Supporting Solar Energy Coordination among Communities

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The transition to renewable energy is likely to require the creation of growing numbers of energy communities: collectives organized around shared, local renewable resources. Unlike individual households however, the requirements for such communities to share a resource and demand-shift their consumption are still unexplored. By deploying a custom sensor energy monitoring kit and data physicalization workshops with 17 households, we examine the factors that impact their coordination around the shared resource. We found that collective demand-shifting has an extended set of considerations including trade-offs related to privacy, flexibility and social cohesion which are core for navigating already delicate neighborly relations. We use these factors to propose design considerations for a digital system that can act as a mediator among households. Such a system should enable multiple levels of immediacy to account for people's routines, should have adjustable levels of privacy to balance policing and fairness and should be able to offload some of the mundane decision-making. This study moves beyond individual energy consumption behavior to help identify energy as a collective issue that demands collective action. Accordingly, our findings contribute to the development of a next generation of Ubicomp technologies that can support collective action for environmental sustainability.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; **Field studies**; **Empirical studies in ubiquitous and mobile computing**.

Additional Key Words and Phrases: energy communities, coordination, demand-shifting, visualization, sensors, data physicalization

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1 INTRODUCTION

Shifting from fossil fuel to renewable energy sources (such as solar and wind) is recognized as a key priority by governments around the world and by the UN [8, 37]. Such a shift implies a fundamental change from centralized, demand-led grids, which provide energy once requested, to supply-led grids, whose output varies in relation to sources of renewable energy. Supply-led grids may thus require the alignment of household activities such as washing or cooking with energy availability, to avoid exceeding grid capacity. Although technologies such as batteries and other forms of energy storage *may* alleviate these challenges in the long term [46], collective local shifts towards more sustainable consumption practices can reduce the need for such technologies and thus enable a quicker, more affordable and accessible energy transition [7].

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Prior research in Ubicomp and HCI proposed systems to support householders in shifting energy consumption. This work centered around awareness of the available resource [34], nudging towards other time-slots [2, 9] and even partial automation of the decision-making [1, 2]. However, the existing demand-shifting work so far has focused on households shifting to match their own renewable generation, or responding to grid management signals such as time-of-use tariffs. Less attention has been paid to the emerging need for *energy communities* to coordinate around a renewable resource [20, 30, 52] with no work so far, to the best of our knowledge, examining the shared access of a common renewable source. Energy communities are household collectives organized around shared, local renewable energy sources, forming supply-led micro-grids. It is estimated they can play a crucial role in the transition to green energy, to the extent that they may end up producing up to half of the EU's renewable energy by 2050 [7]. Communities sharing a renewable resource, have different needs from individuals and the optimal technique for shifting may not be the most obvious. For instance, if many households shift to the same time-slot where generation is high, their collective consumption may be much higher than the energy availability.

To address this gap, this paper reports on a study designed to focus on energy consumption beyond individual behavior and helps identify energy as a collective issue that thus demands collective action. The study involved the deployment of a Ubicomp sensor kit and a series of workshops. It took place within a urban UK context drawing parallels to how other studies have similarly centered on site-specific settings [53]. Using the sensor kit, 14 households without solar panels, monitored and contextually annotated their electricity consumption for a period of 5-15 days. For the workshops the participants' energy data and annotations were 'physicalized' into cardboard blocks so that participants could collectively interact with them to explore coordination strategies. Our sensor-based study design was built on the premise that by having concrete understanding about their own data, households can engage in more grounded discussions about collective energy use. Moreover, the households we worked with, sensitive to sustainability issues, are potential early-adopters of energy collective schemes thus making their perspectives valuable in the design of future coordinating technologies. Accordingly, this work places itself in what Di Salvo et al. [14] refer to as a formative user study for sustainable HCI that is meant to show how individuals *are embedded in social and cultural systems which constrain the potential sustainability of their behavior.*

Our findings offer evidence that collective demand-shifting has an extended set of considerations beyond those relevant to individual households, as there is an inherent need for coordination among households. Specifically, we uncovered trade-offs related to privacy, flexibility and social cohesion, some of which could potentially be mediated through the design of interactive systems. We discuss our findings and offer a set of design implications including how such a system should enable multiple levels of immediacy to account for people's routines, should have adjustable levels of privacy to balance policing and fairness and should be able to offload some of the mundane decision-making. The main contributions of this work can thus be summarized as: (1) a qualitative study grounded in energy data on how people understand and relate to demand-shifting coordination, (2) implications for the design of technology to support solar coordination, and (3) a methodology based on energy sensing, data annotation and data physicalization to elicit perspectives surrounding solar coordination.

2 LITERATURE REVIEW

This work relates to how eco-feedback can inform collective decision-making regarding energy choices. We thus start by describing some of the most popular means for eco-feedback namely the use of digital and physical energy representations. We then specifically discuss research prototypes that are meant to support demand shifting. Finally, we survey emerging work in HCI which, like this research, examine the collective and social dimensions of energy management.

2.1 Annotating, Visualizing and Physicalizing Energy

Energy is a difficult concept to understand and there is a tendency to regard it as something invisible and abstract [40]. To counter this, various types of visualizations have been used which combined with qualitative interviews, they can encourage a richer examination of domestic practices [17]. Visualizations that represent energy data as part of eco-feedback systems, range from statistical representations to more ambient artistic physicalizations (see [6] for a recent overview). For instance, taking an emotional visualization approach, Watts-Burning [44] visualized household energy consumption using elements of the local landscape, making them seem more burned the higher the consumption. In another approach, FigureEnergy [10] visualized energy consumption as a line graph which could be annotated by participants to disaggregate the different devices they were using. Such an activity-level disaggregation (e.g. identifying washing or meal preparation) has been shown to support better understanding of energy consumption [23] with annotation helping this learning process [10, 35].

To counter the de-materialization [40] of energy, researchers have also experimented with the physicalization of consumption data. Data physicalization, i.e., the physical representation of data [26] is shown to be an accessible way to introduce data to novices [16, 24, 26] and in the context of energy, it is shown to facilitate awareness [11, 36, 45, 55]. For instance, the abstract data sculpture Ecorbis [55] consisting of circular clock-style physicalizations, was deployed within a household to represent the effect of various common household activities on the environment such as transportation and electricity usage. The authors found that the translation of such abstract topics into a tangible and personal artifact facilitates environmental awareness. CairnFORM, an ambient spatial display of (solar) generation data, shape-shifts according to amount of renewable energy available [11]. Similarly, Watt-I-See, an interactive installation that depicts the different levels and types of renewable energy sources onto four vortexes, finds that their encoding of the vortexes' movement and the electricity production increased energy literacy and awareness towards renewables [45]. WattsBurning on My Mailbox [44] took a more participatory approach in which the households themselves assembled magnets that represented their daily consumption on their mailboxes, effectively forcing them to reason about their ecological footprints.

Still, as we also return to in our discussion, eco-feedback systems have been critiqued for their tendency to focus on individuals rather than collectives [56]. Besides representing energy outputs and prompting individual reflection, a few physicalization projects have also aimed to facilitate conversation or discussion around energy. Energy Babble [18], for instance, is a home talk-radio device that sonifies news related to energy and the environment. Its playful character allowed it to act as a research tool that highlighted concerns, beliefs and energy practices within the different energy communities it was deployed in. Tidy Street [51] is another community project in which the energy consumption of different households was drawn with chalk on the public streets, encouraging people to reflect on each other's consumption.

