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Household carbon caps and tariffs: A living lab experiment

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ABSTRACT

Transnational efforts to combat climate change are intensifying, with Germany targeting net-zero emissions by 2045. The residential sector is a significant CO_2 emitter but lacks direct mitigation strategies, such as personal carbon budgeting and trading, which are common in industry. Although theoretical research on personal carbon trading exists, real-world household-level studies are scarce. This study addresses that gap by examining the implementation of household carbon caps and tariffs in a living lab experiment. Conducted in the Energy Smart Home Lab, the experiment involved three households under weekly carbon caps, with the option to purchase additional allowances under two different tariffs. In two households, photovoltaic feed-in was accounted for to incentivize load shifting and maximize self-consumption. Additionally, participants were encouraged through economic and non-economic incentives to adhere to a 2 kW power limit during simulated grid congestion. Real-time energy consumption monitoring and weekly interviews provided insights into how participants responded to the imposed carbon limits and power restrictions. Essential household activities, such as cooking and heating, occasionally took precedence over economic motivations, leading to breaches of the power limit. As weekly carbon emission caps were reduced by 45 % to 75 % by the end of the intervention, participants faced substantial challenges, compounded by unmodifiable appliance emissions and external pressures like exams. Although limited in sample size, this study is the first to combine carbon caps, tariffs, real-time feedback, and photovoltaic-based incentives in a living lab setting.

1. Introduction

Despite adopting multiple climate policies, most countries in the European Union still lack behind the ambitions to reach net-zero emissions by 2050 [1]. In 2023, the global average surface temperature already reached about 1.2 °C above pre-industrial levels, however, net zero targets may still be achieved, as more and more countries implement clean energy policies [2]. Carbon pricing remains a key mitigation strategy. The EU Emission Trading Scheme (EU-ETS), launched in 2005, covers the energy, manufacturing, and aviation sectors, accounting for 40 % of overall emissions [3]. The EU-ETS2 coming in 2027 will extend coverage to buildings, road transport and small industries [4].

While central to climate policy, instruments like the EU-ETS and carbon taxes often fail to engage individuals directly in emission reduction efforts [5]. The inclusion of buildings and transport in the EU-ETS2 brings it closer to the individual level, yet its upstream, market-based mechanisms remains abstract [5]. Carbon taxes impact consumer behavior directly by increasing the cost of fossil fuel-based goods and services but show mixed results in the residential sector. In countries with high tax rates, such as Sweden and Finland, household emissions dropped significantly [6]. In other countries, e.g., Canada, the emissions reduction was not that high [5]. The carbon tax, is often hidden within the price, thus limiting consumers' awareness of the carbon price [5]. Moreover, carbon taxes lack a specific carbon cap, and their social acceptability remains contested, particularly if revenues are not redistributed to protect low-income households that bear a disproportionate burden [7–9]. Many consumers remain unaware of the carbon pricing embedded in costs, weakening their motivational effect [5].

To engage individuals more transparently, personal carbon trading (PCT) schemes offer a more tangible approach by directly linking individual actions to emissions [10]. Scientific literature suggests that direct and visible incentives can support behavioral changes to reduce carbon emissions [11,12]. Parag et al. [13] argue that PCT schemes combine economic, psychological, and social mechanisms that create synergies to foster low-carbon behavior. Carbon prices become more visible, carbon budgeting fosters awareness, and shared emissions targets can cultivate

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collective norms [5,10,13]. PCTs also promise greater fairness: low-income households tend to emit less and could financially benefit from trading surplus allowances [14–17]. However, higher income households may be able to pay off their high emission lifestyle, therefore, a trading limit is suggested [16]. Considering these conceptual foundations and existing policy limitations, our study aims to empirically explore how households respond to a digital PCT scheme applied to residential energy use. Specifically, we examine (1) the effects of carbon caps on energy demand behavior, (2) the influence of automated allowance pricing mechanisms, and (3) how participants engage with additional incentive signals for load shifting or shedding in response to grid congestion.

While PCTs have been discussed since the early 2000s, early policy efforts (e.g., in the UK) were abandoned due to concerns over public acceptability[1], technological hurdles, high implementation costs, and complexity [13,19–21]. A 2014 German study echoed these concerns, citing fragmented policy landscapes and challenges in accounting for indirect emissions [22]. Yet, with increasing climate urgency, interest in PCTs is resurfacing [10,23–27]. Alongside political commitments, public support for ambitious climate action has grown, as seen by the global rise of youth-led initiatives like the Fridays for Future movement and climate strikes [28]. The COVID-19 pandemic also revealed a surprising willingness to accept personal restrictions and digital tracking for collective benefit [10]. Moreover, the pandemic accelerated acceptance of contact tracing apps introduced in multiple countries, which could inform the design of applications for tracking personal carbon emissions [10,29,30]. Current policies like the EU-ETS present additional complexities, potentially leading to double-pricing of emissions when overlaid with PCT schemes [11,22]. Nevertheless, the integration of diverse policy instruments to address environmental challenges is a well-established practice, though incorporating a radical, untested policy like PCT into existing frameworks remains risky and challenging for policymakers [10,31,32]. Furthermore, recent advances in digitalization and AI promise to reduce administrative costs associated with PCTs, while improving personalized feedback, information, and user engagement [33–35].

Since not much is known about the impact of PCT schemes on household energy demand behavior, we conducted three consecutive interventions in a living lab in Karlsruhe, Germany, from spring 2023 to summer 2024. In this setting, we tested a PCT scheme that we called household carbon caps and tariffs (HCCT) that allocated weekly free allowances as a weekly decreasing carbon cap to a household of two participants, accounting for heating and residential electricity consumption. With this in mind, we formulated our first research question:

RQ1. What are the potential impacts of HCCT schemes on energy demand behavior when implemented in a residential setting?

The HCCT scheme included an automated purchase option for additional allowances once the weekly cap was exceeded, allowing us to test two different purchase tariffs and address our second research question:

RQ2. How do allowance allocation and trading mechanisms influence household behavior towards energy usage?

Given that future low-carbon energy systems may combine carbon price signals with incentives to respond to critical grid states, such as grid congestion, we also incorporated these incentives to better understand the interdependencies between multiple signals. This approach allowed us to examine our third research question:

RQ3. How do participants interact with incentives to offer load shifting or shedding behavior, while also accounting for the PCT scheme?

[1] Here, the term "acceptability" is used instead of "acceptance" because the discussion about PCT is still a theoretical one [18].

While prior pilots such as CRAGs in the UK, NICHE in Australia, and CitiCAP in Finland laid important groundwork for personal carbon trading, they also faced key limitations that our study seeks to address. CRAGs relied on manual tracking and self-reported data, with little automation [36]. NICHE lacked real-time feedback, limiting participant responsiveness [37]. CitiCAP focused on urban mobility and did not extend their scope to residential energy use [38].

Our HCCT scheme addresses these limitations by targeting residential electricity and heating, using continuous real-time feedback and digital carbon budgeting. Participants received weekly caps, real-time updates, and automatic allowance purchases if caps were exceeded. Instead of full trading, we tested two fixed pricing schemes to assess behavioral responses. The inclusion of photovoltaic (PV) generation and dynamic incentives for grid congestion enables a nuanced analysis of how households navigate complex incentive structures. By answering the three research questions, this study offers new insights into the behavioral and technical feasibility of PCT-like schemes in everyday residential settings.

The remainder of this study is structured as follows: Section 2 presents the theoretical background, followed by the methodological approach in Section 3. The results are detailed in Section 4, and discussed in Section 5. A conclusion and outlook are given in Section 6.

2. Theoretical background

The following provides a more detailed overview of PCT concepts, variations, and real-world pilots to frame the theoretical foundations of the HCCT approach used in this study. Personal Carbon Trading (PCT) refers to downstream cap-and-trade approaches that assign individuals a carbon allowance for activities like household energy use and personal travel, linking personal behavior to national climate goals [39]. First introduced as "Domestic Tradable Quotas" in the 1990s, PCT has also been referred to using terms such as tradable energy quotas, personal carbon allocation, personal carbon budget, CO_2 budgets, carbon budgets, emission allowances, and emission trading [10,17,40–47]. Despite the variety of terms used to describe PCT, the literature broadly agrees on several core characteristics. Emissions caps, surrender of allowances for carbon-intensive actions, and optional trading mechanisms within a declining emissions cap [39,48].

There is no single definition of PCT. Designs vary in population coverage and emissions scope, ranging from household energy use to personal travel or consumption products. Schemes also differ in the rules for allocating, surrendering, and trading allowances, and in how actively individuals are expected to engage with the system. Some proposals stress mandatory participation as a requirement for effectiveness, while others allow for voluntary engagement or a choice between PCT and carbon taxation [39]. This diversity suggests that PCT is best understood as a conceptual family of carbon accountability tools rather than a single policy model.

While related tools like carbon labelling or personal carbon allowances focus on awareness or fixed caps without trading, PCT uniquely combines capping, allowance allocation, and the option to trade surplus units, making it a more comprehensive market-based approach to individual carbon accountability [44].

The HCCT scheme used in this study shares key elements with PCT, namely emissions caps and pricing signals, but applies them at the household level without trading. Instead of a trading mechanism, it incorporates a two-tiered tariff system for cap exceedance alongside incentives for energy demand flexibility. As such, HCCT can be viewed as a foundational or early-stage implementation aligned with the broader principles of PCT.

Over the past two decades, PCT schemes have been explored as viable policy proposals in various countries, examining their potential to integrate with existing environmental strategies and their impact on national carbon reduction goals. A complete overview of historical PCT policy proposals and design variants can be found in Appendix A

(Table A1). Despite most of these policy proposals underlining the fostering of visibility and greater awareness on personal carbon emissions by PCTs, most raise concerns about public acceptability [49] and the costs of implementation [22], or in general describe PCT as a concept ahead of its time [50]. However, most also call for pilots to test PCTs in real-world interventions [5,10,22,41,50].

The first policy investigations related to personal carbon accountability to have departed the theoretical stage have emerged in China and other countries (see Table 1). While these initiatives do not represent full implementations of PCT as defined above, they mark a departure from purely theoretical discussions by operationalizing core elements of individual-level carbon responsibility. Most of these initiatives are better classified as carbon labelling or personal carbon allowance models. They do not impose hard carbon caps or require allowance surrender and thus fall outside a strict definition of PCT. However, they embody key mechanisms such as carbon tracking, visibility of individual emissions, and behavior-oriented incentives, making them important early steps in the broader development of downstream carbon accountability tools. From this perspective, they can be seen as foundational or precursor models that align with the broader conceptual scope of PCT. A smaller number of pilot studies, shown in the second half of Table 1, move closer to full PCT schemes by incorporating baseline emissions measurements and defined reduction targets. These studies vary in their experimental design, such as the details of the PCT scheme, the duration, the sample size, as well as where they have been deployed.

The first early volunteer scheme was established by Carbon Rationing Action Groups (CRAGs) in the UK, which counted 21 groups in 2010 [48], with most having since ended [24]. The Norfolk Island Carbon and Health Evaluation (NICHE) pilot in Australia, introduced a voluntary PCT scheme, starting with baseline surveys in 2012 [51,52], followed by 15-month trial period from April 2013 to June 2014, with 218 participating households (486 people) [37]. For the NICHE study, real-time data transmission of the participants' emissions was not possible due to poor internet connection on the island, so that banking and trading of allowances were waived [52].

These pilot programs illustrate both the promise and the practical challenges of operationalizing individual carbon accountability. For instance, the Norfolk Island Carbon and Health Evaluation (NICHE) in Australia faced infrastructure limitations that prevented real-time feedback or trading of emission allowances [37]. Both pilots, NICHE and CitiCAP saw significant reduction in participants, mainly due to economic downturn and the COVID-19 pandemic, respectively [37,62]. Despite these issues, these pilots provide valuable groundwork and highlight the importance of testing different configurations of incentives, data transparency, and engagement strategies. More detailed information on the design frameworks, baseline conditions, and emission reduction targets of these pilots is provided in Table A2 in Appendix A.

Building on these precedents, our study introduces a highly controlled experimental design to directly address key research questions concerning the implementation and effectiveness of PCT schemes in residential settings. Our research aims to clarify the potential impacts of PCT schemes on household energy demand behavior (RQ1), investigate the influence of allowance allocation and trading mechanisms on

Table 1
Characteristics of the first pilots investigating or implementing personal carbon accountability schemes.

