terms of knowledge transfer and collective engagement, and (iii) collective representations of energy affordability and convenience attributed to such technologies may act as barriers to households' engagement with demand-side strategies. These results can be seen as recommendations for PEDs/PENs stakeholders and policies to foster the development of community-based smart energy technologies.

1. Introduction

The climate and energy crises are hastening the implementation of climate-friendly neighbourhoods in European cities towards net-zero emissions by 2050 [1,2]. The recent shift from building to neighbourhood and district level is a step towards interconnected infrastructural changes between buildings, open spaces and transport systems, encouraging the implementation of Renewable Energy Sources (RES), uptake of electric vehicles (EVs), adoption of smart technologies for energy management, as well as stakeholders' and residents' engagement in the transition [3–6].

Aligned with this approach, the emergent concept of Positive Energy Districts/Neighbourhoods (PEDs/PENs) introduced in the Strategic Energy Technology (SET) Plan 2018 has been guiding sustainable urban development within the EU. PEDs/PENs are "energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy" [7,p. 4], enabled by a multi-level integration of infrastructures and systems that make "optimal use of advanced materials, local renewables, storage, demand response, electric vehicle smart-charging and ICT" [8,p. 42]. Hence, three elements form the conceptual framework of PEDs/PENs: (i) efficiency for demand reduction, (ii) flexibility to match renewable production and (iii) local renewable energy production [7,8]. PEDs/PENs must also focus on social innovation by guaranteeing low energy and housing costs, citizen participation, as well as strengthening

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and transferring knowledge among stakeholders and residents; goals summarised in previous studies as (i) affordability, (ii) governance and (iii) capacity building [3,4,7,9–11].

However, scholars have acknowledged that achieving net-zero emission and surplus renewable energy is challenging on many levels; thus, PEDs/PENs are still a work in progress, having multiple interpretations and depending on lessons from real experiences to evolve conceptually [5,9,11,12]. Among these challenges, demand-side energy reduction and flexibility are crucial elements when dealing with the intermittent nature of renewable energy production. Nevertheless, demand-side strategies have been overshadowed by technological solutionism visions focusing on the potential of renewable energy systems for production and the technical aspects of flexibility, e.g., storage – a recurring issue in several types of energy communities, as noted by Barnes et al. [13]. In this context, scholars have argued that social aspects (e.g., demand-side energy management) essential to PEDs/PENs' functionality are largely overlooked compared to the plethora of research on technological and design solutions for their implementation [4,9]. The extent to which residents of PEDs/PENs have been reducing and time-shifting their energy demand, the role of technologies in assisting these changes in energy practices, as well as meanings and motivations behind such 'shifts' remain unexplored in PEDs/PENs literature. To the best of our knowledge, there are no studies that have contributed empirical insights into households' everyday energy practices in PEDs/PENs cases since existing social science research on the topic focuses on stakeholders and practitioners [5,6], citizens preferences for configurations of PEDs/PENs [14] and critical reviews [4,9,11].

To address this gap, we propose looking at demand-side reduction and flexibility through the lens of social practice theories, shifting the focus from technological innovation to innovation in practices where technology plays a part. From a practice theoretical perspective, changes may occur only through the interwoven dynamic among elements inherent to the practices [15]. For instance, new energy provision systems (e.g., RES) require the development of new skills and competencies by households, as well as their engagement and commitment in reframing energy practices by time-shifting and reducing demand. We argue that such a dynamic is more sensitive in PEDs/PENs due to the multitude of cutting-edge technologies deployed in several spheres of the district/neighbourhood that need to be interpreted and domesticated by households and then incorporated into their everyday practices [16,17]. Given that this dynamic entails complex processes of knowledge acquisition that rely on one's active participation in practices [15,18], we follow the line of investigation of several scholars [16,19,20] who focus on individual variations in the performance of energy practices mediated by technologies to understand their collective nature, since these variations contain the seeds of change in practices as a whole [21]. In this line, we aim to investigate households' energy practices in a Positive Energy Neighbourhood (PEN case), focusing on the role of smart technologies for demand-side energy reduction and flexibility, to answer the following research question:

i) How do smart energy technologies support households' energy practices towards demand reduction and flexibility in PEDs/PENs?

To do so, we applied a mixed methods approach combining in-depth and semi-structured interviews, house tours, actual energy consumption and simulated solar energy production presented in the format of narratives to make the data more relatable and appealing to a broader audience. In addition, we methodologically frame smart home technologies (SHTs) as the 'mediator' of the multitude of technologies often deployed in PEDs/PENs projects. SHTs operate at the household level to a multi-level network since they enable energy monitoring and control for all actors involved in the smart grid: utilities, retailers and consumers. SHTs designed for energy management purposes, or simply smart energy technologies [22,23], are increasingly seen by policymakers, energy and tech industries as the key to demand-side strategies, with a central role coordinating a complex digital network for flexibility, matching renewable energy production with demand [22,24]. Given these considerations, and from a practice theoretical perspective, smart energy technologies cannot be analysed only as single devices but rather as part of sociotechnical networks and infrastructures linking practices together across different levels and spheres, as previously argued by Gram-Hanssen [16]. Hence, we use the term 'smart energy technologies' to refer to a set of interconnected energy management systems and devices embedded in smart homes but digitally connecting sociotechnical networks within and outside PEDs/PENs boundaries.

2. A glance at SHTs for demand-side reduction and flexibility

Scholars acknowledge that SHTs are crucial for demand-side flexibility since "networks capable of shifting the timing of demand require enrolling multiple ICTs and creating new relations between generation and demand" [13,p. 8]. From a practice theoretical perspective, however, time-shifting demand entails changes in the temporality of energy practices, thereby affecting a range of interconnected bundles of practices [19,25]. Studies have demonstrated that time-shifting demand is a complex task because it relies on households negotiating their habits and routines, which are shaped by individual and collective 'temporal rhythms' [26,p. 2], as well as meanings (e.g., caring, convenience, affordability) inherent to the households' engagement [19,25–27].

In contrast to demand-side flexibility, studies have revealed more uncertainty regarding the effectiveness of SHTs in reducing demand [22,28]. Scholars have argued that ICTs (e.g., SHTs) are associated with increases in energy demand and indoor thermal comfort expectations [28,29]. Furthermore, meanings ascribed to SHTs, such as convenience, have been scrutinised by scholars who argue that they promote the disengagement of households from demand reduction based on the notion of 'set up and forget' [30,31]. From another perspective, Hargreaves and Middlemiss [32] showed that three social relations shape energy demand: relations with family and friends, relations with agencies and communities, and relations of identity. This means that demand reduction is more likely to occur in the realm of such social relations, whether SHTs mediate them or not. When mediated by SHTs, demand reduction can be introduced during the process of becoming skilled and competent in SHTs since recent studies have shown that social relations play an important role in learning how to use SHTs [20,33].

2.1. A glance at social practice theories

"There is no such thing as a unified practice theory or practice-based approach" [34,p. 12], but there are overlaps and similarities in concepts and lexicon [34]. With this paper, we are not seeking to explore the rich multiplicity of practice theories nor to reduce them into one unified approach. Instead, we wish to establish our standpoint in a situational manner, i.e., in relation to the case study.

We take practice as the smallest unit of analysis of the social [35] and define practice as a "temporally and spatially dispersed nexus of doings and sayings" [36] held together by different elements. Due to the focus on energy technologies, we consider materialities such as technologies an integral element of practice [15,16,37]. We look at engagement, motivation and meaning as inherently related and more or less interchangeable words [15,16]. We analyse practical and institutionalised knowledge (respectively, know-how and explicit rules) as two elements within the realm of knowledge [16,18]. We use skills, competencies, and abilities to refer to know-how and processes of knowledge acquisition, which are, to some extent, interpreted as learning [18].

Given these elements, we then focus on variations in the performance of energy practices since practice is a 'patchwork' of varied performances enacted and reproduced by practitioners [15]. Thus, "elements holding a practice together may vary from person to person", and this dynamic represents "internal differentiations within a given practice" towards its transformation over time as well as the establishment of new practices [16,p. 74], [21]. Individual variations in the performance of practices, therefore, matter as they plant the seeds of change in practice as a whole – at the collective level [16,21].

In sum, social practice theories offer a valuable theoretical framework to understand changes at the collective level, which is highly relevant in analysing PEDs/PENs as these large-scale projects aim to foster sustainable changes through infrastructural and technological innovation. Through the lens of social practices, reducing and time-shifting energy demand are complex tasks embedded in households' habits and routines, requiring 'shifts' in individual and collective temporal rhythms, affecting a bundle of interconnected practices. Hence, the role of technologies in assisting changes in energy practices, processes of knowledge acquisition, as well as meanings and motivations behind such 'shifts' seem crucial elements to comprehend in a holistic manner demand-side energy reduction and flexibility in PEDs/PENs.

3. Materials and methods

We used a mixed methods approach that combines in-depth and semi-structured interviews, house tours, actual energy consumption and simulated solar production. This study adhered to the General Data Protection Regulation (GDPR). Data were collected, transported and analysed securely once participants had given their consent.