Inspired by these projects and work on participatory physicalization [39] we materialize energy consumption and explicitly encourage the collective negotiation of a renewable resource across households. Accordingly, our study examines the collective dimensions of energy physicalization and additionally uses the physicalisation of real data to ground the still mostly speculative, scenario-driven discussions around energy communities.

2.2 Supporting Energy Demand-shifting

Demand-shifting refers to the alignment of energy consumption to the generation of a renewable energy resource. Some household practices such as laundry and bread-making are in fact much more *shiftable* in comparison to *non-negotiable* practices such as meal preparations [42]. Yet, domestic consumption habits overall are often highly particular to lifestyle, values and the specificity of homes so that what maybe flexible for one household may not be for another [32].

The use of eco-feedback for demand-shifting has been a rich field of HCI and Ubicomp research. To provoke and help households reflect on their washing practices, Jensen et al. designed a prototype they referred to as the ‘Box’ that indicated the availability of renewable energy before participants started their laundry [27]. They found that the feedback provided was successful in making families do their washing when renewable energy was available even though, originally, those same families believed that adapting would be too difficult. Similarly, Rasmussen et al. [48] develop ClockCast, a clock-type physical device that displays the best times to use electricity rather than when not to. They found that even with this overall more positive approach, some participants were still accompanied by feelings of guilt when they do not follow the forecast. Kluckner et al. [34] used a traffic light system of green, yellow, red to indicate the forecast of green energy and grid status. They found that there are ‘zones’ in which shifting occurs, explaining that participants can shift into adjacent colors - not necessarily from red to green. Studying households with solar panels, Bourgeois et al. [2] found that their participants required high-level information such as best shifting time or percentage of green energy over raw energy consumption and generation patterns to help shift laundry and maximize local energy usage. Costanza et al. [9] additionally tested a booking system modeled from a calendar view that took into account the weather forecast to create dynamic pricing of the different laundry slots during the day.

Moreover, the implications of deploying technology for supporting demand-shifting go beyond just energy changes, to also give rise to new social practices such as repeatedly consulting the energy status, or force-spending energy when there is an excess [41].

2.3 Designing for Collective Energy Management

Energy communities are citizen-driven energy actions which generate energy from renewable sources in micro-grids, outside of the main national grid so as to advance local energy efficiency and pursue their individual and collective economic, environmental and social goals [19]. Such communities are considered key actors for achieving a clean energy transition [7]. Accordingly, there is an emerging strand of HCI and Ubicomp research which examines the collective and social dimensions of energy management.

Collaborating with a remote island community in the UK, Simm et al [52] created visualizations that were used to inform and synchronize households’ energy consumption with a renewable energy supply. Similarly, working with housing cooperatives in Sweden, Hasselqvist et al. [21] developed an application that visualized the cooperative’s energy usage and compared it to other cooperatives in the region. They found that by linking community decisions to changes in the data, their visualizations both motivated the cooperative to conserve energy and enabled them to learn from other cooperatives. Dilahunt et al. [13] deployed a social-energy monitoring application in which households in the same community could monitor each other’s real-time energy use. They found that being aware of contextual factors of the other households as well as having opportunities for additional in-person interactions permitted more social engagement around the deployed application. Examining the potential of IoT kits to automate activities in individual households, Salovaara et al. [50] found that the most unexplored uses related to social automation services such as facilitating family members’ agreement on joint household practices (e.g. trash handling) and the use of shared resources (e.g. showers). Wilkins et al. [57] surveyed household reactions to peer-to-peer energy trading to derive design considerations for digital platforms that can support it. They document how peer-to-peer energy trading, i.e. micro-grid collectives that trade energy among themselves, has ecological, economical as well as social benefits for communities. Accordingly, they claim that platforms that are meant to support such trading should provide infrastructure to interact between groups.

Within this strand, we have identified two studies closely related to the present one: Lumen [20] and the Community Energy Planner [30]. The Lumen ambient display aimed to support an energy community in shifting domestic energy-consuming practices to align with times of high availability of sustainable energy [20]. The Community Energy Planner is an eco-feedback app which helped a group of households collaborate and collectively shift around renewable energy [30]. Our work departs from these studies in that we examine the sharing of a single common solar resource among the participating households. In such a case, the resource at

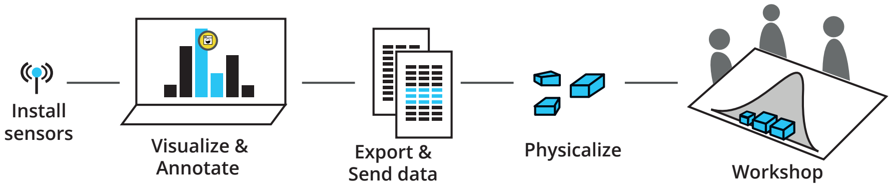
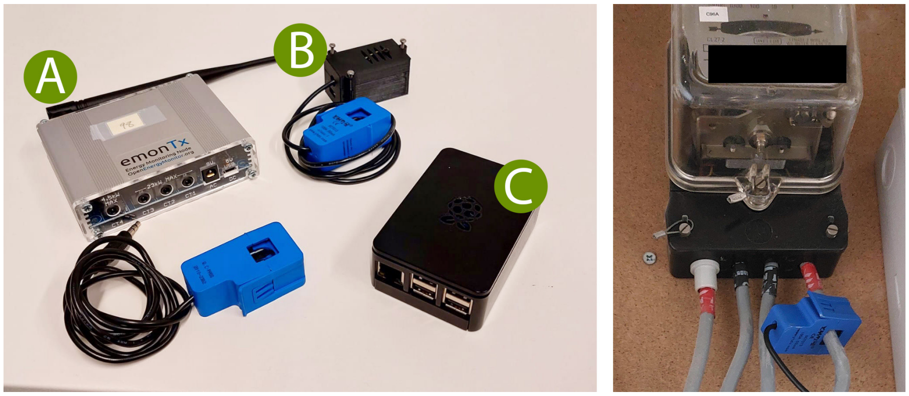


Fig. 1. Process of deployment. During the "Export and Send Data" phase, participants downloaded their annotation and energy consumption data from the annotation interface and shared them with the researchers who prepared the physicalizations.



[redacted]

Fig. 2. Left: Home monitoring sensor kit that included a Raspberry Pi (C) and an OpenEnergyMonitor EmonTx sensor (A). Due to shortages we also custom-soldered a monitoring device based on the same EmonTx design and an Adafruit Feather microcontroller board (B). Right: The clip installed on a participant's meter.

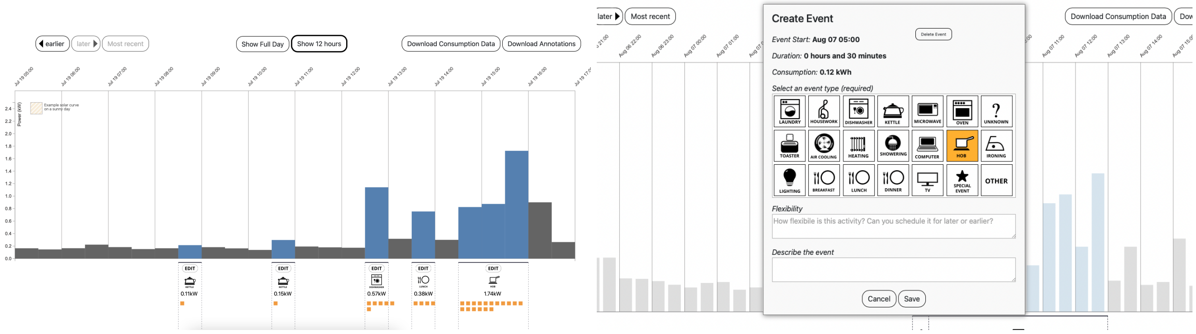
any given time is shared and 'finite' (as it comes from local production) which therefore changes the dynamics among the households.