Project	Year	Country	Scope	Addressees	Communication with participants	Sample size	Real-time feedback	Emission data	Ref.
Real-world personal carbon accountability schemes									
Carbon Generalized System of Preferences	2015-now	China	Consumption-related goods and services such as clothing, food, water conservation, household energy, and travel	Per capita	App-based	Large (Multiple cities and provinces)	Yes	Financial transactions	[24,53]
Credit card	2011-now	South Korea	Consumption products, household energy, transport	Per capita	App-based	15 million credit cards (55 % of the economic active population)	Yes	Financial transactions	[54–56]
Doconomy Credit card	2018	Sweden	Carbon emission purchase tracking	Per capita	App-based	No information disclosed	Yes	Financial transactions	[57–59]
Commons app	2019	California, US	Carbon emission purchase tracking	Per capita	App-based		Yes	Financial transactions	[60,61]
Pilot studies on PCT schemes									
Carbon Rationing Action Groups (CRAGs)	2000–2010	UK	Household energy, personal travel	Per capita (50 %)	Offline and self-assessed	21 groups with 8–12 people; overall approximately 200–300 people	No	Own computations, agreed conversion factors, or one person per group	[48]
Norfolk Island Carbon and Health Evaluation (NICHE)	2012–2014	Australia	Household energy, personal transport	Household	Website (fuel purchases), e-mail (household energy consumption) every 3 months	486 people (218 households)	No	NICHE carbon card (fuel); utilities (energy consumption)	[37,51,52]
CitiCAP	2018–2021	Finland	Urban mobility	Per capita	App-based	350 at the beginning, 47 final surveys	Yes	Mobility traced by phone acceleration sensor	[38]
Energy Smart Home Lab	2023–2024	Germany	Household energy	Household	Tablet	3 households (6 people)	Yes	Real-time energy measurements	This study

household energy use (RQ2), and analyze the interaction between participants and multiple incentive structures within a PCT framework, including critical responses to grid congestion (RQ3). The study investigates how households engage with a scheme that integrates both economic and psychological mechanisms to influence energy behavior

- real-time feedback on emissions,
- transparent allocation and conversion of carbon allowances,
- high allowance prices,
- alongside automated purchasing for cap exceedance,
- two different tariffs for allowance purchasing,
- the inclusion of PV generation into the households' energy balance,
- and (non-)economic incentives for load shifting and shedding during grid congestion

and thus, offers fresh perspectives on the adaptability and behavioral response to complex incentive schemes. These elements are crucial for understanding how multi-faceted incentives can be structured to effectively reduce energy consumption and manage load within a smart home environment, providing valuable data on the feasibility of scaling PCT systems in the residential sector. The highly controlled environment of the Energy Smart Home Lab allows for a detailed examination of these dynamics, ensuring precise measurement of energy use and participant behavior in response to the PCT scheme. This study contributes new evidence on the behavioral, technical, and economic feasibility of adapting PCT principles to everyday household settings, with an emphasis on how complex incentive structures can shape energy use in real time.

3. Method

This chapter details the experimental setup, the design of the interventions, and the methods to assess participant interaction with the implemented carbon budgets and grid congestion scenarios in the Energy Smart Home Lab.

3.1. The Energy Smart Home Lab

The Energy Smart Home Lab, established in 2010 at the Campus South of the Karlsruhe Institute of Technology, blends the elements of a modern apartment and a smart home within a living lab environment. Equipped with programmable appliances such as oven and dishwasher, and a real-time energy monitoring panel, the Energy Smart Home Lab features advanced energy technologies including a 4.7 kW peak PV panel, a heat pump, and a comprehensive sensor and measurement system for detailed electricity and heat monitoring, as presented in Fig. 1. Furthermore, Fig. 1 illustrates the physical layout of the living lab alongside a zoom-in of the graphical user interface illustrating exemplary two incentive mechanisms: a carbon budget with financial penalties for excess emissions, and a grid bottleneck alert encouraging reduced electricity use during specific time windows. The visualization provided participants with immediate insights into their performance, helping them align daily routines (e.g., cooking, heating) with both CO_2 caps and grid signals.

Two persons can live in the Energy Smart Home Lab for multiple weeks up to three months, interacting with various incentives via a tablet with web-interface that provides real-time data on energy use and feedback on energy-saving incentives. Although its small sample size limits demographic representation, the lab is ideal for pioneering and testing early-stage household carbon caps and tariffs (HCCT) schemes and other innovative concepts in a controlled setting. Further details about the Energy Smart Home Lab are available in references [35,63].

Due to the complexity of the intervention and the infrastructure of the Energy Smart Home Lab, the study was limited to a sample of three households. The smart home can accommodate one household (with up to two tenants) at a time. Each intervention requires a full technical setup and participant onboarding. As such, interventions must be conducted sequentially, therefore, only one to two studies can realistically be scheduled per year. Table 2 provides an overview of key socio-demographic characteristics and pre-existing relationships within the participating households. The participants of HH1 did not know each other beforehand but were introduced prior to confirming their participation in the intervention.

While the small sample limits generalizability, the Living Lab provides a highly controlled environment with continuous real-time monitoring and detailed behavioral tracking. This allows for in-depth analysis of participant responses to the HCCT scheme and offers valuable insights into its design and feasibility in residential settings. This study is therefore framed as an exploratory pilot that prioritizes behavioral depth and experimental control over sample size, with the

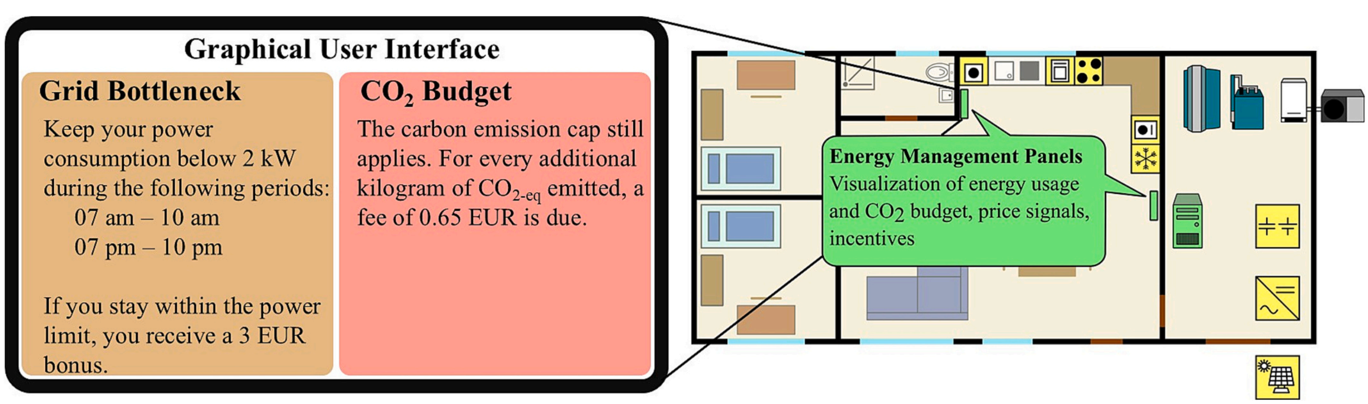

Fig. 1. Layout of the Energy Smart Home Lab and zoom into the graphical user interface.

Table 2
Household characteristics.

Household	Age	Occupation	Relationship	Smart technology experience
HH1	25–35	Student, employee	Acquaintances	No information
HH2	25–35	Student, student	Friends	No, yes
HH3	25–35	Employee, employee	Couple	Yes

aim of testing the feasibility and conceptual design of the HCCT scheme under real-world conditions. This approach aligns with previous small-N living lab studies in energy research, which have likewise employed highly instrumented environments to investigate early-stage behavioral responses to innovative electricity tariffs and energy policies [63–65]. More information about participant recruitment and selection, as well as their socio-demographic characteristics can be found in Appendix B and Appendix C.

3.2. Intervention setup

The study was divided into interventions with three households, each designed to evaluate the impacts of HCCT within a household setting from March 2023 to June 2024. Participants were provided accommodation free of charge and were not university employees. All signed data privacy agreements to ensure confidentiality.

The interventions involved carbon emission caps, grid congestion scenarios, weekly semi-structured interviews, and a final survey to assess participants' responses to the HCCT scheme, as outlined in Table 3. The interviews were conducted to gather qualitative feedback on participants' experiences, challenges, and behavioral adaptations to the HCCT scheme [66]. A survey at the end of the intervention was conducted to capture final feedback from the participants. More information on the interview and survey methods can be found in Appendix D. See Appendix H–Appendix K for the interview and survey protocols.

Carbon caps targeted household heating and electricity demand, excluding personal travel. Further information why we chose household allocation instead of per capita allocation is detailed in Appendix F. When the cap was exceeded, the system prompted the purchase of additional allowances, with a dashboard providing weekly budget updates and real-time feedback on carbon emissions. Fig. 2 presents how the weekly cap and the real-time feedback on emitted $CO_{2\text{-eq}}$ by electricity and heat consumption was visualized on the dashboard.

Up to two grid congestion scenarios per week were communicated through the dashboard, with updates loaded at midnight for planning the next day. The study aimed to understand participant behavior under these combined carbon pricing and grid management scenarios. Appendix E details how we measured and cleaned the energy consumption data for further analysis.

3.3. Household carbon caps and tariffs schemes

The study explored HCCT schemes through a reference week to measure participants' standard energy use, followed by testing monetary penalties for exceeding caps. The overall emissions EM_{CO_2} in $kg_{CO2\text{-eq}}$ were computed based on the thermal and electricity consumption E_{th} and E_{el} multiplied with their respective emission factors, as Eq. (1) shows.

$$EM_{CO_2} = E_{el}*EMF_{el,DE} + E_{th}*EMF_{th,DE} \quad (1)$$

EM_{CO_2} Total emissions in $kg_{CO2\text{-eq}}$
E_{el} Electricity consumption in kWh_{el}
E_{th} Thermal energy consumption kWh_{th}
$EMF_{el,DE}$ Emission factor for electricity consumption in $kg_{CO2\text{-eq}}/kWh_{el}$
$EMF_{th,DE}$ Emission factor for thermal energy consumption $kg_{CO2\text{-eq}}/kWh_{th}$

The electricity consumption was obtained by accounting for the household's overall electricity consumption, which was tracked by an electricity meter. The electricity consumption E_{el} was then multiplied with an emission factor $EMF_{el,DE}$ (0.485 $kg_{CO2\text{-eq}}$ per kWh_{el} - average emission factor of the German electricity mix in 2021 [67]) to get the caused carbon emission equivalents. For the thermal energy demand, we must distinguish between heating and cooling. For the heating demand, we measured the thermal energy E_{th} produced by the heat source with a heat meter and calculated the emissions with an emission factor $EMF_{th,DE}$ that represents the German heating average with 0.25 $kg_{CO2\text{-eq}}$ per kWh_{th} which is still dominated by gas and oil heating systems [68]. In week 4 to 5 of HH1, a correction factor of 0.6 was added because we registered tremendous heat losses from the warm water storage which resulted in a high heating demand that the participants had no influence on. The emissions for the cooling demand were calculated by considering the electricity consumption of the air conditioning and the same emissions factor as for the electricity demand.

Based on findings by Niemeier et al. [49], that receiving money does not change behavior as much as penalties, we did not provide monetary rewards to under-emitters but instead tested two monetary penalties. After a reference week, participants received a carbon budget with no monetary incentives, allowing them to adjust to monitoring their emissions, testing whether the budget itself encouraged them to act, while still providing a buffer for a positive initial experience. All tenants received a 30 EUR credit at the beginning of the incentive intervention, so that the tariffs would not be subtracted from private finances. Depending on their interaction with the cap and the grid congestion scenarios, they could earn compensation or would have to pay a respective fee, thus adding or subtracting from their bonus. In the following weeks, we tested two monetary incentives. The first one included a fee (0.65 EUR/$kg_{CO2\text{-eq}}$) for emissions exceeding the weekly cap. The second, a bulk tariff, automatically purchased an additional five kilograms of carbon allowances for 3.25 EUR if the cap was exceeded. The tariffs were determined by multiplying the EU-ETS average price by a factor of ten to ensure a tangible behavioral incentive, following recommendations in the literature [69]. No separate pilot testing or participant feedback was used to set the tariffs. Values were chosen to align with similar personal carbon trading schemes and social cost of carbon estimates reported in prior studies [38,70]. More information on how we deducted the carbon price is detailed in Appendix G.

Fig. 3 displays the weekly carbon budgets and incentives for all households. Each household started with one reference week without incentives to acclimate participants to the environment. HH2 included two reference weeks due to initially high energy consumption, which did not repeat in the second week, leading to a slightly higher but stable

Table 3
Process of the interventions, showing the scheduling of caps, congestion scenarios, interviews and the survey.