3.1. The case study

The case study is within the conceptual framework of Positive Energy Districts/Neighbourhoods (PEDs/PENs) since it aims to achieve net-zero emissions and trade surplus renewable energy to the grid. Located in Norway,[1] the new district is divided into seven housing zones that will have more than 1500 units when fully developed. Buildings were designed based on the passive house and plus energy standards. Renewable Energy Sources, such as photovoltaic panels and ground-source heat pumps, were used. These renewable energy systems are directly linked to the buildings' ICT ecosystem, enabling real-time energy monitoring and controlling for actors in the smart grid. The ICT ecosystem also enables a range of other types of SHTs implemented in the buildings, creating a fully smart home, as well as EV charging at home using local renewable energy production. Of the seven housing zones, only two are already built with residents. In this study, we focus on the 'houses zone' with around 70 detached and semi-detached houses that comprise one smaller community within the district plan. Considering the common characteristics mentioned above, the only variation among our sample is the house typology.

Regarding surplus renewable energy, the Norwegian tariff scheme for energy trading between prosumers and the grid generally incentivises self-consumption, as Table 1 shows. In addition, a plus customer scheme was implemented in the new district to support prosumers.

Table 1
Energy tariff.

Consumption vs. production	Tariff
When consumption is higher than production	Net rent = capacity link [kr/month] + energy link [øre/kWh] * consumption [kWh]
When consumption is lower than production	Net rent = energy link [øre/kWh] * production [kWh]

Source: Norgesnett AS.

[1] The name and location of the district have been withheld in accordance with GDPR guidelines. Due to the nature of the data analysed in this paper, participants could potentially be identified if the neighbourhood's name and location were disclosed.

3.2. Data collection and sample size

Qualitative data were collected over 10 consecutive days in April 2022. The first author recruited participants through door-to-door canvassing, where nine in-depth and semi-structured interviews combined with house tours were performed with one or more households of adults and, in one specific case, teenagers, totalling thirteen participants (Table 2). Data saturation was rapidly reached due to three factors: (i) the semi-structured interviews allowed researchers to explore the same questions in depth with all interviewees, (ii) the sample was highly homogenous as all residents moved to the new neighbourhood during the same period, lived in similar smart homes, had access to the same smart technologies and prosumer scheme, owned EVs. and (iii) data triangulation between qualitative and quantitative methods enhanced the reliability and validity of the study. Thus, the sample size aligns with the literature on qualitative research [38,39].

The interviews and house tours were audio-recorded after written consent was given by the participants and lasted an average of 67.5 min. We also obtained written consent to collect energy consumption data for two months (10 Feb – 10 Apr 2022). The declarations were sent to a supplier company involved in the neighbourhood project that provided energy consumption data sampled at 10-s intervals. The company also provided an additional hourly vector (used for billing purposes) that was used to interpolate missing values.

Table 2
Overview of housing characteristics and occupants' information.

House ID	Typology and size	Number of occupants	Main informant(s) and (age)	Educational background or current occupation
1	Two-storey detached house with a terrace (148 m2)	2 adults	Brian (61)	Health care
2*	Two-storey detached house with a terrace (148 m2)	2 adults	1 male	–
3	Two-storey detached house with a terrace (193 m2)	2 adults and 1 child	1 female	–
4*	Two-storey semi-detached house (90 m2)	2 adults and 1 child	1 female	–
5	Two-storey semi-detached house (90 m2)	2 adults and 2 children	Lily (30)	Events management
6	Two-storey detached house with a terrace (148 m2)	2 adults and 1 teenager	1 male	–
7	Two-storey semi-detached house (90 m2)	2 adults and 2 teenagers	1 male and 2 teenagers	–
8*	Two-storey detached house with a terrace (148 m2)	2 adults and 2 children	1 male and 1 female	–
9	Two-storey semi-detached house (131 m2)	2 adults and 1 child	Sofie (32) and Arthur (34)	Building technology (Sofie) Geography (Arthur)

Note: only three cases (1, 5, 9) were selected as stories and pseudonymised with personal data such as age and general field of education/occupation disclosed. (*) Houses with missing energy consumption data. According to the EU energy labelling scheme for buildings, all houses are highly energy efficient (Label A).

3.3. Data analysis

The qualitative data (i.e., interviews, including house tours) were transcribed faithfully with minor language editing as most participants were non-native English speakers. The content was analysed through Nvivo software, and an inductive coding method was used to organise the data into categories and subcategories labelled and clustered in similar topics [40]. The interview guideline can be found in Appendix A, and the coding list can be found in Appendix B. Storytelling techniques were then used for selected cases to create coherent personal narratives combining qualitative and quantitative data. Research data in the form of stories are more relatable to a broader audience, especially when the stories accompany quantitative data, as they make sense of the numbers and reveal information rarely displayed by quantitative studies [41].

The quantitative data refer to actual metered energy consumption and simulated energy production from photovoltaics (PVs). Households' energy consumption data were analysed to extract the average hourly and daily energy consumption in order to understand households' energy usage routines. The data sampled in 10-s intervals were pre-processed, and missing values were interpolated. The two-month average daily energy consumption was then calculated to extract the energy intensity of each household. The average energy consumption per hour was also calculated to provide an insight into the time windows during which each household consumed the most energy. The coefficient of variation [42] was also calculated on an hourly basis to depict better how the hourly usage deviated from the average. This metric reveals how consistent the energy usage was across the different households. Lastly, a comparative graph representing the average energy consumption per weekday was also produced to highlight the deviation in consumption between different weekdays. As energy production data were not provided, we calculated them based on geographical data (i.e., location and weather conditions) and the installed PV capacity per household [43]. The average daily energy production was then plotted for each house.

3.4. Selection of cases

A first round of data analysis with a set of qualitative and quantitative data was conducted to select cases to be developed as narratives. The interviews and house tours from the qualitative analysis were used to position the nine cases in a 2 × 2 matrix (Fig. 1) that scrutinizes variations in energy practices based on elements of practice: engagement and competencies in relation to smart energy technologies (materiality), as previously explored by Larsen and Gram-Hanssen [19]. From a quantitative perspective, a general analysis of actual energy consumption and simulated solar energy production was used to identify discrepancies among households in the sample (Fig. 2). Based on this triangulation, three cases were selected with the following criteria:

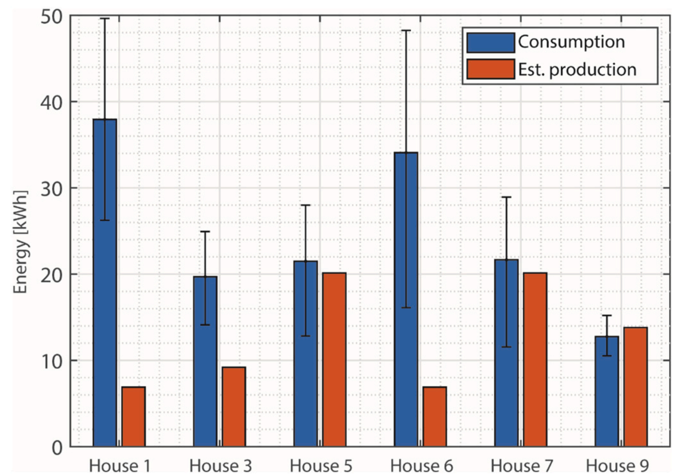

Fig. 2. Average daily energy consumption and estimated PV production from 10th Feb to 10th Apr 2022 (including the winter school holiday from 21st to 25th February). The estimated energy production varied according to the house typologies with different PV capacities installed. The error bars indicate the 25th and 75th percentiles.

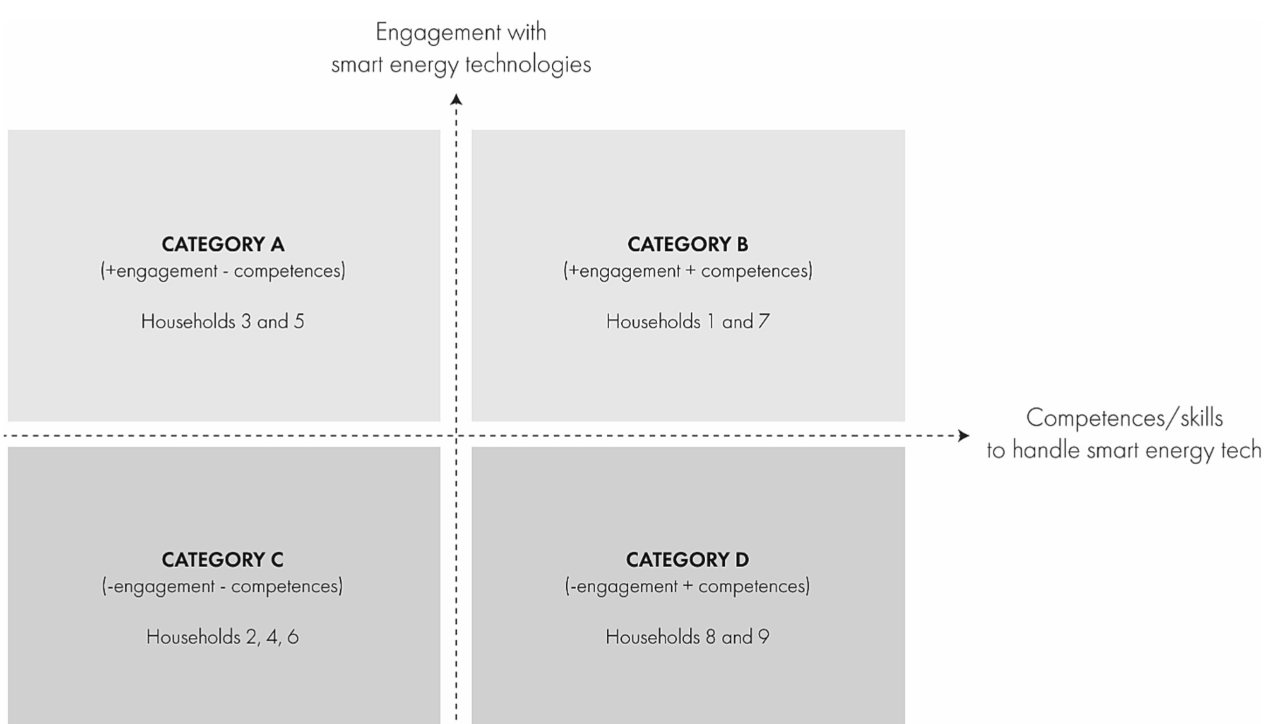

Fig. 1. 2 × 2 matrix between engagement and competencies in relation to smart energy technologies.