3 METHOD

Drawing on the Literature Review, we started from the idea that a concrete understanding of participants' own data would allow them to engage in more grounded and less speculative discussions about their collective energy use and actions. Therefore, we developed and deployed a sensor kit and interactive software to enable our experimental approach. A visual overview of the process is presented in Figure 1. The work was approved by our university's ethics commission.

3.1 Process

After getting consent, two researchers visited the participants' homes to install the sensor kit (Figure 2, Section 3.2) and give a short demonstration of the visualization and annotation tool (Figure 3, Section 3.2). We then asked participants to annotate their activities by encouraging them to identify consumption peaks and fluctuations in the interface. When annotating such fluctuations in consumption we also asked participants to document which appliances were used and whether their activity could be shifted in time (Figure 3-right). Each household monitored their energy use for a minimum of 5 days, to a maximum of 15 including a weekend (mean: 8.8, SD: 3.04) and they were asked to annotate at least once a day so as not to forget what the fluctuations in their consumption were referring to. We did not explicitly specify or track which household members took part in the



Event Start: **Aug 07 05:00**

Duration: **0 hours and 30 minutes**

Consumption: **0.12 kWh**

Select an event type (required)

Flexibility

How flexibile is this activity? Can you schedule it for later or earlier?

Describe the event

Fig. 3. Left: Web-paged screenshot from the visualization and annotation interface. This specific instance is from participant H1. Highlighted in blue are the activities that that household has annotated. Right: The annotation screen from which participants select an activity type, add an optional description and note their flexibility for that activity.

Fig. 4. Snapshot from the workshop. Each participant has their own colored blocks that represent the energy consumption of the devices in a busy day in their household. The length of the block represents time (in 30minute intervals) and the height represents average power, so that the total area represents kWh consumed.

annotation process. We expect however that the majority of the annotations were made by the member to which we introduced the annotation interface to.

Following the monitoring phase, the same participants were invited to three workshops in groups of 3-5 (based on participant availability). We invited one participant per household to permit more scheduling flexibility and so as not to overburden each household. Approximately three days before each workshop, we asked them to email us their annotation and consumption data, which could be downloaded from the interface. We then used the EnergyBlocks (Section 3.2) application to create physical representations of this data.

At each 2-hour workshop, we asked participants to consider a scenario where they were sharing a solar installation with the others present. In this scenario, participating households had the opportunity to access cheaper or free electricity when the solar panels were generating. Savings depended on solar generation and total demand among the group: Higher generation coupled with lower collective demand led to greater savings. Households could therefore potentially maximize savings by coordinating their consumption, so as to ensure their total demand stayed as close as possible to solar generation at all times — rather than (for example) all consuming at the same time.

At the workshop, each participant was given blocks corresponding to their most consumption-intensive day with each thus receiving 4-12 blocks (6.68 on average). Typical activities included laundries, dishwashers, ovens, TVs and kettles, although some especially large blocks stood out, representing the charging of an electric vehicle as well as the batch cooking of 2-weeks worth of bread (the large purple block in Figure 4). Participants were then presented with three exercises. First, they were encouraged to place their blocks on a graph curve that represented the energy generation of a day in June (Figure 6-Right). The x-axis of the curve represented time, so the participants needed to place each block on the time they had originally done this activity. Once all blocks where placed, and after reflecting on individual and collective activity patterns, participants were asked to negotiate if and how they could shift their activities so as to maximize their collective use of solar power. They were also asked how they could coordinate such a shift. The same exercise was then repeated for a more sun-constrained day in March which made it even more difficult to fit all activities 'under the solar curve'[1]. The source of the data for both the days in June and March were drawn and scaled down from our partner charity's solar installation. These two specific dates were manually chosen for their potential to encourage an interesting discussion among participants. We contrasted an 'energy abundant' day in June with March, for instance, as a winter cloudy day would not permit almost any meaningful shifting to take place regardless of participant negotiation.

The researchers then presented the BatterySim application (Section 3.2) on a large screen, to get participants to reflect on how a battery might change the situation. This visual simulation used the same generation curve, as the previous activity. Finally, participants were asked some debriefing questions about their overall experience and reflections using the various visualizations and physicalizations of this project.

Due to individual availability, a workshop with three participants who already owned PV (photovoltaic) installations was conducted online, and lasted approximately 1:30h. For these participants, we did not monitor their electricity use as the sensor kit could not track their consumption. Specifically, our clip-based tracking did not work with PV installations because the meter cable in these cases both imported electricity to be consumed from the grid as well as exported excess production of solar energy to the grid. Accordingly, the clip miscalculated the total grid consumption. Instead, in the online workshop we used data prompts, where we asked them to reflect on the same scenario of shared local generation. During this time participants were guided through similar scenarios with the main differences being that (1) their own consumption data was approximated, (2) they only focused on the more constraining solar generation curve from March and (3) we asked them separately to imagine sharing a PV all together as well as with their real-life neighbors. In further two cases (H7, H13) due to the participants' availability we organized individual online interviews. In all online cases we used the collaborative tool Miro to replicate the physicalization and guide the discussion on coordination.

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[1] The full protocol of the workshop is included as supplementary material

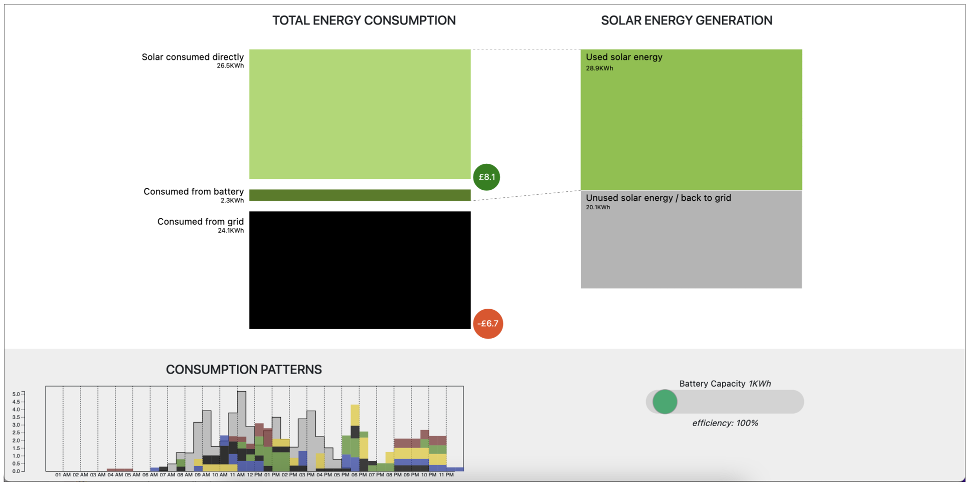

Fig. 5. The BatterySim web application interface which was projected in the workshop on a separate large screen. This specific instance is from Workshop 3.