Household	Intervention method	Week 1	2	3	4	5	6	7	8	9
1	Cap in $kg_{CO2\text{-eq}}$	Ref.	60	40	40	25	20	15	No cap	10
	# Congestion scenarios			1	1			1	1	
2	Cap in $kg_{CO2\text{-eq}}$	Ref.		55	50	40	No cap	30	30	
	# Congestion scenarios							2	2	
3	Cap in $kg_{CO2\text{-eq}}$	Ref.	55	30	40	30	15	15		
	# Congestion scenarios				2	2	2	2		
	Interviews	Short interviews once a week							In-depth interview	
	Survey								After the experiment	

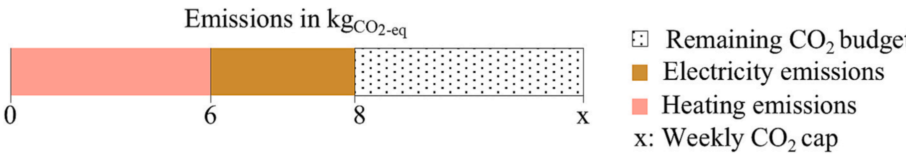

Fig. 2. Visualization of the weekly cap, as well as real-time feedback of the cumulative electricity and heating emissions over the course of the week.

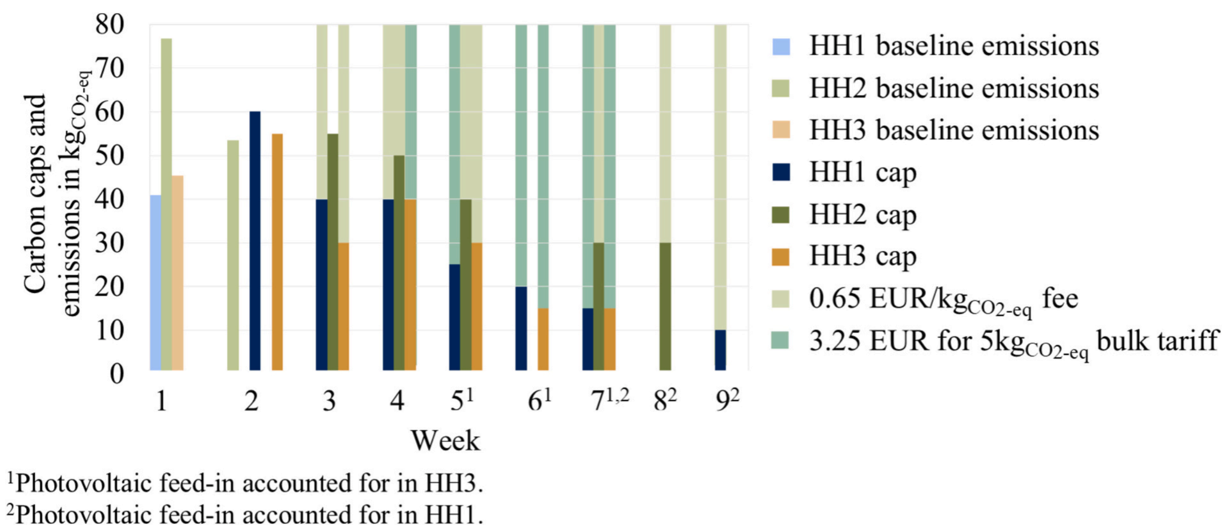

Fig. 3. Carbon caps and cap exceedance tariffs.

consumption level that set the baseline for subsequent carbon budget allocations. Therefore, the carbon budgets for HH2 were consistently higher than in other households.

In our study, the weekly cap generally decreased, starting from an initial high to encourage early success. Since the 60 $kg_{CO2\text{-}eq}$ cap had been set very generously in HH1, this cap was followed in the following week by a significant reduction of about 33 % to 40 $kg_{CO2\text{-}eq}$. To contextualize the carbon cap levels used in this study, it is important to note that the average German household emits approximately 2.9 $tons_{CO_2\text{-}eq}$ per year for electricity and heating (as of 2023) [71]. The reference-week emissions measured in our study households and scaled to one year were lower than the average: 2.1 $tons_{CO_2\text{-}eq}$ for HH1, 2.8 $tons_{CO_2\text{-}eq}$ for HH2, and 2.4 $tons_{CO_2\text{-}eq}$ for HH3, based on actual measured consumption at the household level. These values served as the basis for determining carbon budgets. In the case of HH1, for example, the weekly emissions in the reference week were around 40 $kg_{CO_2\text{-}eq}$, yet the initial cap was set to 60 $kg_{CO_2\text{-}eq,}$ a deliberately generous buffer intended to ease participants into the system and ensure a positive early experience. The subsequent 33 % reduction to 40 $kg_{CO_2\text{-}eq}$ in week 2 appears large numerically, but functionally, it simply brought the cap back in line with participants' actual baseline consumption. This adjustment was therefore not intended as a challenge, but rather a return to a realistic starting point for testing price responsiveness and feedback effects.

A linear decrease in the cap wasn't a priority in our experiment because we tested multiple factors, including PV feed-in that enabled load shifting. In this case the electricity consumption was obtained by subtracting the PV feed-in from the demand for each time-interval of the measurement and this needed to be accounted for by adjusting the cap. For example, in HH3, the introduction of air conditioning required raising the cap by 10 $kg_{CO2\text{-}eq}$ to accommodate the additional usage.

3.4. Grid congestion scenarios

Considering that future low-carbon energy systems might integrate carbon pricing with incentives to manage grid congestion, we introduced similar incentives in our study to examine how they interact. Utilizing our experiences from earlier experiments in the Energy Smart Home Lab [35,63], we simulated grid congestion scenarios during the interventions to evaluate participants' willingness to adjust their electricity consumption.

During these scenarios, participants were incentivized to limit their power consumption to no more than 2 kW over a three-hour interval. Scenarios were scheduled during typical peak household consumption periods, such as morning hours (7–10 am) and evening hours (7–10 pm), or, where applicable, during individually identified household peak usage times (e.g., 12–3 pm or 9 pm–12 am). These periods were selected based on consumption patterns observed during the reference weeks and supported by prior findings [34], as they represent times when participants were least flexible due to daily routines like preparing meals or using household appliances [34]. The specific days on which grid congestion events occurred were randomized to prevent predictability and anticipatory behavioral adjustments by participants. Each household encountered up to two congestion scenarios per week, balancing the need for a sufficient number of intervention data points with the goal of minimizing participant burden. A detailed description of the congestion setup and the derivation of the monetary incentive (3 EUR per day for compliance or non-compliance) can be found in [35].

4. Results

The participants' final bonuses varied significantly across the three households: those in HH1 achieved an increase in bonus to 33.80 EUR, the ones in HH3 14.00 EUR, and the participants in HH2 finished with 8.80 EUR. These variations reflect the differing levels of engagement and success in adhering to carbon budgets and grid congestion scenarios across the households, which will be detailed in the following sections.

4.1. Interaction with carbon budgets

Each household was assigned a progressively decreasing carbon budget, requiring them to actively manage their electricity and heating consumption to stay within the limits. The results reveal distinct household-specific responses to the carbon caps, ranging from highly engaged strategies that prioritized strict adherence to budgetary limits to more flexible approaches where external circumstances, convenience, and comfort played a larger role. HH1 exceeded three out of seven carbon budgets, HH2 exceeded two out of five carbon budgets, and HH3 exceeded two out of six carbon budgets, as Fig. 4 presents.

As shown in Fig. 4, HH1 successfully stayed below the cap when the bulk tariff applied, HH2 maintained relatively stable performance with minor deviations, and HH3 exhibited a more fluctuating consumption pattern with both close compliance and two overages towards the end of the intervention. Since each household consisted of two participants, we also calculated per capita emissions to enable a more meaningful comparison to literature. Dividing the total household emissions by two, HH1 achieved a final per capita carbon footprint of approximately 0.29 $tons_{CO_2\text{-}eq}$, HH2 of 1.13 $tons_{CO_2\text{-}eq}$, and HH3 of 0.64 $tons_{CO_2\text{-}eq}$, extrapolated to an annual basis. These per capita results are discussed in more detail in Section 5.1**.** in comparison to national averages and previous studies.

Behavioral adaptation was observed in all three households, but to varying degrees: HH1 actively sought to optimize their energy usage within budget constraints, HH2 displayed a strong initial commitment but later faced external challenges that influenced their motivation, while HH3 strategically managed their energy use but encountered constraints in their ability to reduce further. The following sections provide a detailed breakdown of each household's experience, including their strategies, successes, and challenges in adhering to the carbon budgets.

4.1.1. Household 1: engaging with the challenge

HH1 exceeded three out of seven carbon budgets, but showed consistent efforts to reduce emissions over the nine-week period, ultimately reaching a reduction of 73 % compared to their baseline emissions. It is notable that they reached all carbon budgets paired with the bulk tariff in week five to seven. Their behavioral adaptations included small but impactful choices, such as replacing oven use with the microwave:

> *"[The bulk tariff] definitely influenced me. I opted for the microwave over the oven for cheese toast to save energy, which wasn't great for the taste. [Laughs.]"*
>
> (participant A, translated from German)

Participant B agreed to this, following with:

> *"I liked the gradual approach best because it felt like the penalty was minor if you didn't meet the target. Buying the extra 5 $kg_{CO2\text{-}eq}$ seemed pointless because if we exceeded, it was always by a minimal amount that wouldn't benefit us."*
>
> (participant B, translated from German)

HH1's response to the bulk tariff was shaped less by convenience and more by a desire to avoid perceived overpayment. Participants often anticipated that they would exceed their weekly cap by only a small margin (e.g., 1–2 $kg_{CO_2\text{-}eq}$), making the flat purchase of an additional 5 kg feel excessive and inefficient. This mismatch between need and cost heightened their motivation to stay within the cap. From a behavioral perspective, this may reflect a form of loss aversion: participants were reluctant to incur a fixed penalty that felt disproportionate to their actual emissions overage, particularly when avoiding it seemed achievable.

In week 7, the participants took extreme measures on the last day, including not cooking, using candlelight, not showering, not using the kettle, and charging devices outside the home, to avoid exceeding the budget:

> "We could see that we would make it barely, therefore we were motivated to not exceed the budget."
>
> (participant A, translated from German)

Without a carbon cap in week 8, more relaxed behaviors among participants were notable, showing a slight rebound effect with a 15 % increase in emissions compared to the previous week. However, total emissions remained at 42 % of the baseline, indicating that many low-carbon habits persisted. The rebound appeared to stem from small comfort-driven behaviors, such as making coffee at home which participant A reported, rather than deferred 'pent-up' demand.

Participant B maintained certain routines, like checking the weather to optimize the use of appliances in sync with solar energy availability. This aligns with literature indicating that rebound may be muted when participants retain internalized behavior patterns and may be driven more by comfort or habit than by overt moral licensing [72,73].

The participants viewed the carbon budget more as a personal challenge than a commitment to broader environmental or social goals. Overall, participants A and B found it challenging to balance comfort with strict energy restrictions. Participant B particularly felt a psychological strain, aware of their above-average energy efficiency yet experiencing it as a form of self-denial:

> "And at the same time with my awareness that we are quite good [in comparison to the] average in Germany anyway. I would then have the feeling that it was a bit of self-mortification."
>
> (participant B, translated from German)

4.1.2. Household 2: The impact of external motivations

HH2 exceeded two out of five carbon budgets and reduced their

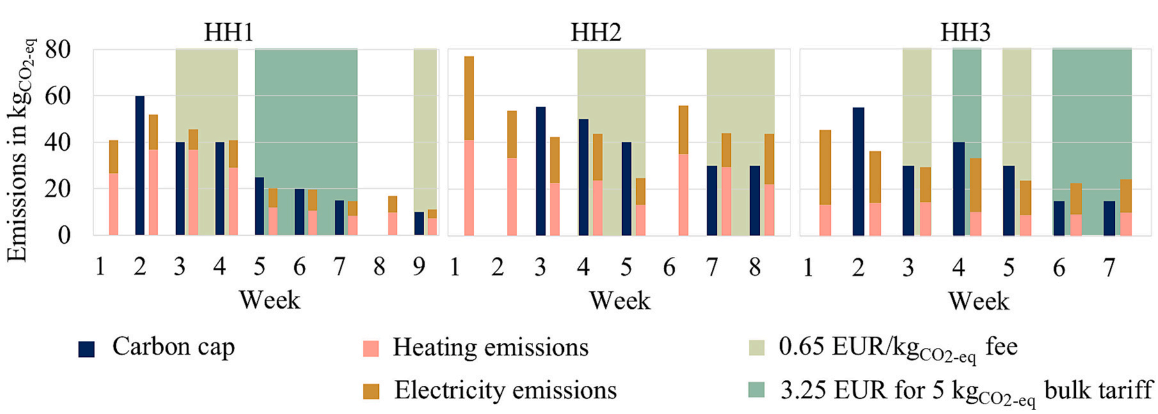

Fig. 4. Carbon budgets over time and the participants electricity and heat consumption for HH1, HH2, and HH3 (no caps in week 1 and 8 for HH1, week 1,2, and 6 for HH2, and week 1 for HH3).

overall emissions by 33 %. They displayed a high level of initial motivation, stating in the first week with a carbon emission cap that they extremely cut back in their energy consumption to try to keep within the given budget.