I. Variations in knowledge acquisition processes and modes of engagement highlight different ways of interpreting and domesticating smart energy technologies.
II. Stories that reveal community engagement in the Positive Energy Neighbourhood.
III. Discrepancies in energy demand: households with the highest, average, and lowest energy consumption.
IV. Different house typologies: detached and semi-detached.

Lastly, the energy consumption patterns of the chosen cases were compared with the average hourly energy consumption of households within the same region as the case study (Fig. 3). This comparison reinforces the relevance of the selected cases, given the distinct characteristics of their energy demand. As explored further in the Results section, contrary to the expected low energy consumption in plus energy-efficient homes, House 1 exhibits higher consumption than the regional average, while Houses 5 and 9 consume less than the average (see Fig. 3 in conjunction with Figs. 4, 6 and 8). Additionally, Fig. 3 facilitates a comparison of the peak time of energy demand between average households in the region and those in the case study, as Houses 1 and 5 demonstrate different demand patterns attributed to time-shifting strategies and energy-intensive loads such as EVs. These different demand patterns also impact the hourly deviation; while the regional average household deviates by approximately 20 %, the deviation of the selected cases, for instance, House 1, can reach 600 % (see Fig. 3 in conjunction with Figs. 4B, 6B and 8B).

4. Results

The results section is divided into two subsections. Firstly, we briefly explore the four categories with insights into the nine households. Secondly, we develop the three selected narratives to reveal how variations in the performance of practices at the household scale are relevant for a macro-level analysis of collective energy practices in the Positive Energy Neighbourhood.

4.1. Overview of households' energy practices in the PEN case

By exploring the entangled relation between engagement and competencies in relation to smart energy technologies, we have inferred that basic tech skills are needed to keep the smart home running properly (i.e., to simply live in smart homes). Thus, the main difference between categories A and C lies in the willingness to learn how to handle smart technologies and concern for energy-related matters. Category A includes engaged households that actively search for information. They rely on professionals' technical expertise and social relations with neighbours to acquire knowledge. Such relations are digital and face-to-face, utilizing technical support from companies, messaging applications, and social media to communicate with neighbours. Additionally, personal guidance, as well as annual community meetings involving residents and companies, contribute to their learning processes. Their engagement is mainly driven by rising energy prices and a particular enthusiasm for technology. They are prone to time-shifting the most energy-consuming practices, as well as demand reduction and or energy optimisation. Category B includes disengaged households that only interact with basic smart home features to keep the house running properly. The disengagement observed in this category is predominantly attributed to factors such as (i) age, as some interviewees, particularly those over 60 years old, perceive themselves as outside the target group for smart technologies; (ii) the perceived complexity of smart systems and the time investment required to learn it; (iii) lack of interest and or awareness regarding energy consumption and production; (iv) lack of interest in energy-related matters due to the perceived low energy costs associated with RES, and (v) delegation of smart home responsibilities to a partner. Consequently, these households neither engage in flexibility strategies nor demand reduction.

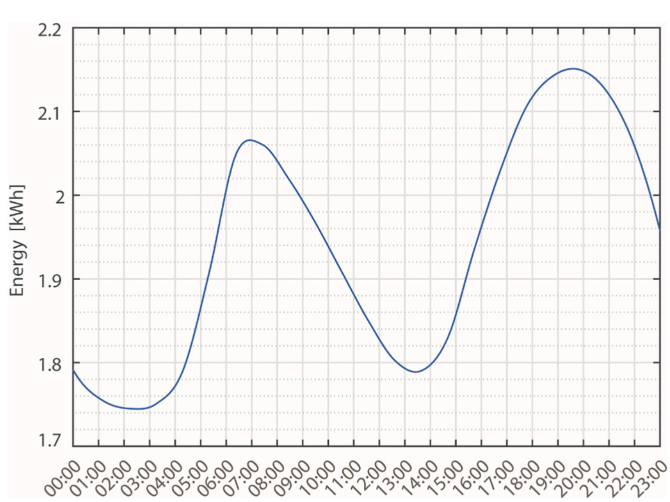

Fig. 3. Average hourly energy consumption of households in the same region for the same period – 10th Feb to 10th Apr 2022. Analysis based on an available dataset by Hofmann, Bjarghov and Nessa [44].

Categories B and D consist of highly competent and skilled households (tech-savvies and energy literates) but with different levels of engagement. In category B, households are tech enthusiasts who think smart technologies are fun. They appreciate the processes of handling technologies and managing energy through interaction with devices and systems. They also engage with professionals and neighbours to exchange experiences and gain more knowledge on tech and energy-related matters. They follow energy consumption, production and price signals to assist them in time-shifting the most energy-consuming practices. They are not much concerned with reducing consumption but rather with optimizing it. Category D comprises households who are tech-savvy and energy literate due to educational background and job occupation. However, their initial enthusiasm for smart homes turned into frustration due to several technical issues disrupting their routines. For instance, unmet convenience expectations, lack of interoperability and reliability of the smart system, and inoperability of smart meters contributed to their disengagement. These cases highlight that even tech and energy experts face troubles with the complexity of the smart home system and often need technical support from companies. Some households exhibit limited engagement with flexibility strategies due to the lack of energy consumption and production feedback resulting from smart meter problems, while others perceive time-shifting demand as having an insignificant impact. Households in Category D demonstrate a general lack of concern for demand reduction. This is attributed to factors such as reliance on the inherent energy efficiency of the house per design, energy affordability of RES, and satisfaction with the annual balance between energy consumption and production perceived through financial compensation.

4.2. Narratives

4.2.1. House 1: tech-savvy and energy-literate household with high energy consumption

Brian (61), his wife and dog have been living in a detached house since 2019. They previously lived in an old house nearby and decided to buy a smart home in the new neighbourhood due to the low maintenance, expected low cost of energy associated with RES and, especially for Brian, the new technologies.

Brian appears to be tech-savvy, energy-literate and highly involved with the community. He is in charge of his smart home, as his wife is not particularly interested in technology. When we requested a house tour to show the smart technologies, he opened a folder on his smartphone called "*hus*" (house) with nine apps for managing the smart home.

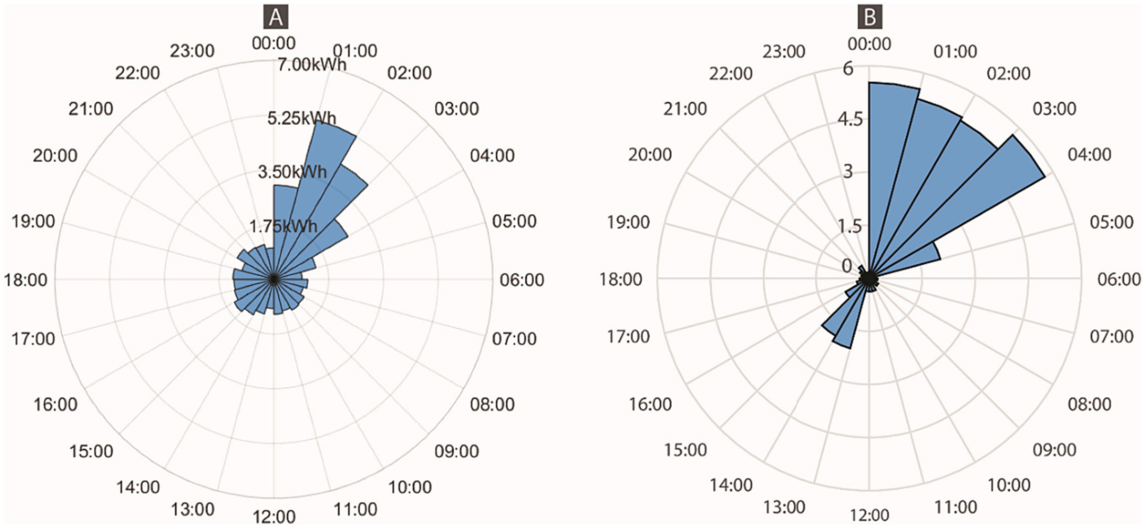

Fig. 4. (A) Average hourly energy consumption and (B) Coefficient of variation – House 1 (Time Zone UTC +1).