3.2 Enabling Technology: Sensor Kit and Interactive Software

To allow participants to reflect on the relation between their domestic practices and their electricity consumption, we re-implemented and extended FigureEnergy: an "interactive visualization that allows users to annotate and manipulate a graphical representation of their own electricity consumption data" [10]. We employed open source hardware, the OpenEnergyMonitor EmonTx[2], to measure electricity consumption at the household level. The EmonTx uses a standard current clamp attached to one of the cables coming out of the participant's energy meter (Figure 2-Right). Due to supply shortages for some of the kit we used a simpler and less expensive custom-made device (Figure 2-B), based on the same EmonTx design[3], and an Adafruit Feather microcontroller board[4].

Electricity consumption data was transmitted from the EmonTx every 30s to a Raspberry Pi equipped with a compatible radio module, and stored in an InfluxDB database[5]. The Raspberry Pi was connected to the household's WiFi and configured as a local web server running Node.js. We developed a custom Node.js web application to implement energy visualization and annotation functionality (Figure 3), along the lines of FigureEnergy. However, while the original FigureEnergy system represented data at 2-minute resolution, we chose to work at 30-minute resolution to match the resolution available from most smart meters. Our intention was to explore whether such lower resolution would still enable meaningful reflection, so that in the future smart meter data could be used, removing the need to install a current clamp and making our kit more widely applicable. The web application can only be accessed by computers connected to the household's WiFi, to avoid transferring energy data outside the home (given the potential privacy concerns). Practically, the sensor kit was set up by firstly installing the clip on the household's meter (as in Figure 2-right) and by plugging in the RaspberryPi into a socket nearby. The RaspberryPi was then set up to connect to the household's WiFi at which point anyone on that same network

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[2] https://guide.openenergymonitor.org/technical/emontx/

[3] https://learn.openenergymonitor.org/electricity-monitoring/ct-sensors/interface-with-arduino

[4] https://www.adafruit.com/product/3076

[5] https://www.influxdata.com/products/influxdb-overview/

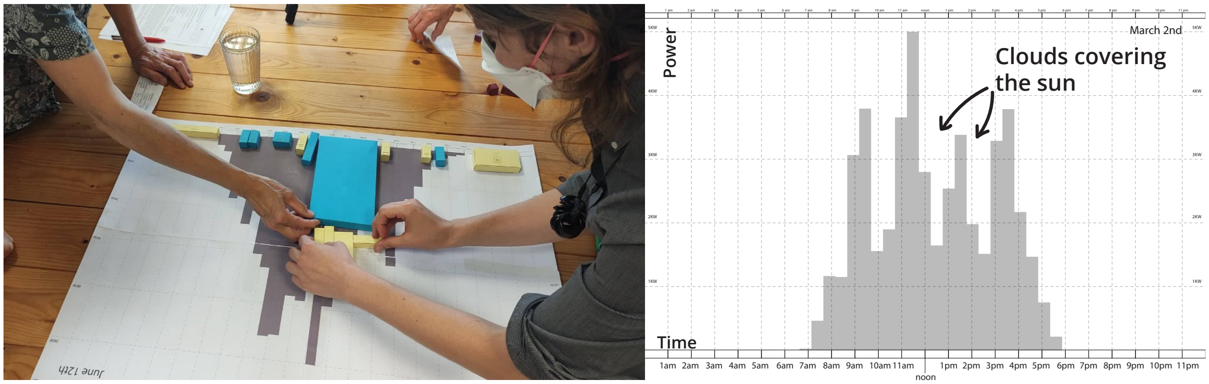

Fig. 6. Left: Snapshot from the workshop. The large blue block represents the electric car charging of one of the participants. Right: A solar generation curve for a sunny day in March. We used this curve and asked participants to align their energy data blocks on it. This way they could easily compare when their collective consumption was going over the generation (out of the curve).

had access to the energy visualization and annotation page. All the software is being released as open source[6]. To enable the workshops we also developed:

- EnergyBlocks: a web application to translate the participant's annotations into unfolded rectangular cuboids on a svg file ready to be lasercut. These physical blocks were designed to be used as data physicalizations in our workshops, to support collective discussion of energy consumption, together with energy generation data curves from solar panels printed out on A1 sheets (Figure 4).
- BatterySim: a web application providing a simple simulation of how a battery could help the workshop participants coordinate their consumption around solar generation. The simulation was based on the participants' energy annotations, and it included a slider to adjust the size of the battery. The output of the simulation was presented during each workshop on a large screen, and it included a visualization of how much solar generation was consumed by participants and how much energy would need to be imported from the grid (Figure 5).

3.3 Recruitment

We recruited participants through the newsletter of a partner energy charity organization[7]. We posted an ad asking participants to contact us if they would like to be part of a research project that explored collective solar energy. In total we recruited 17 individuals, representing 14 non-PV and 3 PV households. There was considerable variation in household composition as can be seen in Table 1 even though there was a skew towards people who were already keen on issues of solar and sustainable energy, as well as towards older/retirement-age, professional backgrounds and two-parent households.

3.4 Analysis

All sessions were video recorded resulting in 8 hours and 48 minutes of material. Video recordings were revisited by the first author to extract snapshots of relevant interaction with the physicalizations. These recordings were then transcribed verbatim and analyzed through thematic analysis [3] by the first author. The first pass generated

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[6] https://github.com/ecostanza/sensor-pi-js

[7] removed for anonymous review

	Ages	Genders	Occupations	Solar	Workshop
H1	55, (60,14)	f, (f,f)	gardener, (retired,-)	no	1
H4	60, (60)	m, (f)	retired, (doctor)	no	1
H5	66	f	not working	no	1
H2	62	f	textile artist	no	2
H10	62	f	operations lead	no	2
H8	47, (45,14,11)	m, (f,f,m)	project manager, (-,-,-)	no	2
H9	57, (58)	m, (m)	artist, (healthcare manager)	no	2
H11	27, (28)	f, (m)	project manager, (association manager)	no	3
H12	44, (34)	m, (f)	IT worker, (IT worker)	no	3
H15	41, (39,13,11,8)	m, (f,f,m,m)	researcher, (teacher, -,-,-)	no	3
H14	59, (61,24)	m	not working, (-,student)	no	3
H6	50+	f	community development	no	3
H3	55, (48, 16, 11)	m, (f,f,m)	senior furniture conservator	yes	4
H16	50s, (50s, teens)	m, (f,f,m)	entrepreneur, (admin,-,-)	yes	4
H17	61	m	systems engineer - retired	yes	4
H7	34, (34,2)	m, (f,f)	engineer, (TV worker,-)	no	(online interview)
H13	59, (57,21,19)	m, (f,m,m)	trainer (journalist, retail, student)	no	(online interview)

Table 1. Participant distribution. Mentioned in brackets are the other household members.

82 codes that were grouped into 13 sub-themes and and 4 themes after discussion with the other authors (see also supplementary material). We coded all related aspects to energy and its perception by participants so as to gain a more contextualized and complimentary picture of our data. Still, the codes were informed by our research focus on coordination and energy communities leading to a more nuanced description of these topics rather than for instance individual perceptions of demand-shifting which have been examined in depth in previous research. For instance, a participant's quote on energy being cheaper at night was coded as such, which together with another 2-3 quotes formed the sub-theme "Energy Preconceptions". Then we grouped this theme under the "Individual Household Practices", as these quotes gave us insight on the individual dimensions of energy usage patterns.

The annotations of the participants where analyzed quantitatively to complement the qualitative data regarding the participants' engagement. Moreover, the open fields of the annotation interface such as the field of 'flexibility' were analyzed qualitatively and quantitatively to understand their patterns of use. Specifically, we extracted the participant responses regarding their flexibility and then manually grouped them in similarity for their level of flexibility.