Fig. 4 shows that indeed, their overall emissions dropped well below the budget that was set similar to the emissions of the previous reference week.

> "[…] the dryer uses a lot, we won't use it, we won't use the washing machine for now and we'll see. So yes, we used very little at the beginning."
>
> (participant D, translated from German)

Participant C reduced the heating temperature early in the study to conserve energy and monitored their consumption closely to maintain a buffer for later weeks. They also optimized energy use by showering at sports facilities, reducing the oven pre-heating time, and charging devices on campus or at friends' homes. Even though there was no financial incentive in this first week, the participants agreed that they wanted to achieve the challenge and see if they were able to keep below the 55 $kg_{CO2\text{-}eq}$ cap. They mentioned knowing one participant from HH1, which motivated them to perform better, so some normative incentive did exist here.

By week four, the familiar cap levels allowed them to comfortably manage their consumption, strategically using high-energy appliances like the tumble dryer later in the week to ensure budget compliance. Similar strategies continued into week five, with extensive use of campus facilities and minimal home heating, though comfort was compromised, prompting a temperature increase and rebound effect in week six. In contrast to HH1, HH2 showed a more pronounced rebound effect, with emissions increasing by 125 % compared to the previous week, reaching 85 % of their baseline emissions. Interview responses indicate that this rebound was driven by pent-up demand as participants expressed relief at finally being able to cook more energy-intensive meals and restore room temperatures that had previously been lowered for savings. Participant D stated:

> *"I was looking forward to finally cooking some meals I had been putting off."*
>
> (participant D, translated from German)

And participant C added:

> *"I turned the heat back up. It had been colder in my room last week, and that was fine until I actually had to spend time in the room."*
>
> (participant C, translated from German)

Unlike HH1, HH2 lacked access to PV generation, which made behavioral alternatives like load shifting less available, amplifying the intensity of their rebound once constraints were lifted.

In week seven, a dislodged thermostat led to unintentionally high heating significantly breaching the budget. This incident caused frustration and highlighted the seeming futility of their efforts when such accidents could undermine their careful planning:

> *"To be honest, I have to say that I lost a bit of motivation because it was already so high, and it was very unrealistic [for us to still keep within the budget]."*
>
> (participant C, translated from German)

In the final week, heightened electricity consumption from activities like laundry and cooking surplus food resulted in a budget breach. Participant D reflected on their changing willingness to conserve energy, stating:

> *"When we moved in, I was much more willing to do things, like taking cold showers […], but by the end I'm no longer willing to do them because of the stress of exams."*
>
> (participant D, translated from German)

The participants found the visualization of their emissions intriguing, though they struggled to interpret the abstract numerical data.

4.1.3. Household 3: managing constraints

HH3 exceeded two of their six carbon caps, managed to reduce their overall emissions by 48 %, and demonstrated their practical limitations of energy-saving measures. The initial week was straightforward, with participants quickly devising strategies to remain within budget limits:

> *"But yeah, I think on the first day I kind of checked how much we used for that day, and it was quite clear that it's going to be not that hard to reach the goal."*
>
> (participant E)

The third week presented more challenges, but adjustments in daily routines such as reduced showering and cooking allowed them to meet the 30 $kg_{CO2\text{-}eq}$ cap. Like earlier interventions, participants occasionally used external facilities for activities like showering and dining to minimize their household energy use. From week 4 onwards the air conditioning was running, which resulted in less energy consumption for heating and more electricity consumption for the air conditioning, necessitating a10 $kg_{CO2\text{-}eq}$ budget increase. Participants actively engaged in load shifting, timing appliance use to coincide with peak solar output. Despite careful timing, unexpected reductions in solar availability led to frustrations, as exemplified by a failed attempt to sync coffee making with solar generation:

> *"One moment I wanted to have a coffee and then pressed [the coffee machine button] while the sun was shining and then the sun was gone. [I] got really mad."*
>
> (participant E)

Despite sustained load-shifting efforts in weeks six and seven, HH3 could not further reduce their energy consumption, indicating they had reached the practical limits of their energy-saving behaviors within the experiment's constraints.

The participants expressed mixed feelings about the tariff structures, with some finding the financial incentives less motivating than the challenge of staying within the budget:

> *"The motivation was always to stay as low as possible."*
>
> (participant E)

They also expressed the psychological strain of adhering to strict carbon caps, particularly in the latter stages of the experiment, underscoring the challenges of relying solely on behavioral changes to achieve environmental targets. The inclusion of PV incentives was highlighted as a positive motivator for reducing emissions. However, in a real-world application a HCCT scheme could be motivating for both participants.

4.1.4. Weeks with photovoltaic generation

In HH1 and HH3, PV energy generation was integrated into the energy management plan, enhancing the participants' ability to manage their energy use by aligning consumption with peak solar output. However, technical issues prevented HH2 from using PV feed-in. Participants generally responded positively to the inclusion of solar power, finding it enabled more active and less restrictive energy management. Participant B, with a flexible schedule, particularly benefited, describing the shift to solar as a transition from mere limitation to proactive adjustment:

> *"Up until the solar challenge, it was a case of restricting everything and with the solar challenge it was just an adjustment. I liked this adaptation effect"*
>
> (participant B, translated from German)

This approach allowed participants to optimize their energy use more freely, reducing stress associated with strict budget adherence.

Participant E added that shifting their consumption towards the PV generation hours gave them more opportunity to play an active part in reducing their emissions. Participant A highlighted the practical challenges of aligning their less flexible schedule with peak solar times, noting difficulties in synchronizing daily activities with solar output, which peaks from noon to 3 pm. This misalignment was evident despite the theoretical advantages of living aligned with solar energy production, requiring substantial adjustments to daily routines:

> "I was actually looking forward to living with the sun. But that didn't work out at all, because it's mainly active between 12 and 3 pm. On a Saturday, I was able to take advantage of it. And I was really pleased that there was already sun on the roof, and I was able to use it. If I only ever wanted to use renewable energies [residential photovoltaic], then I would have to change my whole daily schedule."
>
> (participant A, translated from German)

Load profiles demonstrated significant shifts in energy use during peak solar periods, substantiating the effectiveness of the PV incentive in aligning electricity demand with solar availability, as Fig. 5 presents. Fig. 5 compares electricity demand (blue) and PV generation (gold) over two selected weeks for HH1 and HH3, before and during PV integration. The visible increase in demand alignment with PV generation in the second week for both households illustrates how participants actively timed their energy use to coincide with solar availability. For example, mid-day peaks in PV output during days 3 to 6 in HH1 (week 7) coincide with increased appliance usage, suggesting conscious load-shifting behavior. Specifically, in HH1, the share of electricity demand met by concurrent PV generation increased by 13 %, while in HH3, this share rose by 11 %, confirming that participants were responsive to real-time generation signals.

In contrast, HH2 relied solely on demand reduction to meet their carbon budgets. This contrast suggests that the visibility of electricity generation and self-consumption from PV may have served as a form of positive reinforcement, allowing HH1 and HH3 to shift from purely avoiding emissions to actively aligning behavior with renewable energy availability. This aligns with the notion that feedback mechanisms that allow for load shifting instead of shedding, especially when tied to personal agency, can complement economic signals and reduce perceived burden [63].

4.1.5. Heating demand

Heating demand significantly influenced participants' emissions, necessitating a balance between reducing heating and maintaining comfort.

To interpret heating-related energy use, we analyzed participants' heating setpoints in relation to outdoor temperatures and heating power. Throughout the study, participants adjusted their temperature setpoints in response to the carbon budgets, as Fig. 6 presents. Fig. 6 visualizes how ambient temperature patterns interact with behavioral adjustments, supporting the interpretation of shifts in setpoints and heating power. Due to missing ambient temperature data from the sensor for HH3, we used measurements from the German Meteorological

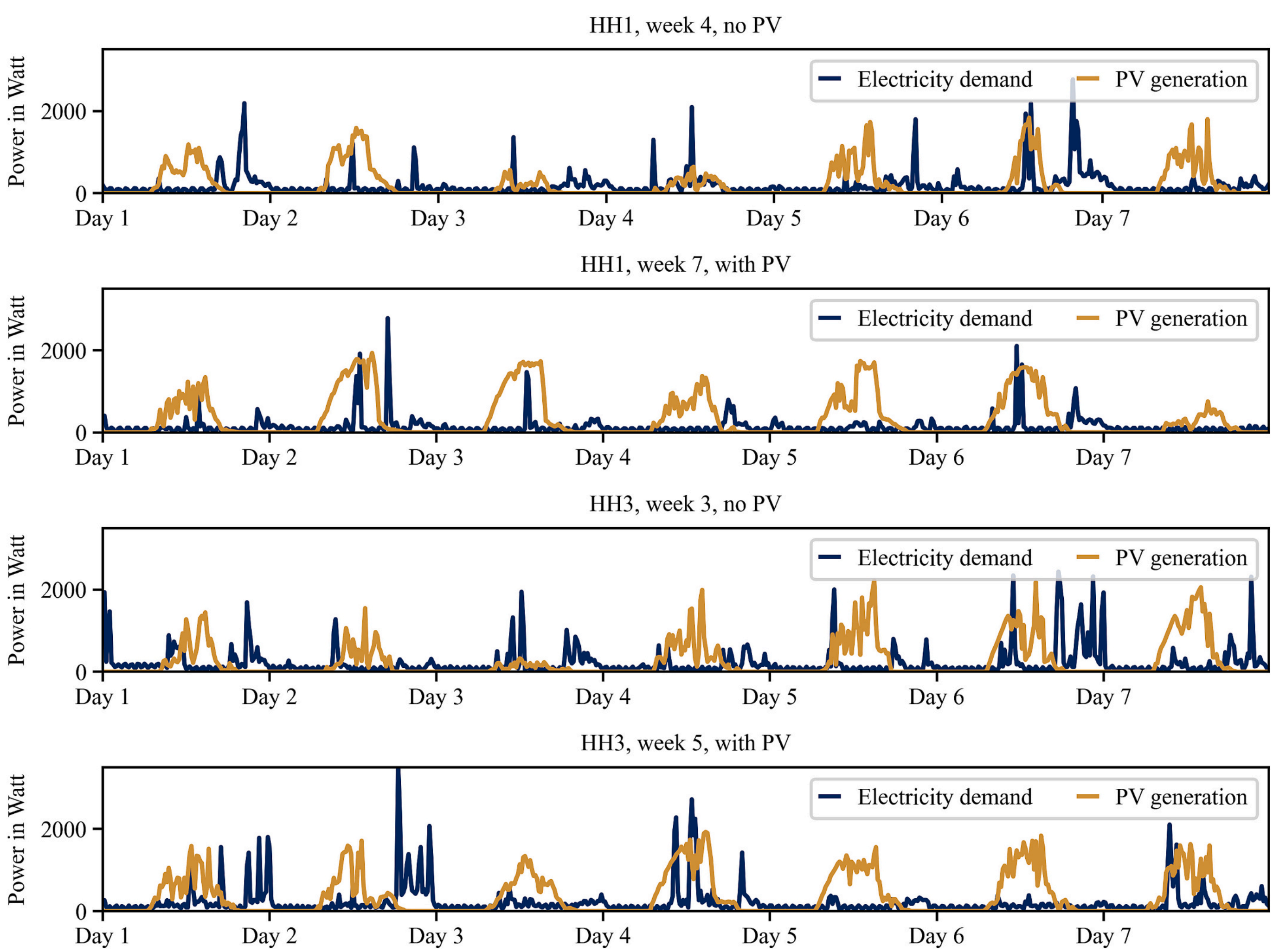

Fig. 5. Exemplary load profiles in household 1 (HH1) and household 3 (HH3) in weeks with and without photovoltaic (PV) generation.