'Walking through' the apps and house, Brian showed how to turn lights on and off, create lighting scenes, configure automation features, adjust the window screens, manage the ventilation system and the temperature of all rooms, check the doorbell camera and visualise his energy consumption and PV production. He was comfortable using every app. He was familiar with the features of the apps, understood the energy feedback, and even knew about features the smart tech company want to launch in the future.

> *Brian: So I have an app to control my home, it's like that (showing the most used app) with security, climate, screens, lights—all the lights—and energy. I can see how much energy I use now, and also follow it by the hour (…) I can see what kind of equipment is using energy (the feature was not set up) but they are working with some AI stuff, so after time they can pick out when you use the oven, or if you charge your car, when in the day you are doing it and how much energy you use.*
>
> *I can also see here (showing another app), this is from my electrical company (…) So here I can follow my usage and how much it costs (…) I can see the dark blue is the energy I buy and the light blue is the energy I sell. So when it's sunny, like it's been the last few days, I produce nearly enough energy to use here in the house, and these peaks is when I charge the car.*

When asked about his interest in technology, Brian replied, "*I work with technology for patients (…) different technologies, so I'm used to working with apps*". Both at work and at home, he seems confident in dealing with slightly different technologies, arguing that he installs devices and sets up features by "*click(ing) and see(ing) what happens*".

Brian also shows concern about rising energy prices. He has been tracking energy prices for a while using the app, but now that he understands how they fluctuate; he does not check it so often. Due to this concern, Brian and his wife have been shifting energy demand, e.g., the time when they charge their EV or use the dishwasher:

> *Brian: I have programmed my charger to start at 1 a.m. because that's when the energy is cheaper. So I always charge my car at night (…) This is the energy price for today (showing the app from the energy supplier company), so I can see that 12 o'clock at night is the cheapest part of the day. It's always like that, it's always cheaper at night and in the morning (…) the most expensive times are breakfast time when people get up, and when they are making dinner because the country needs more power.*
>
> *(…) So we haven't changed so much, we charge the car at night, we don't use the dishwasher in the morning or when we are making food for dinner because that's when the price is high, so we usually turn on the dishwasher when we go to bed because that's when the energy is cheaper.*

As illustrated in Fig. 4, the highest electricity loads are indeed concentrated at night between 12 a.m. and 4 a.m., resulting in a major energy peak during this period and significantly lower consumption throughout the rest of the day. This energy consumption pattern is reflected in their daily routine. On weekdays, Brian and his wife work 8 h per day. He uses the EV during the day and charges it according to energy prices (i.e., at night) rather than when energy is produced (i.e., during daylight). Regarding their laundry practices, Brian notes that they only do laundry on weekends during daylight. Their practices seem very routinised, resulting in a consistent daily energy consumption pattern for the whole week, but with considerable within-day variability, as shown in Fig. 5.

Another important aspect of Brian's tech-savvy and energy-literate profile is his awareness of technological limitations that prevent him from saving energy. For instance, he identifies a problem with his EV smart charger as it is not connected to the home energy system in a way that could automatically charge the car according to energy prices. To him, a higher level of automation could avoid energy peaks in the community.

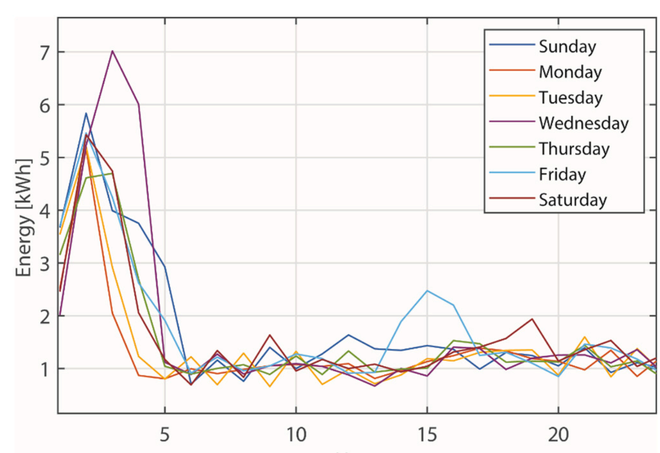

Fig. 5. Hourly energy consumption per day of the week – House 1.

Brian: So if one night, like you saw, the price is higher at 1 o'clock, I still charge the car at 1 o'clock because my charger is not connected to my energy system, so it can't tell when it is cheaper. I know there is a company in Norway [name of the company] with an app where you can set up to charge when it is the lowest price, then, if you charge your car at 7 a.m., it charges for half an hour, and then it stops to wait until it's cheaper again, and then starts to charge. That's so much more functional.

I like things that are automated, and it is also [better] for the community (…) it is the best thing because you don't get these peaks in energy, you get a more even energy consumption during the day because you let the system control it.

Brian also seems aware of his energy consumption and production as well as what equipment consumes the most energy. He affirms that in the summertime, most of his neighbours do not need to pay for any energy and are even paid for surplus energy returned to the grid.

Brian: The first year I lived here I didn't have the electric car, and I didn't have to pay for energy in June, July, August or September, it was free for four months, and in October I got a small bill. It's much, much cheaper [however] *after I got my electric car, I don't think I will get [any money back] anymore.*

Lastly, Brian talks about heating practices, revealing considerably high thermal comfort expectations as temperatures in some rooms are set to around 22–25 °C (underfloor heating) and the ventilation system to 20 °C. Regarding cooling practices, he emphasises that the houses become overheated during summer, and this issue was raised by residents during the annual community meeting with the project developers, leading to the installation of individual air-to-air heat pumps for cooling.

Brian: We have meetings every year, and we just had a case because many [residents] want to install air-to-air heat pumps to use for air conditioning (…) because in the summer, if it is sunny outside, it's 30 °C inside (…) we decided that everyone who wants one can get a heat pump for air conditioning, so we are probably going to do that (…) We have ventilation, but there is no cooling in the ventilation.

4.2.2. House 5: learning through experts and community engagement

Lily (30) has lived with her partner (29) and two children in a semi-detached house since 2020. They used to rent a small apartment and decided to buy their first home in the new neighbourhood due to the financial incentives related to sustainable projects, the expected low cost of living associated with RES and high thermal insulation.

Lily reveals that she was enthusiastic about the smart home since their first visit, while her partner initially did not want to buy it, but eventually, "*he understood why it is better to buy a new house with all this new stuff instead of an old, icy cold house*". She admits to being more interested in smart technologies than he is, and that she has been in charge of smart home management since they moved because he did not have the *"right phone to use the app"*. On the other hand, Lily acknowledges that her partner has become more interested in smart home apps since beginning a technology-related course. For instance, he has warned her about the security and privacy aspects of the smart home app because it has a second profile through which the smart tech company can access certain information. She is aware that the profile can be deleted, but she argues, "*I want them to have access because they can help us with stuff*". Indeed, Lily seems to have established a good relationship with companies involved in the project's development, as she relies on the professionals' technical knowledge to help her comprehend certain aspects of the smart home. For her, experts play an important role in transferring knowledge on indoor thermal comfort. Like Brian, Lily also notes that several neighbours complained of the houses overheating in the summer, but she asserts that she will not install an air-to-air heat pump because she has learned how to keep the house cool from an expert who also lives in the community.

Lily: Last summer was so warm inside and we thought: what are we going to do? And then I talked to some of my neighbours, and (person's name), the one who knows a lot about (name of the smart home app), he told me if you close the windows, close the doors, turn down the heat and try to keep the screens down when the sun is up, it will be much better (…) we also have air coming from the ventilation. So if you turn up the ventilation, it'll be a bit better.

Lily also highlights that during a community meeting, residents wanted to discuss the unexpectedly high energy bills with the real estate company and the energy supplier. According to her, energy prices in Norway have been incredibly high, and despite the RES implemented in the community, her energy bill increased by 600 % in January. As she explains in the following excerpt, Lily and many neighbours were disappointed that the low energy cost promised had not materialised.

Lily: Everyone told us that this is going to be cheaper than everything else (…) So a lot of people were very angry, and then we asked them: why is [the energy bill] so expensive? And they said it's because the temperature in your floor is much higher than what we expected, (…) then a neighbour asked: what is the right temperature? And they said 21 °C.

During this meeting, Lily learned the 'ideal temperature' for heating, as well as how the two RES operate. By explaining the limitations of the ground-source heat pump as well as the need to purchase electricity from the grid to keep the system running efficiently during the winter season, the experts highlighted that the problem relates to a higher heating temperature than the standard (i.e., 21 °C) used in the energy efficiency simulations. Lily's case illustrates this problem as she describes significant changes in heating practices since she moved. Her previous apartment did not need much heating since it was small and heated by the apartment below, while she keeps almost all rooms in her new house at 22–23 °C "*because the kids are always playing on the floor, and it's nice to have, it's more comfortable to have it a bit warmer*".

Once she understood the limitations of the RES and the fact that the high energy bill could largely be attributed to their heating practices, she decided to make some adjustments: *"This winter, we tried to change the temperature in some rooms upstairs to pay less"*. In addition to heating, she is attempting to change other practices based on energy prices, which she occasionally monitors via apps, websites or newspapers. Lily explains how she is adjusting these practices according to the family routine.