4 RESULTS

Each of the following subsections reports on one of the four themes that emerged from the qualitative analysis. We also augment the first theme that relates to the participant engagement with quantitative data from the annotation logs.

4.1 Engagement

Annotating. Participants used the sensor kit for 5-15 days and made a total mean of 39.7 annotations (ranging from 14 to 84). The process seemed to be engaging as participants reported using annotations more often and more creatively than we instructed them *"I found it very interesting. You said do it once a day, obviously, I'm on there every half an hour just to see what I've [consumed]"* (H10). It also seemed to have impacted people's understanding of their own consumption patterns. *"having someone monitor and annotate their data for a week gives [..] a really good perspective."* (H15) *"being [..] asked to think about the flexibility of my consumption has made me more inclined to think we could make solar really work."* (H1). Some participants also expressed a wish to repeat the annotation process during the winter months, further demonstrating its perceived value.

Critically, our decision to present data at 30-minute resolution did not seem to discourage annotation or impact activity recognition. Our participants produced on average 4.79 (SD:3.53) annotations per day per household, which is well above the number reported in the original FigureEnergy study [10] (2.56 annotations per day per household), which used 2-minute resolution. Nevertheless, some of the participants with more technical background wanted to examine their consumption data on finer granularity than 30-minute blocks, to reflect on the patterns of consumption that different appliances have. Similar to the original FigureEnergy study [10] some participants commented that the annotation interface made it difficult to differentiate among the various devices that were simultaneously running at any one time.

The 'flexibility information was provided for 336 (60%) of the 557 annotations. In fact, 5 of the 15 participants added flexibility to more than 90% of their annotations, while 2 of the 15 added to less than 10%. For 170 annotations (51% of 336), participants stated they were flexible and for another 34 (10%) somewhat flexible (noting e.g.: "ish", "possibly"). Besides noting 'yes' or 'no', flexibility was expressed through more ambiguous phrasing such as "very flexible/somewhat flexible/possibly/not really/a bit". Precise time was stated only twice (both from H1): *"yes 30-mins either way"* and *"within an hour"*. Many responses also included some justification which was often conditional to other activities: *"Best done in afternoon when grass is driest"* (H4 - referring to lawn mowing) or "*Had to do this before holiday*" (H11 - referring to their laundry).

Physicalization. Participants were very engaged with the physical blocks in the workshop exercises, as their tangibility was overall well received. They mentioned liking the fact that blocks could be easily and collectively manipulated and that they were fun and intuitive. *"I really liked this. I like the fact that we could stack things and and move them around."* (H15). *"I really liked the physicality of the blocks, it was a good idea. For me it really – that taps into the way my brain works."* (H9).

Analyzing the videos of the in-person workshop sessions, we noted multiple moments in which the energy blocks were used to compare or discuss scale of the phenomena they represented. This was evident in how participants pointed, physically compared but also used the blocks to make sense of the data in their conversations. *"that is awe inspiring huge.. and very expensive looking [pointing to the electric vehicle block of H1]"* (H5). *"Actually, this block here cost me… That cost 15p, that block roughly, OK, so it's still cheaper, than going to Starbucks."*(H4).

We also noted many instances of comparisons among the blocks and household energy consumption, even among participants who stated they were skeptical of the accuracy of the blocks. H12 for instance, who directly states that they are conscious of the blocks' inclusion of the base-load consumption, actively compared their TV with those of other participants to inquire about it's model and energy rating. *"Who's gray? What model TV you got? This is ridiculous! [comparing the blocks]"* (H12).

Nevertheless, some commented on the actual necessity to make the blocks three-dimensional as they perceived that this prototyping effort did not offer much to the process. *"You've taken a great amount of time to make 3 dimensional. I don't know if they need to be 3 dimensional.."* (H12).

4.2 Renewables and Individual Household Practices

The energy monitoring and the workshops made participants reflect and question some preconceptions and habits around how they manage their household. For instance two households (H4, H8) documented how they routinely planned their dishwashers overnight even though they were not on a special tariff[8]. H12 similarly explained to have been educated into some less sustainable practices *"I'm left wondering sometimes if my 60 [degrees] wash is just my mother's talk sitting in my head versus the realism of I need to wash my towels at 60."*(H12).

Participants who had smart meters seem to be in agreement that they preferred our annotation interface because it gave them a graphical representation of their consumption over time as well as included a historical overview of what their household was consuming. Most smart meter in-home displays (IHD) instead give live status information and coarse aggregations of a day or a week's time. *"[The monitoring kit] made me more acutely aware of how we're using energy. I suppose it was kind of what I want in my smart meter, or I thought my smart meter was going to do which has been a bit of a disappointment."* (H8). Moreover, given the current energy climate with raising prices in the UK, one participant highlighted how the ability to relate specific activities and their timing to the availability of solar energy, in the workshops, gave a more positive view than typical smart meters, which focused on cost. *"it's a lot more positive than you know what's gonna be going on in everyone's living room, which is the cost. You know, the smart meter just going up and up and not being able to do much about it. This is a positive message. Like 'use it now! It's good!'"* (H7)

As past research has also revealed [2, 27, 42, 48], participants stated that there were only so many activities that could be shifted into hours with renewable energy generation. However, in contrast to previous studies, this study also reflects the impact of two years of living with a pandemic. Many participants now work from home, increasing their ability to shift activities to times of solar availability. As one of the participants, who owns a solar panel, put it:

> *"Before there was a certain amount of hit and miss with going to the office, but working from home allowed much more control and and scheduling of when things would be done and knowing how sunny it was here rather than being based in an office a few miles away, and being able to control when to put the immersion heater on. All these sorts of things you can micromanage by yourself."* (H17).

Still, in the workshop many participants favored convenience over reduced consumption even if they generally self-identified as sustainability-conscious since *"not everybody can just change at the drop of the hat when the sun comes out"* (H5). When translating their energy blocks from kWh into currency they exclaimed how they preferred to pay for the benefits. *"I always want to watch TV at 8:00 PM. There's no solar at that point [so] I'm gonna pay to get the power to run my TV."* (H12). Feelings of inconvenience were also coupled with stress from having to care not only about the availability of solar energy but also about the practices of other people. *"It's.. this is terribly tricky. This is because at the moment we have complete freedom of choice. And by liaising with other people, you're then restricting your freedom of choice. Hmm, and that's the sort of the hurdle to overcome."* (H13).

4.3 Coordinating the Use of a Common Renewable Resource

Past Experiences of Coordination. Participants had first and secondhand experiences of other systems of coordination, many of which were not mediated by tailored digital tools. For instance H12 mentioned how their friends in Switzerland use shared bookable washing machines located at their building's basement. H10 belongs to a street mailing list that shares resources such as hand-tools. H11 coordinates among the neighbors of seven

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[8] We use the term tariff in its British English meaning of an electricity pricing scheme.

flats over things like service charges. H9 spoke of a WhatsApp group they had created with their neighbors to help coordinate the use of the single electric car charging post on the street.

These experiences of coordination had a double effect on the discussion on coordinating the use of a solar panel. On one hand discussions on common laundries came to show that coordination is possible given that there is enough willingness from the participating neighbors. For them, being environmentally-oriented for instance, the need for coordination seemed obvious. On the other hand, this process of coordination was not presented as easy or straightforward for everyone else. As H9 mentions for their electric charging post, *"the house is more personal than the car"*, making them more conscious of the potential problems that can arise from sharing a resource such as electricity.