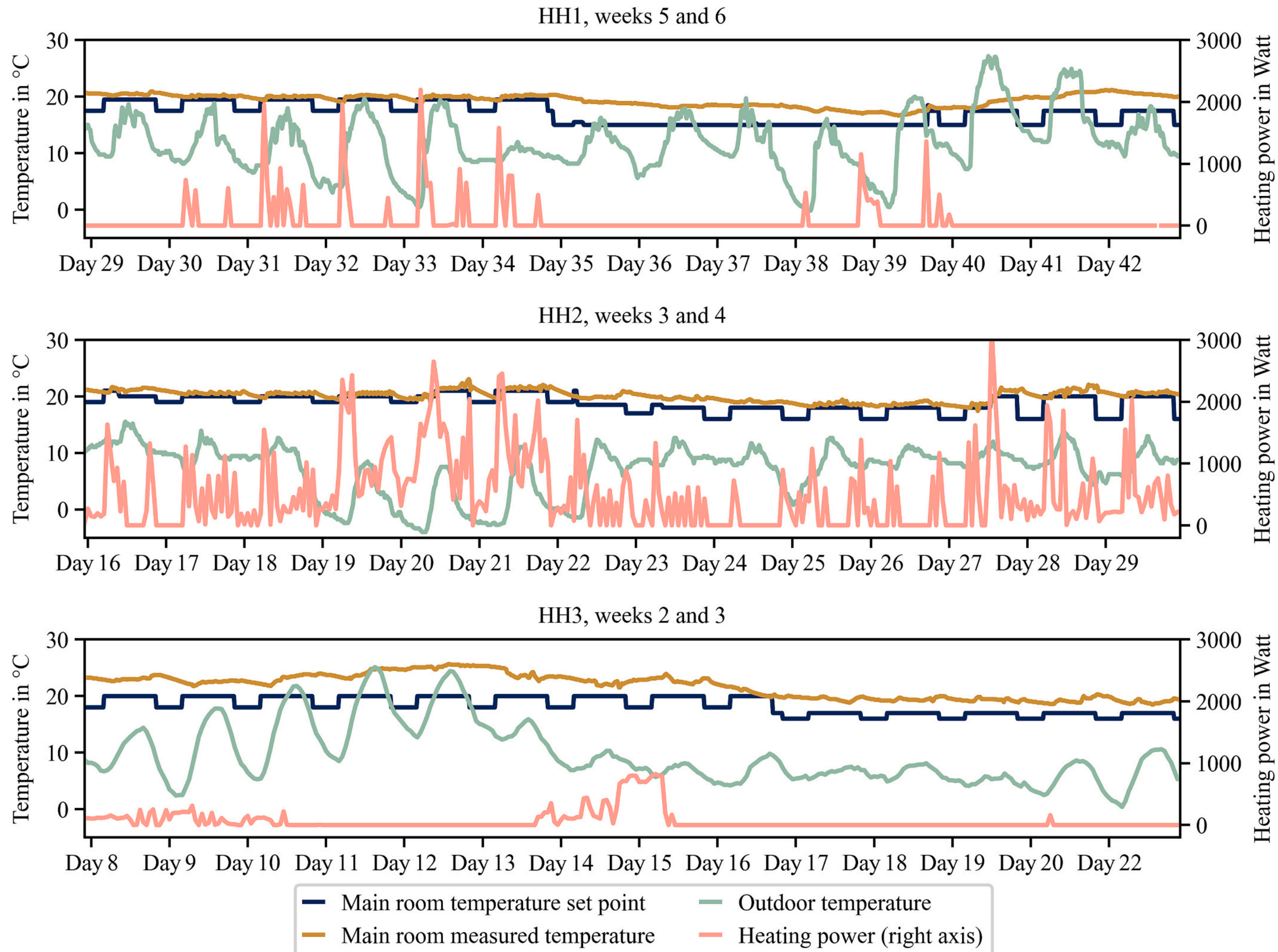

Fig. 6. Indoor temperature setpoints for the main room, measured main room temperature, outdoor temperatures, and heating power for HH1, HH2, and HH3 during selected intervention weeks.

Service for that period [74]. HH1 generally lowered their daytime temperatures but increased them in week three despite warmer weather. In contrast, HH3 set their temperatures on the first day and maintained them for two weeks.

Despite a low carbon budget in week five of HH1, participants initially reduced but later increased their heating to regain comfort, reflecting a tension between emission reduction and comfort. HH2 showed fluctuating temperature settings, as presented in Fig. 6. At the beginning of the fourth week, the participants reduced the setpoint, however increased it again after three days, indicating a loss in comfort that needed to be remedied, despite increasing ambient temperatures. Participant C elaborated:

> *"We turned up the heat again, didn't we? Last week (week 4), as I mentioned, we really turned down the temperature to save on our $CO_{2\text{-}eq}$ budget, and this time (week 5) we set it back to normal."*
>
> (Participant C)

Since the participants stayed well below the given cap in week four, the decrease in setpoint might have been due to comfort reasons and then kept low to comply with the budget as motivated by participant C above. In addition, the container heats up depending on the position of the sun relative to the season. Hence, during spring months the container might heat up more than during the winter months, despite the same measured ambient temperature. This seasonal effect was apparent in HH2 and HH3, influencing the required heating energy despite similar setpoints, as illustrated in Fig. 6. In HH3, one can see that the participants reduced the temperature setpoint of the main room in the third week, indicating that the carbon budget motivated them to reduce their heating consumption. However, it can also be seen that the main room temperature never fell below the set temperature, despite a very low heating power consumption. Participant E also confirmed:

> *"We haven't used any heating yet; it's never dropped below 22 (°C) here."*
>
> (Participant E)

Participants gained insights into heating management, realizing excessive heating in their absence led to unnecessary energy use:

> "[…] in the first few weeks, we really heated too much without anyone being there. […] So, heating means simply blatant consumption."
>
> (participant B, translated from German)

Participant A reflected on the balance between comfort and conservation, sharing a personal experience of overly restrictive heating:

> "It also showed me that I don't just have to turn off all the heating per se. After all, when the war in Ukraine broke out, my [partner] decided we wouldn't heat the house anymore. It was very cold then [Laughs] and I had a lot of colds then. […] you don't have to restrict yourself completely."
>
> (participant A, translated from German)

Both participants suggested that user-friendly automation in heating systems could optimize energy savings without significant personal inconvenience.

4.2. Flexibility provision during grid congestion

The ability of participants to adjust their energy use in response to grid congestion scenarios varied significantly across the three households of the study. HH1 demonstrated the highest adaptability, achieving most of the available incentives, followed by HH3, while HH2 showing limited success due to external pressures such as illness and exam stress.

All households generally recognized and responded to the congestion challenges, seeming to monitor the congestion hours closely, as the power peaks directly before and after the congestion period in Fig. 7 suggest. Each subplot in Fig. 7 represents one selected congestion day per household, highlighting both the daily power profile and the set power limit (2000 W). This often led to minor but manageable behavioral adjustments, such as delaying coffee or pizza preparation:

> "I found that interesting because it was a restriction, but it was usually manageable for me. I found that exciting and good. And I wouldn't find that dramatic in my own home either."
> (Participant B, translated from German)

In each household, the effectiveness of the congestion management was critically dependent on the participants' daily schedules, their engagement with the energy management system, and the practicality of the incentives provided. To a certain degree, participants were willing to adjust their schedules or integrate their friends into the congestion constraints, however the monetary compensation was not enough to incentivize load shifting or shedding in all cases.

In week 5, participant B stated about the monetary incentive:

> "The money isn't much now. But when I think about how much a coffee costs and if I'd gone over the limit just for the coffee, then I could have had a coffee in a café for the money."
> (participant B, translated from German)

For a detailed breakdown of the days and specific load shifting successes and failures, along with comprehensive participant feedback, please refer to the supplementary materials.

4.3. Value scale assessment

Values are defined by Schwartz as "desirable transsituational goals varying in importance, which serve as a guiding principle in the life of a person or other social entity" [75]. Steg et al. [76] have developed a framework that categorizes values into self-enhancement (hedonistic, egoistic) and self-transcendence (altruistic, biospheric), which aids in understanding environmentally relevant behaviors. The value scale framework suggests interventions should consider the hedonic impacts on behavior since these might oppose behavior change [76]. Results indicate varying motivational profiles. Although biospheric values were not regarded as extremely important by all participants, three participants put emphasis on it. Hedonic values reached the highest importance across participants, followed by altruistic values. Egoistic values were the least important, although one participant rated it as the most important value for them. Further details on the value scale results are presented in the supplementary materials.

5. Discussion

In the Energy Smart Home Lab, three households navigated weekly $CO_{2\text{-eq}}$ caps and grid congestion scenarios across three multi-week interventions. These setups offered insights into how non-economic and economic incentives influence energy consumption behaviors. While participants began the study with below-average household carbon footprints, all households further reduced their emissions during the intervention, albeit to varying degrees.

5.1. Interpreting energy consumption behavior through economic, psychological, and social mechanisms

In line with Parag et al. (2011), who identify three key mechanisms, economic, cognitive, and social, through which PCT schemes influence behavior, we structure this discussion around these mechanisms [13]. Before exploring these mechanisms, we briefly summarize the overall emissions outcomes across the three participating households to contextualize the observed behavioral changes.

The average per capita carbon footprint for Germany was 7.72 $tons_{CO2\text{-eq}}$ in 2020 [77], and 8.72 $tons_{CO2\text{-eq}}$ in 2021 [78]. If only accounting for heating, hot water, and electricity, the average emissions lie around

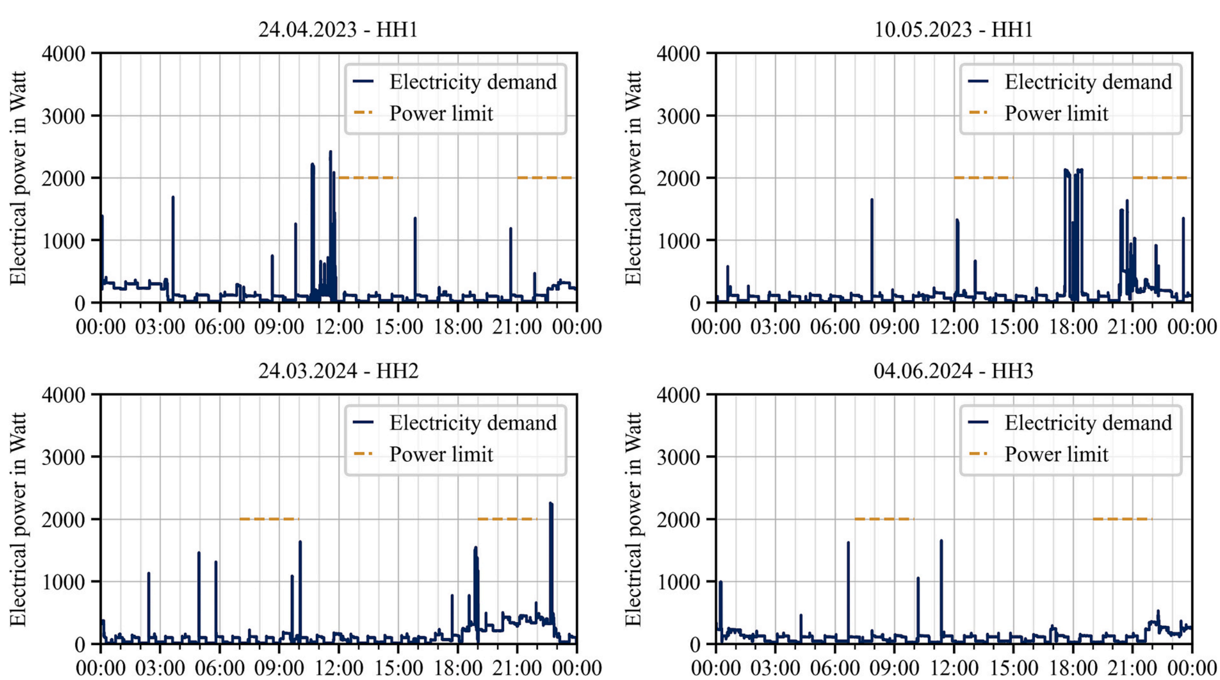

Fig. 7. Exemplary days with successfully shifted loads during grid congestion scenarios.

2.9 $tons_{CO2\text{-}eq}$ in 2023 [71]. Extrapolating the baseline carbon emissions to an annual basis, the participating households lay with 1.07, 1.39, and 1.18 $tons_{CO2\text{-}eq}$ per capita for HH1, HH2, and HH3, respectively, already at the beginning well below average. During the experiment the participants' performance in emission reduction varied. Comparing the first and the last week of the respective intervention, HH1 was able to reduce their carbon footprint by 73 % to 0.57 $tons_{CO2\text{-}eq}$, HH2 by about 19 % to 2.23 $tons_{CO2\text{-}eq}$, and HH3 by 46 % to 1.27 $tons_{CO2\text{-}eq}$. In HH2 the PV feed-in could not be factored in due to technical issues with the PV system. Hence, here the potential for reducing the footprint was limited. Despite that, all lay far below the German average by the end of the experiment.