Lily: Power was very expensive around 4 p.m. to 6 p.m. when everyone comes home and makes dinner. We have small children, so we are up early, so I always try to wash clothes and stuff early in the morning because the power is cheaper, and (…) when I wash clothes or do the dishes, I try to do it at times when I know the prices are lower.

Regarding their EV driving and charging practice, Lily explains that they charge the car every night because they do not yet have a smart charger and are currently charging the car using a standard cable. Their daily routine requires using the car, as Lily's partner commutes to Oslo for work, and they transport the children to and from school by car. Lily, on the other hand, has a flexible work schedule that allows her to work mostly from home and drive around only for meetings. Fig. 6 shows

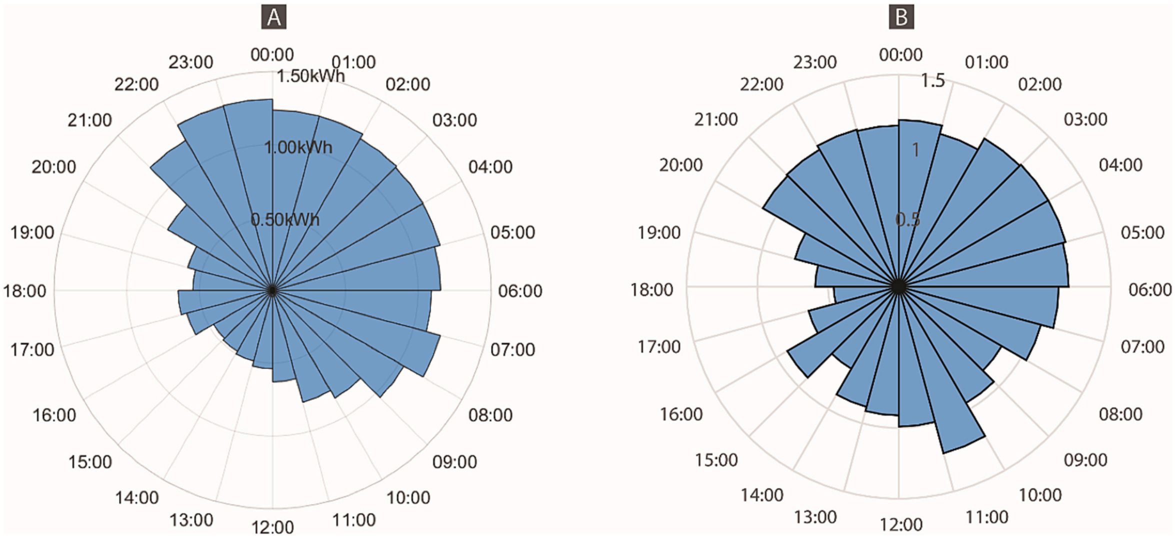

Fig. 6. (A) Average hourly energy consumption and (B) Coefficient of variation – House 5 (Time Zone UTC +1).

Lily's household's average hourly energy consumption, clearly illustrating what she states about their EV charging practice and willingness to shift demand to off-peak hours.

Analysing the differences per day during the week, Fig. 7 shows a significant variation in the morning, while the consumption is usually lower and similar in the afternoon, as also highlighted by the coefficient of variation (Fig. 6, B). This variation may be connected to Lily's flexible work routine, which allows her to do housework at different times of the day.

Regarding the smart home app, she rarely asks for help as she now feels confident in her tech skills. She only needed help to set up the automation feature for the screens, yet she argues that she is capable of setting up automation features if she spends time doing so, "*but sometimes it's easy for me to just go into the app and turn on the lights and stuff*". In addition to the smart home app, Lily has three other apps for managing the smart home, and she checks the energy supplier app frequently because "*it's fun to watch how much [energy] we can sell and I think it's important to see how much we use*", highlighting her ability to interpret energy feedback.

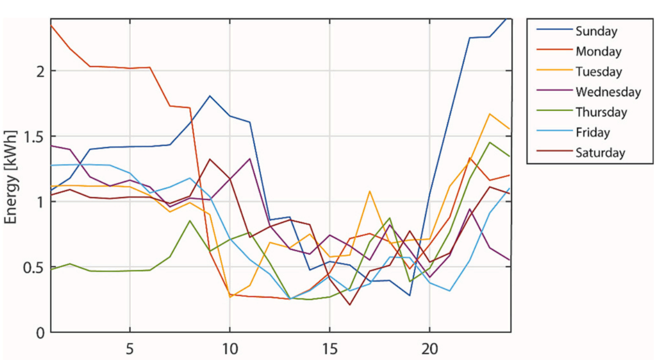

Fig. 7. Average hourly energy consumption per day of the week – House 5.

4.2.3. House 9: building technology expert but disengaged consumer

Sofie (32), Arthur (34) and their child have been living in a semi-detached house since 2019. They used to rent an apartment, but Sofie reveals that this specific house could be a financial investment for them due to the innovative and sustainable aspects of the project. In addition, she states that solar energy and thermal insulation were much more relevant in their decision to purchase the house than the SHTs.

Sofie and Arthur are not engaged with SHTs in general. They rarely use the smart features and are highly critical of their smart home, especially Sofie, who works on building technology projects. These criticisms are associated with two concepts: automation and convenience, neither of which their smart home achieved, as they argue in the following excerpts:

> *Sofie: The idea I have of the whole smart thing is that it makes life better, not like my life is bad without it, just like, I don't know, easier I guess, and I don't think they've achieved that here (…) When people think of a smart home, I think they think it's really sort of integrated into your life where you don't even have to think about it, like, oh my home is smart so I don't have to think about that stuff (…) I don't have to think about controlling the screens or setting the temperature, and I think that's sort of where it loses it, because to be honest, I don't find it that smart, I have to say.*

> *Arthur: I feel like the question is not why we don't use [the smart functions], but why should we? (…) It doesn't really add anything (…) it's not that I'm not interested in it, it's just, I feel like it doesn't offer anything revolutionary.*

Despite these criticisms, Sofie and Arthur tried to incorporate smart energy technologies into their daily lives but were unsuccessful due to factors such as lack of interest and technical problems. Sophie, several times, attempted to be more engaged but quickly lost interest. For instance, she mentions a recent new feature of the smart home app that displays real-time energy consumption, and she enjoyed tracking it for the first couple of days and even "*turned different things on and off to see how it affected consumption,*" but she quickly lost interest because "*it was just the novelty of it.*"

Technical problems significantly impact engagement because they contradict Sofie and Arthur's vision of smart homes making life easier and better (i.e., convenience). They describe how the entire smart home system can become inoperable if the hub goes offline. Arthur notes that *"the smart hubs go offline several times a day"* and remembers that *"it was offline for like a week and we barely noticed"*. Sofie adds that they *"don't care enough to really do anything about it, though"*. In addition, the technical problems also extend to the companies as they rely on households' competencies to make the system operable.

Sofie: We were putting this new meter in our electrical box to see how much electricity we were using, and there was some stuff that we had to do to hook it up and send it to the electrical company (…) and for the longest time I didn't do it, and then I got [a reminder] email from the people setting up, so like, okay, I'll set it up, and when I was setting it up, I didn't even know that there was a new version of the smart app because we had barely used it, and I don't even know how old the new version of it was, but we didn't even use that.

Arthur: Yeah, the stuff that the electrical company wanted us to do didn't work.

Another factor contributing to the non-adoption of smart energy technologies is how Sofie positions herself in relation to energy consumption. She claims to be *"not very conscious of"* or bothered about how much energy she uses. She admits to occasionally checking energy consumption and production to evaluate whether or not she will receive money back but pays less attention to energy consumption per se. This also influences her opinion on time-shifting energy demand.

Sofie: I know that a lot of people, or I think some people, will maybe wait to do laundry or something but to be honest, I don't want to do that. I don't want to change any daily activities according to energy prices or energy usage because, well, these houses are great in terms of energy, with the solar panels and everything, but I guess (…) I don't want to change anything because I just want to be comfortable [at home] so, and maybe it's selfish (…), but I don't think not doing laundry at 6 p.m. is going to really make a major difference. At home, I just feel like I'm at home—it's my place—and I can do and live as I want.

An example of Sofie and Arthur's lack of interest in energy demand is their charging practice. They have a hybrid vehicle, and they charge the car at home, usually late in the afternoon *"when we remember because we come back almost out of battery"*, says Arthur. As they do not have a smart charger, Sofie notes that they *"just plug it in, like a normal outside socket", thus* requiring more time to charge. Fig. 8 confirms these aspects of Sofie and Arthur's routine, revealing a high average energy consumption during peak hours. In addition, Fig. 9 highlights that the increase in energy demand in the morning and late afternoon/early evening is a relatively stable consumption pattern throughout the week.