Coordination Mechanisms. When negotiating the placement of their blocks, participants proposed quite a few types of coordination mechanisms that varied from having allocated time-slots, booking time-slots, or even proposing direct device-to-device coordination. In an allocated time slot for instance, different households might agree to using their larger devices such as laundry and dishwashers different days in a week (workshops 1 and 2) or hour bands (workshop 3). These proposals were the result of trying to take into account the specific conditions of the various individuals in the sessions.

> *"We're gonna set our [timetable] to help our dishwasher or washing machine for example. So alright, you're gonna put your washing on at 11:00 o'clock. That's your slot, and my slot is at 1:00 o'clock."* (H7).
>
> *"I also just think it's more inclusive if we can have so, so we could easily agree really washing Mondays or Tuesdays, Wednesdays and Thursdays, Fridays and Saturdays [pointing at different workshop participants]. So [..] you can have those kind of rules and that could work for kind of maybe any kind of household."* (H1)

Booking slots or bidding were further proposals for coordination. For instance, participants suggested that households could use a calendar with dynamic pricing and 'smart' notifications (workshop 1 and 2), spend a variable number of 'points' to book more desirable time-slots such as weekend mornings (workshop 3), or bid for amounts of kWhs during a day (H7).

> *"But it's the perfect application for machine learning, it could basically say 'hey, [NAME] we noticed you do X, Y, and Z at a certain time, maybe you should move it a half hour to this time because you're more likely to get free energy, all that is readily available to do.' "* (H8).
>
> *"But I do like the idea you mentioned earlier about like you're booking [and] you're spending more of your points on the high demand areas [..] a Friday night might be really high for for certain activities Umm, you know more lights on, cooking or because even having friends over whatever it may be. But like on a Wednesday morning, no one really wants that just because it's Wednesday"* (H15).

More technically savvy participants proposed device-to-device coordination or *'demand sculpting techniques'* (H12) in which the larger household appliances themselves coordinated without the need for intervention from their owners. Such a device-to-device coordination would allow for more detailed timing of the devices as their electricity consumption patterns are not uniform over time even if such technology is only now being developed.

> *"I would like that. I'm happy to submit to the robot overlord, but yeah, if I could just close the dishwasher and I knew it was going to run at the best time, load the washing machine and press on automatic, the same with the electric car, I like the stuff that would be – that's just the way it's going to go."* (H8).

The participants of the second workshop proposed a longer-term progressive learning mechanism using visualizations such as those offered in the workshops. They argued that by collectively looking at their consumption graphs, they can eventually, intuitively learn how to align their consumption without straining neigborly relations. *"I think if you had that real-time view of what other people are doing, it probably could be awkward, but I* *think looking at it more historically saying, this week we did really well, this week we didn't do so well, would be probably less contentious."*(H8).

Automation, Engagement and 'Smartness'. Allowing for more flexibility in engagement was perceived as more inclusive. *"But to have less of that to-ing and fro-ing about the micro consumption feels a bit more inclusive, so that different sorts of households could participate."* (H1). The workshop with the PV owners highlighted how meticulously detailed decision-making on energy consumption is necessary to make the most out of solar energy. Enthusiasm for this level of daily engagement was not shared by all participants. Some stated how *"I've got other things to think about rather than you know when's the best time to use the solar energy"*(H13). Even for one of the households that has solar installed (H16), the expectation was that only one member would be responsible for shifting activities to align with solar or battery availability. Accordingly most participants were in favor of using a digital application for offloading some of the decision making in the coordination process. Firstly because of time-efficiency and urgency household tasks have for them but also interestingly, so as to avoid interpersonal friction.

> *"I could see it getting tense around people coordinating [..], whereas I think if you all agree to it at the beginning that you're going to allow these smart machines to do it for you, you've already agreed to the idea of the machines doing it, so that to me would seem less potentially difficult and fractious."* (H9).

What was being proposed therefore is that a more centralized coordination in which the technology or algorithm served as core facilitator and expert within the system. When asked whether they would trust such a system many participants seemed positive. Still, some participants (H1, H10, H6, H9, H13) were quite skeptical of 'smart' devices, for various reasons, including security (H13) and overall trust in their abilities (H10,H1). H9 also remarked how our workshops made him realize the value of smart devices for the first time. *"It's the first time I've figured out why anyone would want their dishwasher worked off their phone, I remember when we got our dishwasher and there was – you know, 'you can set it up as an app on your phone', I thought that was completely ridiculous, why on earth would you ever want that, and I couldn't understand why."* (H9).

Coordination with a Battery. When shown the BatterySim simulation which included a battery alongside a solar installation and their collective consumption, participants in all of the workshops agreed that the battery helped relax expectations and make coordination more 'casual' (H14, H9), 'flexible' (H2), 'relaxed' (H15) and 'neutral', avoiding 'that terribly British kind of thing [of needing to coordinate]'(H15). *"I suppose the kind of democratic solution to that is the battery, isn't it?"*(H1). *"The thing is actually; it can be a bit more casual. There's, like, you know, there's a battery in there which has got power. So I mean, you know, 'really I should be putting this on now, but actually I will stay in bed for another half an hour, yeah – sod it'. So that's the risk perhaps with it."* (H14). As the previous quote also demonstrates, relaxing such coordination by using a battery also runs the risk of *"making you a bit complacent and not bother to learn quite so much if it was easier."* (H9).

Still, our simulation did not visualize the cost of installing or maintaining a battery. In reality, the size of battery needed to completely iron out conflicts may be prohibitive in terms of both cost and space. This lack of a sense of adequate scale pertaining to such infrastructure was also evidenced in comments comparing it to the National Grid. *"You can depersonalize it, can't you? Yeah. [..] it's just like, it's just a bit like the National Grid, but it's a bit more local."* (H5).

Comparison, Competition & Gamification. Three participants also mentioned experiencing a game-like feeling that the collective coordination introduced. Unlike previous studies [20, 30], however, this was not perceived as something necessarily negative. Participants who claimed to experience a sense of competition also mentioned that they generally enjoyed goal-setting. *"It is quite satisfying to see how you're doing against a target, like a Blue*

Peter fundraising style thing[9]*, so if you know collectively, maybe not individually, but you know collectively how well you're falling within a boundary, maybe that's quite satisfying to see"* (H10). *"If you gave me this graph to follow then I would want to follow it. Does that make sense? It's like that, but that's a part of my personality that isn't all shared with everyone.."* (H7).

Notably negotiating with others during the shifting stage of the workshops participants treated the collective energy consumption as a jigsaw to be solved by rearranging their individual energy blocks. *"I think the physical one [visualization] is good because we can physically manipulate it collectively. [..] here we're doing more of that comparative thing, aren't we? You know, this is what your life looks like and this is what my life looks like and how can we like the fit together?"* (H1)

4.4 Relations to Neighbors and Barriers to Coordination

Fairness, Equity and Accountability. Overall participants seemed reluctant to put strain on what were often already-delicate neighborly relations. And, when asked to consider their current neighbors, they often envisioned coordination producing such strain. As participants noted, unlike recycling, which has no immediate effect on one's neighbors, using shared solar power excessively or out of turn has direct financial implications for the energy community. For instance, people with high-consumption devices such as electric vehicles (H1) or those in the process of purchasing a heat-pump (H8) were very conscious of their potentially outsized consumption needs and the possible impact of such needs on their relationships.