These reductions compare favorably with findings from other PCT pilots. The NICHE study reported an 18 % reduction in household carbon emissions [37]. The members in CRAGs reduced their average per capita carbon footprint by 32 % in their first year, from 4.95 $tons_{CO2\text{-}eq}$ down to 3.36 $tons_{CO2\text{-}eq}$, the latter being 35 % below the UK average (5.2 $tons_{CO2\text{-}eq}$) for direct carbon emissions, not counting public transport emissions, but accounting for emissions from air travel [48]. Our findings fall within or above this range, despite the small sample size and contextual differences. Differences in carbon accounting methods, like the inclusion of public transport and air travel in the CRAGs study, complicate direct comparisons.

The following sections explore the ways in which economic, psychological, and social mechanisms contributed to these outcomes.

5.1.1. Economic mechanisms

The economic mechanism operates through financial incentives or penalties designed to steer behavior. In our study, carbon budgets were coupled with two tariffs for excess emissions as well as an economic tariff or bonus for the grid congestion scenarios.

Drawing on prior examples of PCA schemes, such as the CRAGs, financial penalties in these community-based initiatives ranged from 2 £ to 10 £ per excess kilogram of carbon emissions, translating to around 2.40 EUR to 11.88 EUR[2] per kilogram at current conversion rates [79]. Many CRAGs capped the maximum amount of what a member had to pay (typically at 100 £), which would translate to a weekly cap of 2.27 EUR in our experiment [79]. The cap from Howell would have been overtaken one time in HH1 (3.90 EUR), two times in HH2 (9.10 EUR for each week), and two times in HH3 (6.50 EUR for each week). By comparison, our tariffs, set at 0.65 EUR per excess kg CO_2-eq, where deliberately moderate, reflecting the goal of simulating a realistic, socially acceptable carbon price signal in early-stage piloting. Despite the presence of these financial incentives, their influence on participant behavior was limited. Interviews revealed that most participants were not strongly motivated by economic considerations. As such, participants attempted to reduce emissions consistently, whether or not they faced actual penalties. These findings echo Howell's conclusion that financial penalties often had minimal behavioral impact.

In the case of grid congestion scenarios, which offered a modest 3 EUR incentive for compliance, participants generally responded positively, but again, feedback and awareness played a more prominent role than the monetary reward itself. Overall, the economic mechanism appeared to function primarily as a reinforcing or symbolic structure rather than a dominant driver of behavior in this sample.

5.1.2. Psychological mechanisms

Psychological mechanisms refer to the intrinsic motivation driven through the allocation of allowances, the visibility of, and awareness to the carbon emissions related to one's individual actions [39]. In this study, these processes were primarily enabled through real-time feedback, transparent carbon budgeting, and weekly reflections during interviews. Participants were consistently exposed to data on their energy use, and received visual cues on whether their current behavior would remain within the assigned carbon cap.

Participants reported developing a deeper understanding of how their daily routines affected carbon emissions and, consequently, the feasibility of remaining within budget. This resulted in considerable behavioral changes, such as avoiding the use of energy intensive applications, or shifting those activities into peak solar hours. This enhanced understanding and the behavioral changes indicate that carbon literacy can be significantly improved through targeted interventions like this experiment. The increased carbon literacy and behavioral changes were also found in other pilots, such as the CRAGs in the UK. Howell [48] found that carbon literacy was one of the most obvious outcome of CRAG participation. In our study, this learning occurred not only through active experimentation but also via reflection during interviews, where participants described becoming more attuned to invisible energy flows and trade-offs, and actively inquired about, e.g. their energy consumption, the visualization and real-time feedback on the dashboard.

Despite these overall gains in carbon literacy and a considerable reduction of 45 % to 75 % in emissions from initial levels for all households, a further reduction of emissions proved challenging for the participants. Especially, as they contended with unmodifiable emissions from essential appliances such as the fridge or the freezer, or heating and cooling. This highlights the need for realistic carbon cap settings that consider unavoidable energy uses. It needs to be noted that, in this experiment, extremely low levels of carbon budgets were tested, to see if the participants would reach the lowest consumption possible (and practical) with their daily life.

Overall, our findings underline the essential role of psychological mechanisms in HCCT design. Learning, raising awareness, visibility, and the opportunity to experiment with the energy consumption behavior allowed participants to develop more effective strategies for managing their energy use, such as timing appliance use, prioritizing essential consumption, and adjusting comfort expectations rather than simply reacting to the carbon cap as a fixed constraint.

5.1.3. Social mechanisms

Beyond economic and informational cues, participants also referenced moral reasoning, environmental identity, and social norms when explaining their behavior. These social mechanisms often shaped engagement with the carbon budget in ways that were emotionally motivated rather than purely instrumental. Several participants described their motivation as a perceived environmental responsibility. Carbon caps and grid congestion scenarios were perceived as self-imposed challenges aligned with personal values. Participants adopted several strategies such as altering cooking habits, high-energy appliance use, turning the lights off when leaving a room, and scheduling energy usage during peak solar production hours to align with load-shifting incentives. Importantly, these adjustments were often maintained even in the absence of strong economic incentives, underscoring the influence of intrinsic motivation and value alignment.

However, social dynamics also introduced tension. In HH2, for example, participants were unable to comply with the power limit during one congestion event due to prioritizing comfort during an exam period. Similarly, social obligations, such as hosting guests, sometimes conflicted with load shifting incentives, leading to intentional non-compliance. This fits to previous observations in a previous intervention, where participants tried to adhere to the incentive and would fail to finish preparing a meal that needed more oven heat than expected [35].

Overall, these findings affirm the importance of social and normative mechanisms in HCCT participation. Moral identity, environmental concern, and lifestyle compatibility played substantial roles in shaping behavioral responses, sometimes reinforcing, and sometimes conflicting with, the HCCT scheme.

[2] Exchange rate as of 30th August 2024.

5.2. Limitations

This study faced several technical and methodological limitations that affect its generalizability and highlight directions for future research:

Technical challenges included an occasionally unresponsive user interface that at times hindered participants' ability to control heating settings. Household-specific issues, such as initial high consumption in HH2 or malfunctions in PV and thermal sensors, further complicated data collection and analysis.

Selection, participant, and sample bias may have influenced the results. Recruitment through academic and professional networks, along with the voluntary nature of participation, likely attracted individuals with above-average environmental awareness or comfort with digital technologies. The short duration of the interventions and the small, socio-demographically homogenous sample (three households, six participants aged 25–35) limit the generalizability of the findings. Additionally, some participants had prior exposure to sustainability topics due to their educational or professional background. Future studies should include more diverse age groups, income levels, and educational backgrounds, as well as a larger sample size, to assess broader applicability.

Displacement behaviors, such as charging electronic devices or showering elsewhere reduced the accuracy of the measured household emissions and underscore the necessity to apply a holistic carbon budget accounting.

Complexity in carbon allocation: To effectively apply carbon budgets in real-world settings, all these factors must be meticulously accounted for in the carbon allocation method. This requirement likely makes the allocation process complex and time-consuming, posing significant challenges for policy design based on individual or household behavior data.

Contextual limitations: While the study took place in a highly controlled environment, many of the core appliances used, such as the dishwasher and dryer, were standard models from 2010, representative of those still common in German households [80]. This supports some degree of realism in energy use behavior. Therefore, although the appliance baseline may reflect common household standards, the advanced sensor and measurement infrastructure limits full comparability to a typical German household. More research is needed to validate findings across a broader range of household types, technological setups, and longer timeframes.

Study duration: While the study duration did not cover a full annual cycle, some seasonal variation was included. The interventions were conducted through winter-to-spring and spring-to-summer periods, which allowed for observation of differing energy demands, such as heating in the colder months and cooling via the heat pump-based air conditioning in early summer. Nevertheless, longer-term studies are needed to fully capture the influence of broader seasonal patterns, as well as to assess the persistence and adaptation of behavioral changes over time.

Heating comfort: While participants clearly adapted their behavior in response to both carbon caps and thermal comfort, this study did not explicitly distinguish between psychological and physical comfort thresholds. Future research could integrate humidity and air movement measurements, as well as structured comfort perception surveys.

Baseline knowledge could be assessed more systematically. While some participants linked global events (e.g., the war in Ukraine) to personal restraint, the role of systemic awareness, climate policy understanding, or geopolitical salience in shaping engagement warrants deeper exploration in future studies.

5.3. Scalability and policy implications

This study demonstrates the conceptual feasibility of HCCT in a smart home setting but also highlights key barriers to scaling.

The behavioral changes observed in this study were strongly supported by real-time energy feedback, sensor-based monitoring, and smart home control systems, which are not yet widespread. Scaling HCCT would therefore require investment in hardware, user interfaces, and digital literacy support, particularly for older buildings and under-resourced communities. However, the EU-wide rollout of smart meters offers a foundation: while these devices lack appliance-level data, they can still enable real-time feedback on overall consumption. Although this would initially be limited to households' electricity consumption and only account for heating if electric heating (e.g. via a heat pump) was realized, it offers a potential pathway for a soft launch focused on electricity. Furthermore, smartphones are now widely owned across demographic groups, and developing user-centered apps for visualizing energy consumption based on smart meter data is technologically feasible [10]. The primary barriers may lie less in technological development than in establishing appropriate regulatory frameworks and data security standards.

Participants often treated carbon budgets as personal challenges, driven more by intrinsic motivation than financial incentives. Still, some experienced stress balancing comfort with carbon limits, indicating that HCCT systems must be psychologically sustainable. This includes setting realistic caps, offering adaptive options, and communicating clearly to avoid resistance or disengagement.

Displacement behaviors may shift rather than reduce emissions and could disproportionately affect those without access to alternative resources (e.g., public facilities or workspaces). To ensure equity, HCCT schemes must consider social safeguards, differentiated caps, or targeted support for vulnerable groups.

Financial penalties in the study played a limited role in driving behavioral change, calling into question the universal effectiveness of uniformly applied price signals in HCCT schemes. Policymakers should explore more nuanced pricing designs that align with household routines and values. Incentive systems should also prioritize clarity and transparency, particularly in households with limited digital or energy literacy, or where daily stressors reduce the capacity to engage with complex incentive systems.

At the policy level, HCCT could serve as a complementary, downstream mechanism within the EU-ETS2 framework, offering granular behavioral engagement where upstream carbon pricing remains abstract. To avoid overlap and double-counting, HCCT could operate as a soft-coupling approach using virtual caps at the household-level that are informational and tied to emissions budgets without formal market trading. Integration pathways could include municipal pilots nested within national targets. In the longer term, EU-ETS2 could evolve to formally accommodate PCT schemes, particularly if aligned with e.g. utility billing platforms.

In summary, while this study supports the conceptual feasibility of HCCT, practical implementation must address infrastructure costs, behavioral sustainability, fairness, and policy alignment. Concrete next steps could include:

- Piloting HCCT in lower-tech households or social housing to test minimum requirements, possibly through municipal utilities or housing cooperatives,
- Developing cap-setting methods that account for essential consumption, in collaboration with consumer groups and energy regulators to ensure fairness and transparency,
- Exploring integrating HCCT with carbon pricing schemes like EU-ETS2,
- Embedding support for vulnerable households, including differentiated caps or safeguard mechanisms, to avoid disproportionate burdens.

These actions could help transition HCCT from an experimental model to a scalable component of inclusive and effective climate policy.

6. Conclusion

This study demonstrates the feasibility and effects of household carbon caps and tariffs (HCCT) as a behavioral instrument for reducing residential emissions. Through a living lab experiment with three households, all participants significantly reduced their emissions, by 73 %, 33 %, and 48 % compared to their baseline emissions. Hence, all households actively adapted their behaviors to the constraints imposed by the carbon budgets.

The observed behavioral changes were shaped by economic, psychological, and social mechanisms. Economic mechanisms, such as carbon tariffs and economic incentives for grid load shifting were acknowledged by participants but were not the primary driver of behavior. Participants reported that financial penalties played only a secondary role, with their effectiveness varying by tariff design and personal circumstances. This suggests that while price signals may provide structure and reinforce behavioral boundaries, their standalone effect in HCCT schemes may be limited without complementary motivational strategies.

Psychological mechanisms proved more influential. Real-time feedback and visualized carbon caps fostered carbon literacy, enabling participants to experiment with and refine their energy consumption habits. Strategic adaptations, like shifting appliance use or aligning consumption with solar availability, reflected increased awareness and self-regulation. Importantly, the study revealed that the emotional and psychological responses to carbon caps ranging from stress over stringent limits to satisfaction from meeting reduction targets play critical roles in the efficacy of HCCT schemes. These insights suggest that HCCT can effectively drive behavioral changes necessary for emission reductions, although the emotional and psychological burden must be carefully managed to sustain long-term engagement.