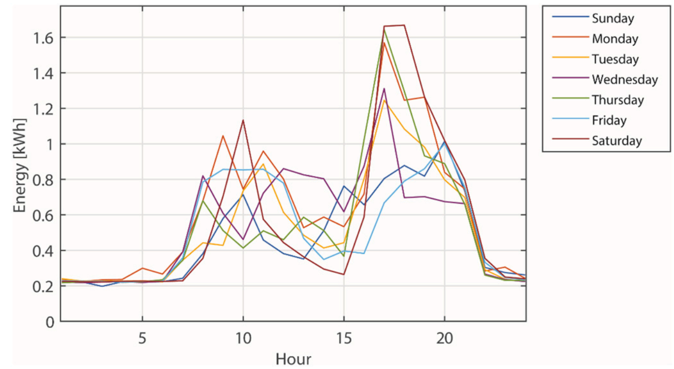

Fig. 9. Average hourly energy consumption per day of the week – House 9.

5. Discussion

The results section explored variations in the performance of energy practices among households, emphasising the role of smart energy technologies in the reconfiguration of such practices. As previously stated in the Introduction section, the analysis of variations at the household level gives insights into changes in the dynamic of collective energy practices at the neighbourhood level. Indeed, our findings revealed a considerable change in households' energy practices after moving to the new houses and neighbourhood; for instance, changes in heating, cooling, driving/charging and laundry practices mediated by smart technologies were highlighted in the narratives in connection with demand reduction and flexibility. In the following section, we explore the three main lessons learned from variations at the household level that may aid the conceptualisation and operability of PEDs/PENs towards net-zero emissions.

5.1. Different ways of interpreting and domesticating smart energy technologies impact demand reduction and flexibility at the individual household level with implications at the neighbourhood level

Our results show that different ways of interpreting and domesticating smart energy technologies can impact demand reduction and flexibility of households with implications at the neighbourhood level.

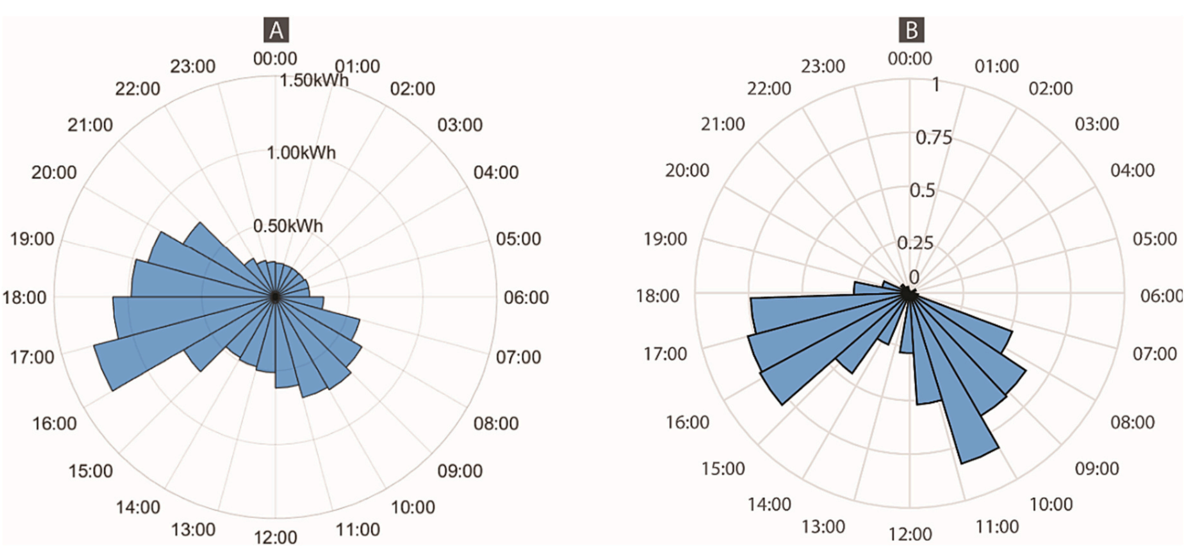

Fig. 8. (A) Average hourly energy consumption and (B) Coefficient of variation – House 9 (Time Zone UTC +1).

For instance, Brian's case (i.e., the household that consumed the most energy) indicates that adopting smart energy technologies does not necessarily lead to demand reduction as often assumed by the smart tech and energy industries [22,31,45]. Despite his eagerness to fully adopt the technologies due to his tech-savvy profile, he has essentially interpreted smart energy technologies as tools for shifting demand rather than reducing it. Furthermore, Lily's case highlights that less technological solutions could be more effective at reducing energy demand, such as simply lowering the heating temperature in less frequently used rooms during winter and learning how to keep the house cooler during summer to avoid the installation of air conditioning. Indeed, previous studies have revealed uncertainties about the effectiveness of smart energy technologies in helping to reduce demand [22,28,45] and have explored "the more controversial possibility of not using smart devices to support sustainability outcomes" [31,p. 38]. Our findings support these studies and take a step further in analysing the collective outcomes of variations in the interpretation and domestication of smart energy technologies for PEDs/PENs projects. For instance, Lily's and Brian's narratives show how several households discussed rising energy bills and air conditioning installation during community meetings with the real estate and energy supplier companies, issues intrinsically related to the domestication of smart energy technologies and interpretations of smart homes and renewable energy systems in general (explored further in Sections 5.2 and 5.3).

The results also highlight that demand-side flexibility relies much more on a complex ICT ecosystem than demand reduction, as previously noted by Barnes et al. [13]. For instance, Sofie and Arthur do not time-shift demand as they have not fully integrated smart energy technologies into their daily lives, while Brian and Lily do shift demand with assistance from smart home applications for energy management. This means that households' domestication processes and interpretation of smart energy technologies are important in understanding their engagement/disengagement with flexibility strategies at the neighbourhood level. Flexibility is one conceptual element of PEDs/PENs, and its demand-side aspects are largely overlooked, as mentioned in the Introduction. Our results can thus contribute to a better understanding of the topic.

5.2. The individualistic design of smart energy technologies does not afford community interaction in terms of knowledge transfer and collective engagement

Given the previous discussion, the results show how smart energy technologies afford certain possibilities for those who embrace them, such as demand-side flexibility. However, the narratives also revealed what these technologies do not afford. By 'walking through' the houses and smart home apps with the interviewees, we noted that smart energy technologies suffer from an individualistic design approach that does not afford any community interaction – digital social interactions are happening through other channels, such as social media and messaging apps. Thus, regardless of how the system works in the background and how the energy flows within the neighbourhood boundaries, all feedback given to households for energy management is at the household level. No socially contextualised energy consumption and production feedback was found, nor any mechanism for knowledge transfer and engagement between neighbours. To this extent, our findings raise an important debate for future studies on how smart energy technologies could be better designed to support community interaction in PEDs/PENs projects. Socially contextualised energy feedback may be beneficial for energy-saving, as previous studies indicate [46,47]. Beyond energy feedback, the analysis of energy practices reveals interesting social dynamics of knowledge transfer and engagement that such technologies could potentially assist.

For instance, Sofie and Arthur's narratives show how social relations are important to those households with low engagement when it comes to technical knowledge transfer among companies and residents. As illustrated in the 'new smart meter' case, they rely on technical support (emails and calls) when installing devices or updating systems for smart home technical functionality. Lily's story serves as another example, as she often relies on experts and community engagement for knowledge of how to handle smart energy technologies as well as demand reduction and flexibility strategies. Through community meetings, she engaged in a learning process that challenged households' over-consumption through an understanding of the limitations of RES as well as the 'ideal' heating and cooling practices. Personal advice from experts helped her acquire skills in setting up automation and keeping the house cool to avoid having to install air conditioning. Through social experiences, Lily developed a range of competencies and a new understanding of energy demand and technologies, which led her to reframe energy-intensive practices. This case illustrates the crucial role the community plays in acquiring the knowledge needed to change energy practices, corroborating the argument of Hargreaves & Middlemiss [32] that social relations shape energy demand – highlighting the dissonance between the individualistic design approach of smart energy technologies and the collective nature of PEDs/PENs projects.

Such a design approach seems effective only for tech-savvy and energy-literate households that readily engage with energy management. For example, Brian appreciates the process of becoming skilled in smart energy solutions through interaction with technologies mediated by rules embedded into the system design. This is often a "trial-and-error interaction" [33] based on rules and observation, or in Brian's own words: "click and see what happens". The outcome of this type of interaction is mostly demand-side flexibility. To some extent, our findings are aligned with Strengers' [31] critiques on the design of smart technologies for the envisioned and unrealistic Resource Man persona, but we also highlight the implications of such a design approach for the collective aspects of PEDs/PENs projects.

5.3. Representations of affordability and convenience attributed to smart energy technologies may act as barriers to households' engagement with energy reduction and flexibility strategies

By exploring the motivations behind individuals' decisions to purchase a smart home in the new neighbourhood, we have inferred that motivations are shaped by collective meanings ascribed to technologies used in the homes and neighbourhood and that these meanings are intrinsic to households' engagement/disengagement with demand-side reduction and flexibility. Two key factors for engagement emerged from the narratives: energy affordability and convenience.