> *"I'd be wary of doing shared solar if I wanted to go down the road of electrification of my house because I'm going to be a big consumer of this, and that could be awkward."* (H8).
>
> *".. putting myself in this situation where we are sharing these panels in the summer, I would definitely be plugging that [the electric vehicle] in middle of the day. Definitely. But in the winter I'd go and plug it into a lamppost charger and charge it overnight somewhere else. I'd make a different decision because we're playing with different resources."* (H1).
>
> *"I was thinking that this might have a really negative effect on the way that we interact with our neighbors. Like we might be like. Ohh. 'You know number 57 is using a lot of power when they shouldn't be let's evict them and let's find someone else who uses less energy'."* (H15).

In order to ensure equitable use, participants proposed a peer-to-peer-style system [57] in which energy could be 'bought' or exchanged within the community to balance out differences in needs that may emerge from unequal household sizes or activity patterns. *"..So you get a fifth, but you don't need a fifth. But I know I need more than a fifth, so yeah, I'd be quite happy to [..] get your extra power off this versus the 50p I'm gonna buy off the power company. [..] Basically sell to me at 10p, and that works out pretty well."* (H12).

The need for dealing with 'free-riders' was also raised in every workshop, although no participant offered any concrete proposals for addressing this challenge. One suggestion was the reframing of potential penalties for abusing the system as 'discounts' for proper use (at 'correct' times of day and/or within allocated slots). This issue also related to what participants often identified as core motivations: to '*tread lightly on the planet*' (H5) or to maximize their energy savings. As they note, while it would be in their interest to use a renewable resource, they could still draw from the grid when they need to.

> *"if he's baking his bread, and then you want to do your washing, it's not the end of the world, it just means somebody is going to spend a few more pence from the grid isn't it? So it's kind of like it's not a massive penalty,[..] it's not awful, and that's probably to do with how much we [..] care about it from an environmental perspective probably more than the money."*

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[9] Blue Peter is a long-running UK television show which introduced a fundraising thermometer to count collected donations.

Privacy. Privacy was a recurring topic that related closely to feeling freedom in making personal choices. Nevertheless, it was a divisive topic. Some participants stood categorically against the possibility of seeing consumption data from each household - wanting only to contribute to and view aggregated data for the collective as a whole. Meanwhile, for others, this was less of an issue. Some participants noted that they were accustomed to living in households that already offered less privacy *"I can hear my neighbors sneeze"* (H1). Others remarked that they were on such good terms with their neighbors that they shared much more personal data than their consumption *"I know their kids' birthdays"* (H7). Reflecting on the community solar, H13 was instinctively against sharing or showing *any* data and mentioned that he would *"find it slightly uncomfortable having a dial say let's say it's a dial on the wall showing me the power consumption across 5 houses in the street, one of which was mine. but you know, damn it, it'll be interesting."* (H13).

The discussion with the participants suggested three levels of aggregation or privacy preservation in data sharing. The most open (least private) entailed sharing at the same level of detail as in the workshop — i.e., sharing which devices were turned on at different times during the day. This was the least popular option, and was brought up only once, when discussing a coordination system that required almost-manual communication among participants. The second involved sharing the total, aggregated consumption of each household without being able to identify different appliances or activities. This was more popular, with participants describing a system where they could track the daily overall consumption of different homes, much like how smart meters currently allow for the live monitoring of individual homes' consumption *"I think human nature you just want to know if it's fair, if we've all put 25 percent of our share to this kind of thing, is it fair if someone consuming 60 percent of it ? [so I would] like to know."* (H8, on whether to show aggregated consumption individually or collectively). Finally, participants also suggested systems where only collective aggregated consumption would be necessary - so as not to be able to differentiate among households and therefore avoid 'policing' (H14). Indicating a similar view, PV owner H16 suggested to only indicate the remaining available solar energy rather than those consumed by the community.

5 DISCUSSION

Eco-feedback systems that are deployed for sustainable management of resources, have been critiqued for focusing on individual behavior change, overlooking the cultural, political and social dimensions of sustainability [5, 15, 41]. They have even been shown to leave participants 'helpless' with a feeling of an 'inability to act' [43]. The approach we presented went beyond the individual management of resources, towards examining how to empower communities to share, utilize and manage a shared solar resource. As Dourish [15] explains, through this work we are not trying to connect people *to* their actions but connect people *through* their actions to support them in their collective endeavors.

Overall, besides confirming previous work on individual attitudes towards energy shifting (e.g. [29, 42]), our findings indicate that in collective settings, participants are not only sensitive to their energy consumption but also to other factors including neighborly relations. Examining the potential for Ubicomp technology to mediate collective coordination in these settings, we find that it is a story of trade-offs. How can we avoid policing and ensure accountability among households without infringing privacy concerns? How to support fair collaboration without damaging delicate social fabric of a neighborly relations? How to bridge among the varying conflicting priorities that people have in their daily lives which often do not involve around energy consumption? But also more practically, how to balance the need for detailed information of energy patterns without overwhelming less energy literate households? We address these questions through implications for design.

5.1 Routines, Flexibility and Lifestyle choices

Our participants were keen to make coordination work and they proposed solutions that suited not only their own interests, but also their whole group. From facilitating immediate shifting for those working from home to longer-term planning for families with children, each workshop concluded with a different coordination mechanism taking into account the peculiarities of each individual. Moreover, participants mentioned how in other societies, similar coordination is already being practiced thus viewing demand-shifting coordination as a matter of 'getting used' to things. Still, echoing past work [9, 29, 56], we also noted how existing energy usage habits shaped expectations and routines that informed how households engaged with energy monitoring and collective-solar scenarios, even as they sought to move beyond a focus on their own resource management. For instance, even our sustainability-sensitive participants mentioned not wanting to give up their cups of tea and TV time, regardless of the lack of solar. Previous studies examining such routines, found that households expected an additional financial incentive to shift to more 'green' hours of the main grid if it meant that they would need to change their existing practices [33]. Extending such prior work, our workshops revealed that such a need to change routines and expectations is further exacerbated when the routines of multiple households need to align as well. While these reactions initially come across as discouraging, the workshop discussions and the annotation data support a somewhat more positive narrative of flexibility where more than half the activities annotated for flexibility were deemed flexible (Section 4.1). This is especially relevant as this annotation was captured in context and relatively close to the time of starting an appliance, rather than in an interview or workshop taking place days or weeks after the fact.

The **implication**, therefore, is that there is potential for digital systems to support shifting among groups of motivated individuals. Based on our findings, the design of such a tool would need to move beyond current IHDs to *offer historical view of the energy consumption and generation data*. Moreover, our analysis of the participant's suggestions surfaced *a need for three levels of planning or immediacy*: (1) immediate action (e.g. notification from the system that *now* is a good time to consume energy), (2) short-term (e.g. booking), and (3) long-term (e.g. permanent dedicated time-slots, or ongoing feedback). These different temporal scales, and their proposed solutions are indicative of the different realities and occasionally conflicting priorities people's daily lives have. One wants to be informed of an immediate opportunity to spend excess energy, can imagine themselves better planning some of their activities but also expect the flexibility and non-policing of their and their neighbors' actions. At the same time, *energy consumption would need to be represented on multiple, interchangeable levels of granularity* in the visualizations. In this deployment, we experimented by using 30-minute bins to represent the consumption data unlike previous work that has been using 2-minute representations. For the most part we found that this was a successful strategy, and unlike other studies where for instance kettles were thought of as the energy intense devices (e.g. [43]), participants here had a more accurate view of the kWh spent overall.