Social and normative motivations, such as environmental values or personal commitment to the carbon budget, often outweighed economic considerations. Participants largely viewed carbon caps as self-imposed challenges rather than enforcement tools. At the same time, comfort and social obligations occasionally overrode these motivations, particularly when tied to social obligations or personal well-being.

This study contributes to the personal carbon trading (PCT) literature by demonstrating how a simplified, household-level variant, HCCT, can induce emission reductions in a real-world, digitally enabled environment. By integrating carbon caps, differentiated tariffs, and load shifting incentives, the study highlights how economic, psychological, and social mechanisms interact to shape household energy behavior. Unlike many prior PCT pilots that relied on self-reported data or focused solely on mobility, this experiment shows the feasibility of applying dynamic, digital, and feedback-based carbon budgeting to residential energy use.

Future research could explore more diverse demographic settings to understand the broader applicability and potential barriers to widespread adoption. Long-term studies could provide insights into the sustainability of behavioral changes induced by HCCT and whether initial reductions in emissions are maintained over time. Additionally, integrating a wider range of emission sources and examining the interplay of various types of incentives could offer deeper insights into enhancing HCCT schemes for different residential contexts and individual preferences.

CRediT authorship contribution statement

Leandra Scharnhorst: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Thorben Sandmeier:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Max Kleinebrahm:** Writing – review & editing. **Wolf Fichtner:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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.

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Appendix A

Table A1
Literature overview on policy proposals discussing PCT schemes for different regions.

Reference	Year	Region	Category	PCT scheme	Scope	Addressees
Raux and Marlot [14]	2005	France	Policy proposal	CO_2 permits	Transport (domestic car fuel consumption)	Per capita
Fleming [41]	2007	UK	Policy proposal	Trading energy quotas	Household energy, personal travel	Per capita
DEFRA [50]	2008	UK	Pre-feasibility study	PCT system	Household energy, personal travel	Per capita
Darrell [81]	2008	Ireland	Policy proposal	Pollution authorization permits	Presumably all sectors, not further detailed	Per capita
Niemeier et al. [49]	2008	California, US	Policy proposal	Household carbon trading system	Household energy (electricity and gas consumption)	Households
Duscha [22]	2014	Germany	Policy discussion	Comparison of PCT-schemes	Household energy, personal travel	Per capita, per household

(*continued on next page*)

Table A1 (*continued*)

Reference	Year	Region	Category	PCT scheme	Scope	Addressees
Guzman and Clapp [5]	2016	British Columbia, Canada	Policy proposal	Carbon Health and Savings System	Household energy, personal travel (excluding public transport)	Per capita
Woerdman and Bolderdijk [11]	2017	Europe	Policy proposal	Emission trading for households in the EU-ETS	Household energy use and personal surface transport (no air travel)	Per capita

Table A2
PCT pilot's reduction targets, challenges and take-aways for the present study design.

Project	Reduction targets		Challenges	Take-aways for our study	Ref.
	Annual baseline in $kg_{CO2\text{-}eq}$	Reduction targets from baseline in %			

Carbon Rationing Action Group (CRAG)	4950	10 % from UK average of direct emissions	• Sporadic unforeseen issues
			• Make children walk too long distances
			• Diversity in PCT designs
			  • Debates on PCT scopes and conversion factors
			  • Undecided in accounting children
			  • Fairness concerns for elderly in per capita schemes
				• Transparency in allocation and conversion factors is crucial
				• Regular or real-time feedback essential for effective carbon budgeting
				• Motivated individuals can achieve carbon footprints well below UK average
				• Financial penalties in PCT viewed as negligible by participants, even at high carbon prices
				• High allowance prices necessary to motivate environmentally indifferent participants
				• Simplified purchasing of additional allowances needed for those exceeding caps
					[48]

Sevenoaks CRAG	20,000-15,000	25 %			[48]
	≤ 5000	5 %			
Fownhope CRAG	Individual	10 %			[48]
Leeds CRAG	Members choose own targets lower than baseline of previous year				[48]
Redland Bristol CRAG	Members choose own targets lower than baseline of previous year[a]				[48]
Langport CRAG	9240	10 % reduction of group average			[48]
Glasgow CRAG	2200	10 % reduction on estimated global footprint			[48]
Norfolk Island Carbon and Health Evaluation (NICHE)	633 1 1012 2 1083 3 1249 4 & 5 Per member household	10 %	• Poor internet connectivity hindered trading schemes • Sharp decline in participation due to economic and political instability, and subsequent island emigration • Questionnaire fatigue	• Unforeseen events impact participation • Technical difficulties obstruct emission trading implementation • Increased carbon literacy noted among participants	[37,51,52]
CitiCAP	844	20 %	• Decline in participation and reduced mobility due to COVID-19 pandemic	• Unforeseen events affect mobility and participation	[38]
Energy Smart Home Lab	2,077[b] 3384 2091	75 % HH1 54 % HH2 63 % HH3	This study		

[a] After one year with a fixed target.
[b] The baseline taken here is the average of the actual emissions of the first few weeks before the first budget lower than the actual emissions was set and multiplied by 52 to receive a value comparable to the annual values of the other studies.

Appendix B. Participant recruitment and selection

Participants were recruited in November 2022 and December 2023 via an open call for applications disseminated through multiple channels, including university mailing lists, social media, and professional networks. The flyer provided information about the smart home setup and the planned residential intervention. Interested individuals were asked to submit a short application, including a CV, a brief motivation statement (½ DIN A4 page) explaining why they wished to participate in the study, and their availability to begin an 8-week stay in November, December 2023 or January, February, March 2024.

All applicants were invited to a short video call for clarification of study expectations and assessment of eligibility. Hard exclusion criteria included employment at KIT (due to legal restrictions), lack of availability over the full intervention period (e.g., planned vacations), and unwillingness to cohabitate with another participant in the smart home. Preference was given to working individuals or recent graduates with limited home-office days, to ensure a more realistic approximation of everyday residential energy use.

No formal screening process was conducted for environmental attitudes or technical literacy. However, we aimed to avoid participants whose academic or professional background was closely related to the research topic to minimize bias. This goal met with mixed success, largely due to the limited pool of applicants. In both 2022 and 2023, we received eight applications per year. As a result, some selected participants had backgrounds adjacent to energy or environmental studies. Among eligible candidates, final selection was based on the date of application submission, following a first-come, first-served principle.

Appendix C. Socio-demographic characteristics

This section provides an overview of the socio-demographic characteristics of the six participants, aged between 25 and 35, including four women and two men. The descriptions below are based on participants' self-assessments collected through a Likert-scale questionnaire (1 = not existent to 5 = very extensive) and supported by insights from final in-depth interviews conducted after the intervention. Ratings such as “average” or “below average" reflect the participants' own positioning on the scale, and comparisons are made within the small study sample rather than against an external reference group. Household one (HH1) comprised one employee and one student, both environmentally conscious, with one participant very active in integrating sustainability into all aspects of life, including choosing sustainable service providers. Household two (HH2) involved two students with varying experience with smart appliances, average knowledge of energy saving measures, below-average knowledge of residential electricity prices, and high motivation to respond to environmental and economic incentives. Household three (HH3) included two employees experienced in interacting with smart technologies and average knowledge of electricity prices, being both highly motivated by normative, environmental and economic incentives.

Appendix D. Behavioral data collection and analysis

To assess participant attitudes, behavioral change, and incentive engagement, we conducted weekly semi-structured interviews, a final in-depth interview, and a survey across all three interventions. Instruments were refined iteratively over the course of the study to deepen insights and improve coverage of relevant constructs such as environmental values, perceived control, and response to incentives.

Interviews

All participants took part in weekly semi-structured interviews, as well as an in-depth interview conducted at the end of the residential period. The weekly interviews took between 15 and 30 min, the final in-depth interview between 30 and 60 min. All interviews were recorded, transcribed, and subsequently analyzed and coded. The interviews explored changes in daily routines, comfort trade-offs, behavioral strategies, and emotional responses to the incentive prompts communicated via the dashboard (see Appendix H and Appendix I for the interview protocols of the semi-structured weekly and the final in-depth interviews). The interview transcripts were analyzed using an inductive thematic coding approach. Initial codes were identified manually through close readings of the transcripts, focusing on recurring behavioral patterns, emotional responses, and contextual factors. These codes were then iteratively grouped into broader themes such as "comfort vs. compliance," "adaptation strategies," and "motivational shifts," which structured the qualitative findings presented in the results. This process enabled a grounded understanding of participant experiences without imposing predefined analytical categories [66].

Survey

Each intervention concluded with a survey designed to capture participants' perceptions of the smart home experience, their engagement with carbon budgets and grid signals, and their broader attitudes towards energy consumption and environmental responsibility. All surveys included a standardized value scale adapted from Linda Steg, assessing the importance of 16 personal and environmental values on a 9-point scale ranging from −1 (opposed to my values) to 7 (of supreme importance) [76].

The remainder of the survey content evolved between the first and the last two interventions:

For HH1, the survey focused on six Likert-scale items measuring environmental concern (e.g., "I take potential environmental impacts into account when making decisions"), alongside basic socio-demographic[3] and employment-related questions (e.g., net income, weekly working hours, home office share) (see Appendix J). For HH2 and HH3, the survey was expanded to include more detailed items regarding (see Appendix K):

- Smart appliance familiarity and energy knowledge,
- Perceived openness to energy management system based behavioral prompts (for cost, environmental, and social reasons),
- Motivation and willingness to comply with real-time incentives,
- Reflections on the learning experience and behavioral changes, and
- Open-ended feedback on organizational aspects of the intervention and the Living Lab setup.

This extended version allowed the analysis of participants values, motivations, and reflection on the incentives and the living lab setup.

Appendix E. Data measurements and cleaning

Data for the electric energy consumption in the Energy Smart Home Lab is available for every household device and socket with a temporal resolution of one second. To get the electric energy consumption for the calculation of the carbon emissions, we sum up the consumption of all devices inside the living area, calculate the average consumption since the start of the current cap interval and aggregate it over the respective period. For the assessment of the grid congestion scenarios, we again sum up the consumption of all the appliances in the living area and then check the resulting time series with a temporal resolution of 1 s for exceedances of the defined power limit.

The heating energy consumption is measured by a heat meter located between the heat pump and hot water storage. This means energy used for space heating as well as hot water is considered. For the period from the third day in week five to the second to last day in week six[4] during the third intervention the data transmission from the heat meter to the database malfunctioned, resulting in a loss of data. We reconstructed the missing data by approximating the thermal energy consumption profile with the heat pump's electricity demand profile and the average coefficient of performance (COP) for this period.

[3] Income data were only collected from one participant in HH1. The corresponding survey questions were omitted in HH2 and HH3, limiting our ability to assess the financial relevance of the incentive structure across households.

[4] Overall, for a time of 12 days, 18 h and 3 min

Appendix F. Household carbon allocation

As in the Californian policy proposal by Niemeier et al. (2008) [49], allowances are allocated to the overall households which means here the two participants living in the Energy Smart Home Lab, in contrast to the equal-per-capita allocation in other PCT schemes. The smart home's energy consumption can be automatically monitored. However, allocating the respective energy consumption to each participant would require a non-negligible effort from participants who would need to document when and how they used appliances, which was considered impractical for this study. Furthermore, household-level allocation better reflects how energy consumption decisions are made in shared living environments, where consumption is typically collective and not easily disaggregated to individuals [37]. Energy consumption and costs generally do not grow proportionately with the number of household members [82]. So, while single-person households may exhibit higher per capita emissions, this can be addressed through household-level allowance structures, e.g. using differentiated tiers accounting for the amount of household members [83].

While individual-level carbon accounting may be appropriate for personal consumption goods or mobility-related emissions, it is considerably more difficult to attribute household energy use, such as electricity and heating, to specific individuals [37,38]. In this sector, assessing emissions at the household level is often both practical and sufficient. Such an approach aligns with existing billing systems and can be more easily implemented [49]. In the context of a broader individual-based carbon trading scheme, household emissions could still be integrated by retrospectively dividing the measured total among household members and allocating it to their individual carbon budgets. For this study, a household-level carbon budget was therefore deemed the most efficient and behaviorally realistic approach. Intra-household dynamics and individual responses were captured through interviews with all household members.