Energy affordability is within the conceptual framework of PEDs/PENs, as mentioned in the Introduction. Indeed, our results show that energy affordability is the primary meaning ascribed to RES, attracting those concerned about energy prices, like Brian and Lily, to the PEN case. However, after moving to the neighbourhood, some households (e.g., Lily and Brian) had increased energy demand, likely due to changes in heating and driving/charging practices (EVs).[2] To avoid high energy bills, they started time-shifting demand based on price signals. This indicates that energy prices play an important role in demand-side flexibility, as highlighted by Christensen et al. [27], but for the most part, our results are consistent with previous studies that highlight affordability as the driving force for participation in energy communities, as well as the complex relationship between such representation and demand-side energy management as this may lead to increases in energy demand [13].

[2] Energy consumption (Fig. 2) is affected by factors such as the type of electric vehicle (full electric in houses 1 and 5 and hybrid in house 9) and the presence of a smart fast charger (house 1). However, the mixed-methods approach (e.g., in-depth interviews including questions about households' energy practices before and after moving to the new neighbourhood, see Appendix A) allows us to argue that households have considerably changed heating and driving practices in connection with the set of new technologies available.

To this extent, the analysis of meanings and modes of engagement reveals the complex relationship between self-sufficiency based on local energy production and time-of-use tariffs. Although energy trading tariffs encourage self-consumption in the PEN case, households' routines often do not match the energy production (e.g., EV charging time). This leads those with high and average energy consumption (e.g., Brian and Lily) to shift demand according to price signals rather than self-consumption. In contrast, those with considerably low energy consumption (e.g., Sofie and Arthur) overlook demand-side flexibility throughout the year as long as trading with the grid is favourable. This corroborates the issue described by Erba and Pagliano [48], where PEDs/PENs' annual energy balance may conflict with the idea of "maximising the self-use of on-site-generated renewable energy" [48,p. 26].

In addition, convenience was the primary meaning ascribed to smart energy technologies, significantly impacting households' engagement with such technologies and, as a result, demand-side energy management. Sofie and Arthur's story is illustrative because their high expectations of a convenient smart home were quickly transformed into frustrations along the way, and the numerous technical issues they faced with the systems contributed to this. Indeed, convenience may lead to disengagement and non-adoption of smart energy technologies, as mentioned in previous studies [30,31]. However, we go further and argue that: (i) visions of convenience may prevent demand-side flexibility and reduction even in cases where households like Sofie's have knowledge of it, and (ii) such disengagement with flexibility strategies jeopardises the goal of PEDs/PENs projects in achieving net-zero emissions since flexibility is crucial for meeting demand with renewable energy production.

6. Conclusion

This paper aimed to investigate households' energy practices in a Positive Energy Neighbourhood in Norway, focusing on the role of smart technologies for demand-side energy reduction and flexibility. We used a mixed methods approach combining in-depth and semi-structured interviews, house tours, actual energy consumption and simulated solar energy production. By presenting the results as narratives, we have explored how variations in the performance of energy practices can offer insights into the collective dynamic of energy demand reduction and flexibility at the neighbourhood level and highlighted the crucial role of smart technologies in such a dynamic.

Within this framework, the study addressed the research question *'How do smart energy technologies support households' energy practices towards demand reduction and flexibility in PEDs/PENs?'* by presenting three central lessons on households' energy practices that may aid the conceptualisation of smart energy technologies for PEDs/PENs projects. Firstly, different ways of interpreting and domesticating smart energy technologies impact demand reduction and flexibility of households with implications at the neighbourhood level. Secondly, the individualistic design approach of smart energy technologies does not afford community interaction in terms of knowledge transfer and collective engagement. Thirdly, collective representations of energy affordability and convenience attributed to such technologies may act as barriers to households' engagement with demand reduction and flexibility strategies.

These lessons reveal how the overlooked aspects of everyday life in PEDs/PENs may jeopardise their primary goals: net-zero emission and surplus renewable energy production. Energy reduction and flexibility are crucial for meeting demand with local renewable energy production, and we have shown that smart energy technologies play a central role in assisting households in such tasks, mainly in flexibility. However, regardless of how the system works in the background and how the energy flows within the neighbourhood boundaries, the energy feedback given to households is at the individual level. No socially contextualised energy consumption and production feedback was found, nor any mechanism for knowledge transfer and engagement between neighbours mediated by smart energy technologies. Thus, there is an urgent need to rethink the design of such technologies to address the collective nature of PEDs/PENs projects. In such contexts, smart energy technologies may link many levels of social and technical networks, potentially supporting knowledge transfer and engagement among households and stakeholders since our results have shown that social relations are crucial for demand reduction. Future studies may address questions on how these technologies can be better designed with a community-based approach as they are central elements in the dynamic of energy practices at the neighbourhood level; therefore, they cannot be understood only as single devices but rather as part of sociotechnical networks linking practices together across different levels and spheres.

Lastly, our study contributes with a methodological framework to analyse energy practice dynamics in PEDs/PENs projects, combining quantitative and qualitative data presented in the form of storytelling. This approach provides an in-depth understanding of how energy demand may vary over time, in different ways and in different households, the causes of these variations, and the impact at the neighbourhood level. We believe these data and insights may be of great value to various stakeholders involved in developing PEDs/PENs or similar climate-friendly neighbourhoods in Europe. Notably, the results can be seen as recommendations for PEDs/PENs policies in similar contexts in Scandinavia, primarily for developing community-based smart energy technologies fostered by policies to support community engagement in demand-side energy management.

6.1. Limitations

As a single-case study, the results have inherent limitations to this type of research. Its exploratory and descriptive nature prevents broad generalisation, which could be achieved through a cross-case comparison, possibly revealing a wider range of factors that impact demand-side flexibility and reduction in PEDs/PENs and enabling the formulation of hypotheses. However, as the first study to offer insights on households' energy practices in a PEN case, we are contributing to future research by providing qualitative and quantitative data that can be of great value for such cross-case comparisons.

CRediT authorship contribution statement

Fernanda Guasselli: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Validation. **Apostolos Vavouris:** Writing – review & editing, Methodology, Formal analysis, Data curation, Software, Visualization. **Lina Stankovic:** Methodology, Supervision, Project administration, Funding acquisition. **Vladimir Stankovic:** Methodology, Supervision, Project administration, Funding acquisition. **Sébastien Didierjean:** Supervision, Resources. **Kirsten Gram-Hanssen:** Writing – review & editing, Methodology, Validation, Supervision, Conceptualization, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2024.103436.

References

[1] J. Brozovsky, A. Gustavsen, N. Gaitani, Zero emission neighbourhoods and positive energy districts – a state-of-the-art review, Sustain. Cities Soc. 72 (103013) (2021), https://doi.org/10.1016/j.scs.2021.103013.

[2] IEA, Net Zero by 2050 - a Roadmap for the Global Energy Sector, IEA, Paris, 2021 [Online]. Available: https://www.iea.org/reports/net-zero-by-2050.

[3] J. Salom *et al.*, 'An evaluation framework for sustainable plus energy Neighbourhoods: moving beyond the traditional building energy assessment', Energies, vol. 14, no. 14, p. 4314, Jul. 2021, doi:https://doi.org/10.3390/en14144314.

[4] S. Koutra, J. Terés-Zubiaga, P. Bouillard, and V. Becue, '"Decarbonizing Europe" a critical review on positive energy districts approaches', Sustain. Cities Soc., vol. 89, p. 104356, Feb. 2023, doi:https://doi.org/10.1016/j.scs.2022.104356.

[5] M. Mattsson, T. Olofsson, L. Lundberg, O. Korda, and G. Nair, 'An exploratory study on Swedish stakeholders' experiences with positive energy districts', Energies, vol. 16, no. 12, p. 4790, Jun. 2023, doi:https://doi.org/10.3390/en16124790.

[6] A. X. Hearn and R. Castaño-Rosa, 'Towards a just energy transition, barriers and opportunities for positive Energy District creation in Spain', Sustainability, vol. 13, no. 16, Art. no. 16, Jan. 2021, doi:https://doi.org/10.3390/su13168698.

[7] JPI Urban Europe, White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods vol. 3, JPI Urban Europe / SET Plan Action, 2020, p. 2.

[8] European Commission, The Strategic Energy Technology Plan—At the Heart of Energy Research and Innovation in Europe, Publication Office of the European Union Luxembourg, 2018.

[9] D. Baer *et al.*, 'Approaches to social innovation in positive energy districts (PEDs)—a comparison of Norwegian projects', Sustainability, vol. 13, no. 13, Art. no. 13, Jan. 2021, doi:https://doi.org/10.3390/su13137362.

[10] S. Bossi, C. Gollner, and S. Theierling, 'Towards 100 positive energy districts in Europe: preliminary data analysis of 61 European cases', Energies, vol. 13, no. 22, Art. no. 22, Jan. 2020, doi:https://doi.org/10.3390/en13226083.

[11] A. X. Hearn, A. Sohre, and P. Burger, 'Innovative but unjust? Analysing the opportunities and justice issues within positive energy districts in Europe', Energy Res. Soc. Sci., vol. 78, p. 102127, Aug. 2021, doi:https://doi.org/10.1016/j.erss.2021.102127.

[12] S. G. Krangsås *et al.*, 'Positive energy districts: identifying challenges and interdependencies', Sustainability, vol. 13, no. 19, Art. no. 19, Jan. 2021, doi: https://doi.org/10.3390/su131910551.