5.2 Privacy in Collective Shifting: Balancing Policing and Fairness

Like individual demand-shifting, collective shifting mostly centers around larger, more programmable devices and less on appliances such as kettles and toasters. Such devices can be tracked, compared and programmed to operate at specific times. To facilitate such responsive shifts, our workshops revealed the need for an interface that could visualize the collective consumption data of all households in the energy community. Indeed, during the workshops participants were excited to see and compare the consumption of their appliances. Previous studies have found that real-time comparison to households with similar profiles (i.e. 'social' or 'normative' comparison) has longer lasting effects on reducing electricity consumption rather than simply providing personal consumption feedback [12]. However, our findings suggest that an interface with as much fidelity as the workshop exercise was seen as potentially infringing on privacy (in contrast to comparing with an aggregated median of similarly profiled households, as in prior work).

Privacy and fear of profiling are evident considerations of households using smart energy technologies [25, 31, 35, 47, 49, 54] — even if households are motivated to share data for various reasons [47]. Our findings demonstrate another, more local dimension of such privacy concerns, pertaining to neighbors. We find that trust in data sharing through a digital system, at a local community scale, directly relates to the in-person interaction opportunities that that local community has. Participants that '*knew their [neighbor] kids' birthdays*' or that already shared personal information with their neighbors were more open to sharing the detailed information of their appliance consumption.

An **implication** for design is that *privacy needs to be adjustable*. There needs to be a design around aggregated versions of the participant's consumption data in interfaces that are meant for wider consumption. Still, to ensure accountability among the community, some disaggregated information over time for each household should be added. As a concrete example, households can choose whether others can just see their events as 'energy blocks' or whether they can see more detail like device type, or if they see anything at all. Another approach would be sharing the activity's flexibility rather purely the energy 'reserved'. Many of the flexibility fields in our annotation interface were filled-in indicating that it was both a useful reflective exercise as well as an easy information point to enter. Moreover, more qualitative, ambiguous wording such as *somewhat flexible, not very flexible*, seemed to capture the nature of their activities best. Signaling flexibility on a larger scale could even be related to financial or other types of incentives – e.g. one could get some form of 'points/credit' by *offering* to shift and even more by *accepting* to shift [38].

5.3 Automation in Energy Collectives

Our participants suggested or expected some form of autonomous technology to mediate the coordination of demand, in such a way that would minimize interaction among households. This is because they approached the possibility of coordinating with neighbors partly through the lens of past experiences, which have at times seemed fragile and held the potential for becoming '*fractious*'. In the past, similar forms of autonomous technology pertaining to domestic energy management have been approached with caution by individual households [49, 57] — for instance, having been found to make it "difficult to understand who's monitoring you and how's it been designed" [57]. Some of our participants presented a different more positive and accepting stance towards autonomous systems. This is perhaps because in our study the benefit of such systems was more easily comprehensible as an alternative to having to manually coordinate with neighbors: automated methods are easier than manual ones as they require less micromanaging of all circumstances. Autonomous or semi-autonomous systems also allow the underlying algorithm to become the driver or decision-maker, thus removing the burden of personal accountability, and helping avoid neighbor conflicts. Nevertheless, it is not clear to what extent these views about the *potential* of automation may correspond to how participants would actually act in relation to an actual automating system. Still, flexible autonomy, in which participants can change the automated decision proposed by an agent, has shown promise for sustaining users' engagement in the longer-term, despite its occasional errors in finding an optimal solution [1]. An **implication** for further research is that there is a needed to empirically test if such flexible autonomy can also work well for solar community coordination. A digital system could thus mediate the relations among neighbors by *partially automating the more mundane and cumbersome parts of coordination* such as recommendations based on availability and forecast.

5.4 Scalability

The EU estimates that energy communities may end up producing up to half of the EU's renewable energy by 2050 [7]. Participants such as those we worked with, are potential early-champions of such collective schemes and whose opinions should be well accounted for in the design of future coordinating technologies. Indeed, past research has consistently documented the negative implications of designing sustainability technologies without user participation (e.g. most recently [28]). Still, while our participants were keen to make coordination work, they were also in consensus that energy communities will be challenging to coordinate outside of groups of like-minded participants like themselves. Having felt that they are already the ‘odd ones out’ in their street or even families, these sustainability-focused participants were excited but wary about the scalability of such solutions. In their view, such an endeavor would require a new level of household micromanaging that only a select few could support, e.g. retired folk, households without children, people who can afford to work from home. Their ‘democratizing’ suggestions mostly included the addition of energy storage so that an energy community can act like “a bit more local" version of “the National Grid" and make energy consumption more “casual". This tension between micromanagement and inaction is an interesting one to unpack when deciding to design technologies that are meant to support diverse communities. Such reactions moreover, further demonstrate the potential for technologies such as semi-automated interactive systems and batteries to help act as mediators.

An important **implication** of our findings around “accountability” (Section 4.4), then, is that for coordination to work *at a larger scale*, it might be necessary to think about solutions that rely on *policy*, in addition to interactive Ubicomp technology. Comments about ‘free-riders’ and ‘discounts’, for example, remind us of the kind of financial incentives and penalties linked to dynamic energy pricing (a product of policy), as it has been advocated in the energy literature [22] as early as the 1970s.

5.5 Reflection on Method: Energy Meets Data Literacy

Our sensor-based research method included two stages. Households ‘learned’ about their own consumption, and honed their energy ‘awareness’ [52] through individual annotations before they were brought together with other households to understand their collective data. We find that this first step was essential for focusing and informing discussion in the workshops. As previous research has shown, it is the coupling of data to concrete activities that informs literacy around energy topics [21]. Participants reflecting on their data during the workshops, often remarked that *“this was not a typical day"* for them. This disassociation of how people *believe* they act versus how they actually act is well documented in HCI. Using real data sources elicited more honest, contextual and situated narratives from the participants, making their responses more indicative of the messiness in daily life.

At the same time, the physicalization of the annotations brought the data up close and personal and demonstrated how energy has a shape not just an abstract quantity. Physicalization provided a memento [40] - a personal artifact that one could form attachments to and manipulate. Pierce and Paulos [40] name this behavior as energy attunement, *an experiential materialized presence of energy that invites focal engagement.* Research in the Netherlands [4] has shown that energy literacy among households, i.e. their awareness and decision-making capability regarding their electricity and gas consumption, is low. By using device annotation and physicalization we are bringing the benefits of constructivist teaching associated with tangible tokens [24] to the problem of improving energy literacy.

6 CONCLUSION

This work examined how a community of households might plan and coordinate their electricity use to make the most of a shared renewable energy source, specifically a solar panel installation. By deploying a custom sensor energy monitoring system and then organizing data physicalization workshops, we found that collective demand-shifting has an extended set of considerations such as trade-offs related to privacy, flexibility and social cohesion among neighbors. Using our rich findings, we proposed a set of design considerations for a semi-autonomous interactive system that can help mediate solar energy coordination among energy communities, which are expected to play an important role in climate change mitigation [7].

More in general, our findings demonstrate the potential of sensor-based technology to help understand the relation between everyday practices and resources consumption, beyond *individual* eco-feedback. Hence, they contribute to the development of a next generation of Ubicomp technologies that can support collective action for environmental sustainability. Given the importance and urgency of the current climate crisis, we hope this work will encourage others in the IMWUT community to further investigate this line of work.

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