Appendix G. Carbon price deduction

The carbon price was deducted by taking the average of the yearly average carbon prices of the EU-ETS in 2021 and 2022 [84], which resulted in 66.41 EUR/t which we rounded off to 65 EUR/t and multiplied by ten to give the participants a tangible incentive to deploy low-carbon energy consumption behavior in their daily live [69,85]. This relates to the approach of Kuokkanen et al. [38] who further argue, that the EU-ETS rather reflects system design, including oversupply of allowances, than social cost of carbon. Their overview about the highly varying social cost of carbon stated in literature still ranges from 125 $\$/t_{CO2\text{-}eq}$ estimated by Van den Bergh and Botzen in 2015 [70] to up to 1500 $\$/t_{CO2\text{-}eq}$ by Ackerman and Stanton in 2012 [86]. More recent studies estimate the social carbon costs at similar levels, such as 120–340 $\$/t_{CO2\text{-}eq}$ by the U.S. Environmental Protection Agency [87] and 1065 $\$/t_{CO2\text{-}eq}$ by Bilal and Känzig [88]. Kuokkanen et al. [38] set a starting price for their urban mobility PCT scheme at 1 EUR/$kg_{CO2\text{-}eq}$, which corresponds to 1000 EUR/$t_{CO2\text{-}eq}$, as rewards or penalties for under- or over-emitting their freely allocated allowances. Thus, we lie in the medium range of these studies with our carbon price estimation.

Appendix H. Semi-structured interview protocol

The following questions were used in the weekly semi-structured interviews conducted during the intervention. The interviews aimed to explore participant experiences with the HCCT scheme, behavioral adaptations, heating comfort perceptions, and responses to carbon caps and grid congestion events.

1. Introduction and general questions

- How are you doing, and how have the last days in the smart home been?
- Is everything functioning as expected, or do you have any remaining questions, requests, or comments?

2. Reference week (baseline) questions

- **Settling In and Initial Impressions**
  - o How have you settled into the smart home over the past few days?
  - o Have any questions or uncertainties come up during your first days here?
  - o Do you feel comfortable with the living situation in the smart home?
- **Familiarity with devices and interfaces**
  - o Have you familiarized yourselves with the household appliances?
    - o Household appliances: e.g., washing machine, coffee machine, dryer
    - o Heating system: adjusting temperature, using the dashboard to set room temperatures
  - o Are there any household appliances in the ESHL you haven't used yet? If so, which and why?
  - o Are there any appliances you expect not to use during the intervention? Why?
- **Thermal comfort and heating behavior**
  - o What temperature have you currently set in your room? Why did you choose this setting?
  - o Would you describe this as your comfort temperature (assuming standard clothing and no additional measures)?
  - o At home, would you typically set the heating to the same temperature? If not, why is it higher or lower?
    - o Prompt: If the difference is cost-related (e.g., due to the energy crisis), how did you heat your home in the previous winter (2021/22)? Has your behavior changed since then?
  - o If the temperature in your room/home doesn't match your comfort level, what adjustments do you typically make? (e.g., wearing extra clothing)
- **Daily routines and space use**
- o Where do you spend most of your time during the day in the smart home? Is this space at a comfortable temperature for you?
- o Over the past few days, have you mostly stayed at home (e.g., for remote work) or have you spent time outside the smart home?

3. Reactions to incentives

Last week, you received a new incentive message on your tablet. How did that affect you, and what was your reaction?

4. CO_2 budget

- Did you adjust your energy consumption behavior in any way to meet last week's CO_2 budget?
- Have you developed new habits?

5. Heating comfort

- How did you find the daytime indoor temperature in the living lab?
- Have there been any disagreements or discussions between you regarding preferred indoor temperatures, for example, one of you preferring it warmer or cooler—or has everything gone smoothly so far?
- Did you change the heating set points?

6. Grid congestion scenarios

- How did you experience the grid congestion scenario?
- Did you adapt your electricity consumption to it?
- What motivated you to adapt your consumption?
- Did the tariff have any effect on your energy consumption behavior?
- Did the information about the photovoltaic electricity feed-in motivate you to adjust your energy consumption?

7. Daily routines and representativeness

- How often were you at home during the day, and how frequently were you away for work or other activities?
- Was this a representative week for your usual schedule?

8. Closing
   [Planning the interview date for the upcoming week.]

Appendix I. Final in-depth interview protocol

The final interview, conducted at the end of the intervention phase, lasted approximately 30–45 min and was designed to elicit participants' reflections on living with carbon budgets and grid constraints, their behavioral adaptations, heating comfort perceptions, and potential long-term impacts.

I. **Reflections on the final week of the intervention.**

[Questions of the weekly interviews].

II. **Overall reflections on the intervention**

1. How would you describe your overall experience living in the smart home? Was it comfortable throughout, or were there less comfortable periods?
2. Did the incentives (CO_2 budget and congestion signals) pose any challenges?
3. In which areas did you feel you restricted yourself the most to stay within the carbon budget?
   Potential prompt: e.g., fewer showers, no baking, reduced coffee machine use, etc.
4. When did you feel most restricted during the intervention?
5. Which of the different incentive structures motivated you the most?
6. Did the integration of the photovoltaic electricity generation influence your behavior in any way?
7. How did you experience the grid congestion events?

- Did you actively try to comply, or were there times when it didn't matter to you?

8. Did the credit balance display on the dashboard motivate you to comply with the incentives?

- [Total earnings from participation were: __ €]

III. **Long-term impact on energy use, comfort, and values**

1. Do you think this experience will have a lasting impact on your energy consumption behavior? If so, how?
2. What was your comfort temperature in the smart home?
3. What is your usual comfort temperature at home?
4. In which areas did you feel most restricted? Would you be willing to accept similar restrictions in daily life?
5. Would you accept CO_2 budgets in your everyday life?
6. What types of restrictions would you be willing to accept long-term or short-term - and which would you not?

7. How does it feel to live without grid congestion signals now? Is it more comfortable? Are you aware this could change in the future?
8. Would you describe yourselves as environmentally conscious individuals?

- If yes: What actions do you take in everyday life?
- What motivates you to act sustainably?
- Do you believe incentives help you act more sustainably?
- Are you more motivated by economic incentives or by environmental concern (e.g., climate change mitigation)?

IV. **Closing**

1. We will send you the final online survey in the next days.
2. Would you be willing to participate in a similar research project again?
3. What would your expectations be for future participation? What could be improved?

Appendix J. Final survey protocol HH1

Residential Phase in the Energy Smart Home Lab.
Institute for Industrial Production (IIP)
Hertzstr. 16, Bldg. 06.33, R110
76187 Karlsruhe
Web: www.iip.kit.edu

Analysis of user acceptance and behavior regarding CO_2 budgets and grid constraints in the Energy Smart Home Lab

Dear Participants,

Thank you for participating in the residential phase at the Energy Smart Home Lab. We would like to conclude with the following survey. This is intended to analyze your self-assessment, and your environmental attitudes. This survey will take approximately 10 min to complete.

Thank you for your participation!

Leandra Scharnhorst Tel.: +49 721 608-44578	Thorben Sandmeier Tel.: +49 721 608-44402

Section 1: environmental attitudes

[Response scale: 1 = Strongly disagree, 5 = Strongly agree].
It is important to me that the products I use do not harm the environment.
I consider the potential environmental impacts when making many of my decisions.
My consumption behavior is influenced by concern for the environment.
I am concerned about wasting the Earth's resources.
I would describe myself as environmentally conscious.
I am willing to accept inconvenience in order to act in environmentally friendly ways.

Section 2: socio-demographic and occupational information

Please enter your year of birth: [Short text field].
What is your highest level of education? [Single choice].
What is your current employment status? [Dropdown].
How many hours do you work on average per week? [Short text field].
How many days per week do you work from home? [Short text field].
In which industry or sector are you employed? [Short text field].
What is your monthly net income? [Dropdown or income bands].
Do you have any further feedback for us? [Open text field].

Appendix K. Final survey protocol HH2 and HH3

Residential Phase in the Energy Smart Home Lab.
Institute for Industrial Production (IIP).
Hertzstr. 16, Bldg. 06.33, R110
76187 Karlsruhe
Web: www.iip.kit.edu

Analysis of user acceptance and behavior regarding CO_2 budgets and Grid constraints in the Energy Smart Home Lab

Dear Participants,

Thank you for participating in the residential phase at the Energy Smart Home Lab. We would like to conclude with the following survey. This is intended to analyze your self-assessment, your expectations for the residential phase, and your motivation for participation and collaboration during the residential phase. This survey will take approximately 10 min to complete.

Thank you for your participation!

Leandra Scharnhorst Tel.: +49 721 608-44578	Thorben Sandmeier Tel.: +49 721 608-44402

1. Have you had contact/interaction with smart appliances (e.g. washing machine where you can set the time, robot vacuum cleaner, energy management system in your flat) before starting the residency period in the Energy Smart Home Lab.?
   ○ Yes
   ○ No
2. How would you rate your knowledge level considering energy economics?
   ○ Very extensive
   ○ Extensive
   ○ Average
   ○ Less than average
   ○ Not existent
3. How would you rate your knowledge level about saving energy in your household (e.g. switching light in a room off, when you are not in the room for a longer period of time)?
   ○ Very extensive
   ○ Extensive
   ○ Average
   ○ Less than average
   ○ Not existent
4. How would you rate your knowledge about current electricity prices of private households?
   ○ Very extensive
   ○ Extensive
   ○ Average
   ○ Less than average
   ○ Not existent
5. How would you rate your own energy consumption behavior in the household (electricity consumption) in comparison to the average inhabitant?
   ○ Very low consumption
   ○ Low consumption
   ○ Average consumption
   ○ High consumption
   ○ Very high consumption
6. Would you consider yourself to be open to calls to action from your apartment's energy management system (EMS) in order to optimize your energy consumption behavior regarding energy expenses?
   ○ Very open
   ○ Open
   ○ Neutral
   ○ Less open
   ○ Not open
7. Would you consider yourself to be open for calls to action from your apartments EMS in order to optimize your energy consumption behavior regarding environmental reasons?
   ○ Very open
   ○ Open
   ○ Neutral
   ○ Less open
   ○ Not open
8. Would you consider yourself to be open for calls to action from your apartments EMS to optimize your energy consumption behavior regarding social aspects (e.g. helping your neighbor or your neighbor helping you by adapting your energy consumption according to your respective needs)?
   ○ Very open
   ○ Open
   ○ Neutral
   ○ Less open

- ○ Not open

9. How would you rate your motivation to participate in the experiments after experiencing various daily incentives during the residential phase?
   - ○ Very motivated
   - ○ Motivated
   - ○ Neutral
   - ○ Less motivated
   - ○ Not motivated at all
10. How would you rate your willingness to follow the incentives during the residential phase? (Turning devices on/off, saving/using energy, scheduling the use of your devices)?
   - ○ Willing to follow every call to action
   - ○ Willing to follow almost every call to action
   - ○ Willing to alternately following calls to action
   - ○ Less willing to follow calls to action
   - ○ Not willing to follow any call to action
11. How much do you agree with the following statements? **I have expanded my knowledge about smart energy usage in private households during the residential phase.**
   - ○ Strongly agree
   - ○ Agree
   - ○ Agree Somewhat
   - ○ Neutral
   - ○ Disagree somewhat
   - ○ Disagree
   - ○ Strongly disagree
12. Please briefly describe your experiences with the calls to action and incentives during the residential phase. How did you feel when you tried to follow them? (Was it a motivating, challenging, frustrating, or interesting experience?)

13. How much do you agree to the following statements: **I contributed to optimize my energy consumption and helped pushing forward the implementation of the energy transition by doing so.**
   - ○ Strongly agree
   - ○ Agree
   - ○ Agree Somewhat
   - ○ Neutral
   - ○ Disagree somewhat
   - ○ Disagree
   - ○ Strongly disagree
14. How much do you agree to the following statements: **I am content with my performance during the residential phase, regarding following the calls to action.**
   - ○ Strongly agree
   - ○ Agree
   - ○ Agree Somewhat
   - ○ Neutral
   - ○ Disagree somewhat
   - ○ Disagree
   - ○ Strongly disagree
15. How much do you agree to the following statements: **I want to live in a similar smart home setting in the future.**
   - ○ Strongly agree
   - ○ Agree
   - ○ Agree Somewhat
   - ○ Neutral
   - ○ Disagree somewhat
   - ○ Disagree
   - ○ Strongly disagree

16. How much do you agree to the following statements: **I would again participate in such an experiment.**
    - Yes
    - No
    - Depends, on… please elaborate:
17. What opportunities for improvement do you see in the residential phase in the Energy Smart Home Lab? Taking into account: - the organization - the living lab setup - the messages sent - the surveys - the interviews

Organization:
Living lab setup:
Messages and communication via dashboard:
Interviews:
Final survey:

18. Value scale by Linda Steg, see [76].

Appendix L. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2025.104294.

Data availability

To protect the anonymity of the study participants, only a subset of the data can be made publicly available. The anonymized energy consumption data is accessible as open-access on RADAR4KIT via the following link [65]: https://dx.doi.org/10.35097/txjj7yawp9gr4ts8.

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