[13] J. Barnes, P. Hansen, T. Kamin, U. Golob, M. Musolino, and A. Nicita, 'Energy communities as demand-side innovators? Assessing the potential of European cases to reduce demand and foster flexibility', Energy Res. Soc. Sci., vol. 93, p. 102848, Nov. 2022, doi:https://doi.org/10.1016/j.erss.2022.102848.

[14] D. Mihailova, I. Schubert, A. L. Martinez-Cruz, A. X. Hearn, and A. Sohre, 'Preferences for configurations of positive energy districts – insights from a discrete choice experiment on Swiss households', Energy Policy, vol. 163, p. 112824, Apr. 2022, doi:https://doi.org/10.1016/j.enpol.2022.112824.

[15] E. Shove, M. Pantzar, M. Watson, The dynamics of social practice: everyday life and how it changes, Dyn. Soc. Pract. (2012) 1–208.

[16] K. Gram-Hanssen, 'Understanding change and continuity in residential energy consumption', J. Consum. Cult., vol. 11, no. 1, pp. 61–78, Mar. 2011, doi: https://doi.org/10.1177/1469540510391725.

[17] T. Hargreaves, C. Wilson, and R. Hauxwell-Baldwin, 'Learning to live in a smart home', Build. Res. Inf., vol. 46, no. 1, pp. 127–139, Jan. 2018, doi:https://doi.org/10.1080/09613218.2017.1286882.

[18] T. Schatzki, Practices and learning, in: P. Grootenboer, C. Edwards-Groves, S. Choy (Eds.), Practice Theory Perspectives on Pedagogy and Education: Praxis, Diversity and Contestation, Singapore, Springer Singapore, 2017, https://doi.org/10.1007/978-981-10-3130-4.

[19] S. P. A. K. Larsen and K. Gram-Hanssen, 'When space heating becomes digitalized: investigating competencies for controlling smart home Technology in the Energy-Efficient Home', Sustainability, vol. 12, no. 15, p. 6031, Jul. 2020, doi:https://doi.org/10.3390/su12156031.

[20] L. V. Madsen, A. R. Hansen, and S. P. A. K. Larsen, 'Embodied competencies and smart home technology in energy use: three ways users integrate smart heating systems in everyday practices', Energ. Effic., vol. 16, no. 6, p. 55, Aug. 2023, doi: https://doi.org/10.1007/s12053-023-10138-0.

[21] A. Warde, 'Consumption and theories of practice', J. Consum. Cult., vol. 5, no. 2, pp. 131–153, Jul. 2005, doi:https://doi.org/10.1177/1469540505053090.

[22] D. D. Furszyfer Del Rio, B. K. Sovacool, and S. Griffiths, 'Culture, energy and climate sustainability, and smart home technologies: a mixed methods comparison of four countries', Energy Clim. Change, vol. 2, p. 100035, Dec. 2021, doi:https://doi.org/10.1016/j.egycc.2021.100035.

[23] Y. Strengers, Smart Energy Technologies in Everyday Life, Palgrave Macmillan UK, London, 2013, https://doi.org/10.1057/9781137267054.

[24] R. Robison *et al.*, 'Shifts in the smart research agenda? 100 priority questions to accelerate sustainable energy futures', J. Clean. Prod., vol. 419, p. 137946, Sep. 2023, doi:https://doi.org/10.1016/j.jclepro.2023.137946.

[25] F. Friis and T. Haunstrup Christensen, 'the challenge of time shifting energy demand practices: Insights from Denmark', Energy Res. Soc. Sci., vol. 19, pp. 124–133, Sep. 2016, doi:https://doi.org/10.1016/j.erss.2016.05.017.

[26] S. Hagejärd, G. Dokter, U. Rahe, and P. Femenías, '"It's never telling me that I'm good!" household experiences of testing a smart home energy management system with a personal threshold on energy use in Sweden', Energy Res. Soc. Sci., vol. 98, p. 103004, Apr. 2023, doi:https://doi.org/10.1016/j.erss.2023.103004.

[27] T. H. Christensen *et al.*, 'The role of competences, engagement, and devices in configuring the impact of prices in energy demand response: findings from three smart energy pilots with households', Energy Policy, vol. 137, p. 111142, Feb. 2020, doi:https://doi.org/10.1016/j.enpol.2019.111142.

[28] I. Røpke, T.H. Christensen, J.O. Jensen, Information and communication technologies – a new round of household electrification, Energy Policy 38 (4) (2010) 1764–1773, https://doi.org/10.1016/j.enpol.2009.11.052.

[29] E. Shove, Comfort, Cleanliness and Convenience, Berg, 2003.

[30] L. K. Aagaard, 'The meaning of convenience in smart home imaginaries: tech industry insights', Build. Cities, vol. 2, no. 1, pp. 568–582, Jun. 2021, doi: https://doi.org/10.5334/bc.93.

[31] Y. Strengers, 'Resource man and the smart wife: implications for sustainability in the home', Interactions, vol. 30, no. 2, pp. 36–40, Mar. 2023, doi:https://doi.org/10.1145/3582566.

[32] T. Hargreaves and L. Middlemiss, 'The importance of social relations in shaping energy demand', Nat. Energy, vol. 5, no. 3, pp. 195–201, Feb. 2020, doi:https://doi.org/10.1038/s41560-020-0553-5.

[33] L. K. Aagaard, T. H. Christensen, and K. Gram-Hanssen, 'My smart home: an auto-ethnography of learning to live with smart technologies', Pers. Ubiquitous Comput., Apr. 2023, doi:https://doi.org/10.1007/s00779-023-01725-0.

[34] D. Nicolini, S. Gherardi, D. Yanow, Introduction: Toward a Practice-Based View of Knowing and Learning in Organizations, 2003.

[35] A. Reckwitz, 'The status of the "material" in theories of culture: from "social structure" to "artefacts"', J. Theory Soc. Behav., vol. 32, no. 2, pp. 195–217, Jun. 2002, doi:https://doi.org/10.1111/1468-5914.00183.

[36] T. Schatzki, 'Materiality and social life', Nat. Cult., vol. 5, no. 2, pp. 123–149, Jun. 2010, doi:https://doi.org/10.3167/nc.2010.050202.

[37] S. Gherardi, How to Conduct a Practice-Based Study: Problems and Methods, Second edition, Edward Elgar Publishing, 2019.

[38] P. Fusch and L. Ness, 'Are We There Yet? Data Saturation in Qualitative Research', *Walden Fac. Staff Publ.*, vol. 20, no. 9, Feb. 2015, [Online]. Available: https://scholarworks.waldenu.edu/facpubs/455.

[39] M. Hennink and B. N. Kaiser, 'Sample sizes for saturation in qualitative research: a systematic review of empirical tests', Soc. Sci. Med., vol. 292, p. 114523, Jan. 2022, doi:https://doi.org/10.1016/j.socscimed.2021.114523.

[40] T. Bjørner (Ed.), *Qualitative Methods for Consumer Research: The Value of the Qualitative Approach in Theory and Practice*, Hans Reitzels Forlag vol. 1, Denmark, Copenhagen, 2015.

[41] M. Moezzi, K. B. Janda, and S. Rotmann, 'Using stories, narratives, and storytelling in energy and climate change research', Energy Res. Soc. Sci., vol. 31, pp. 1–10, Sep. 2017, doi:https://doi.org/10.1016/j.erss.2017.06.034.

[42] L. Stankovic, V. Stankovic, J. Liao, and C. Wilson, 'Measuring the energy intensity of domestic activities from smart meter data', Appl. Energy, vol. 183, pp. 1565–1580, Dec. 2016, doi:https://doi.org/10.1016/j.apenergy.2016.09.087.

[43] S. Pfenninger and I. Staffell, 'Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data', Energy, vol. 114, pp. 1251–1265, Nov. 2016, doi:https://doi.org/10.1016/j.energy.2016.08.060.

[44] M. Hofmann, S. Bjarghov, and S. Nessa, 'Norwegian hourly residential electricity demand data with consumer characteristics during the European energy crisis', Data Brief, vol. 51, p. 109687, Dec. 2023, doi:https://doi.org/10.1016/j.dib.2023.109687.

[45] C. Wilson, T. Hargreaves, and R. Hauxwell-Baldwin, 'Benefits and risks of smart home technologies', Energy Policy, vol. 103, pp. 72–83, Apr. 2017, doi:https://doi.org/10.1016/j.enpol.2016.12.047.

[46] R. K. Jain, R. Gulbinas, J. E. Taylor, and P. J. Culligan, 'Can social influence drive energy savings? Detecting the impact of social influence on the energy consumption behavior of networked users exposed to normative eco-feedback', Energ. Buildings, vol. 66, pp. 119–127, Nov. 2013, doi:https://doi.org/10.1016/j.enbuild.2013.06.029.

[47] A.H. Hansen, et al., Lumen: A case study of designing for sustainable energy communities through ambient feedback, in: In *32nd Australian Conference on Human-Computer Interaction*, ACM, Sydney NSW Australia, Dec. 2020, pp. 724–729, https://doi.org/10.1145/3441000.3441001.

[48] S. Erba and L. Pagliano, 'Combining sufficiency, efficiency and flexibility to achieve positive energy districts targets', Energies, vol. 14, no. 15, Art. no. 15, Jan. 2021, doi:https://doi.org/10.3390/en14154697.