INCENTIVIZED ENERGY CONSUMPTION ADAPTION IN PRIVATE HOUSEHOLDS FACING THE ENERGY CRISIS

Results from a Living Lab Experiment

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Abstract

The ongoing energy crisis led to high energy prices and the call for energy savings in the winter months of 2022 to 2023. As the fulfilment of these demands is directly linked to the people's well-being, this challenged many households in the colder months. To analyze the interaction and willingness to reduce one's comfort level with regard to adjusting heating patterns and react to bottlenecks in the electricity supply, a field study was conducted with two tenants living in the living lab Energy Smart Home Lab (ESHL) for a time period of eight weeks. The ESHL combines a smart home with a sophisticated sensor and measurement system. During the experiment, the tenants received calls to action linked to non-economic and economic incentives to adapt their heating and electricity demand. Their reactions were analysed based on a mixed methods approach utilizing the recorded energy consumption data, temperature set points for the heating system, surveys and interviews. The results indicate a typically high motivation to meet the incentivized adaption in heating and electricity consumption, regarding both economic and non-economic incentives. Especially the reduction of the heating demand does not seem to have challenged the tenants too much. They stated not to have lost comfort despite lowering temperature set points significantly. Not all the calls to action, though, were carried out. Notwithstanding the incentive, the main reasons to ignore the electricity calls to action were social gatherings or pre-planned daily schedules, while maintaining comfort levels served as primary justification for increasing heating.

1 INTRODUCTION

The protracted conflict in Ukraine has caused an energy crisis that threatens the German gas supply, and the security of supply of the electricity system (International Energy Agency [IEA], 2023a). Challenges to security of supply are also emerging from decarbonization efforts, including a growing share of renewable energy sources, especially on the electricity supply side, a rise in electrification on the demand side, and bottlenecks within the transmission grid (IEA, 2023b). Many households struggle to fulfill their daily heating and electricity demands due to rising prices and the call for energy savings (Guan et al., 2023; Tollefson, 2022). Fulfilling these demands is directly linked to people's well-being, especially in the colder months. Various studies have assessed the potential impact of the Russia-Ukraine war on energy and food security (Zhou et al., 2023), with a focus on increased household burdens such as increased household energy costs (Kalkuhl et al., 2022), energy insecurity (Cozzi et al., 2022), and poverty (Mahler et al., 2022). They found that despite numerous national subsidy measures to keep energy bills at a manageable level, people may decide to reduce heating or not heating their homes at all as long as possible, regardless of their effects on comfort or health, in order to save heating energy and avoid skyrocketing energy bills (Sgaravatti et al., 2023).

Despite the difficulties faced by consumers, the energy crisis highlights the vulnerability of relying on foreign fossil fuels and offers an opportunity to accelerate the transition toward a more sustainable energy system (IEA, 2022). Multiple nations have responded quickly to the current developments, such as the US Inflation Reduction Act, the EU's Fit for 55 package and REPowerEU, Japan's Green Transformation (GX) program or Korea's aim to increase the share of nuclear and renewable electricity generation (European Commission, 2022; IEA, 2022; The White House, 2023). In speeding up the energy transition, the challenges, such as enabling demand to follow the increasingly volatile electricity supply from renewables, need to be addressed as soon as possible. While the industry sector is already participating in load shifting or shedding in Germany (AbLaV, 2016), limited options exist for private households, comprising so far only dynamic and variable electricity tariffs by a handful of electricity providers (Weigl, 2021). Tariffs that account for energy and power consumption do not exist in Germany so far. To ensure the success of such tariff schemes, it is vital to consider the households' decision process to adopt these tariffs. A household's willingness to engage in variable tariffs may be reduced by the effort to provide load shifting (Schlereth et al., 2018) and unpredictable price developments (Ruokamo et al., 2019). Existing research analyses various economic and non-economic incentives to address the domestic load shifting abilities under real-world conditions, revealing varying results (Alan et al., 2015; Azarova et al., 2020; Bartusch & Alvehag, 2014; Ito et al., 2018; Nilsson et al., 2018; Scharnhorst et al., 2021; Stamminger & Anstett, 2013). Few pilot studies exist, however, that evaluate household acceptance and participation in load shifting or shedding to maintain below a specified power threshold along with a detailed empirical examination (Scharnhorst et al., 2021). Furthermore, the urgency of the energy crisis has not allowed for pilot studies that investigate the incentives and circumstances motivating tenants to prioritize energy savings over comfort. To address this gap, we conducted a field study in the Energy Smart Home Lab (ESHL), where two tenants lived for six weeks, receiving various calls to action to alter their heating and electricity consumption behavior in response to different economic and non-economic incentives.

Hence, our study approach is two-fold: First, to assess the tenant's reaction and engagement with calls to action on their room heating behavior and second, how the tenants respond to various incentives designed to induce demand response behavior. This leads to the following research questions:

I. *To what extent are tenants willing to lower room temperature set points to comply with a given incentive?*
II. *What incentives and other factors influence the tenants' willingness to comply with load shifting or shedding?*

2 MATERIALS AND METHODS

This Section describes the experimental setup in the Energy Smart Home Lab, as well as the experiment design. We further elaborate on the participants' demographics and present the measuring and sensor system, the empirical methods applied for data collection and analysis.

2.1 The Energy Smart Home Lab

The Energy Smart Home Lab (ESHL) located on the Karlsruhe Institute of Technology (KIT) campus, is a fully operational smart home and living lab with integrated sensor and measurement systems. The 60 m² space includes a combined living and kitchen area, two bedrooms, and a bathroom, accommodating up to two tenants simultaneously. Tenants can adjust temperature set points in 0.5 °C increments for the living room and bedrooms through a dashboard. Further details on the ESHL setup are available in (Scharnhorst et al., 2021).

2.2 Experiment design

We used various calls to action along with economic and non-economic incentives to elicit the tenants' responses and behavioral changes. Regarding heating, we introduced calls to action to lower room temperatures for a pre-determined time (several days) to reduce the heating demand. For electricity demand, we implemented load shedding or shifting during designated hours. Economic incentives involved monetary rewards for compliance and penalties for non-compliance. Non-economic incentives tapped into tenants' environmental and societal values.

In September 2022, Germany's national energy conservation regulation came into effect, enacting a maximum room temperature of 19 °C in public workplaces (Federal Cabinet, 2022). Private households are not required to abide by this law, but it gives them the option of voluntarily providing energy savings by suspending contractual obligations of residential tenancies to maintain a specific minimum temperature to avoid damage (such as mold or frost) inside the rented asset (EnSikuMaV, 2022). To decrease the chance of mold formation, the federal environment agency advises not allowing room temperatures to fall below 16 to 18 °C and maintaining room temperatures between 19 to 20 °C (during the day) throughout the heating period of 2022-2023 (Moriske et al., 2017; Umweltbundesamt [UBA], 2022a, 2022b). We designed the experiment accordingly, starting with a reference period without any calls to action, followed by four heating calls to action lasting four to seven days.

Table 1 - Overview of calls to action incentivizing the adjustment of temperature set points

No.	Incentive E: economic N: non-economic	Proposed set point temperature [°C]	
		Day (6 am -10 pm)	***Night (10 pm – 6 am)***
I	N	No given set point, voluntary reduction of heating. Advice to not set below 16 °C.	
II	E	No given set point, voluntary reduction of heating, compensation starts below 21 °C, lower bound 16 °C.	
		Automatic set points:	
III	E	19 °C	16 °C
IV	N	19 °C	16 °C

Tenants were encouraged to set room temperatures below 21 °C for energy savings, with the first call appealing to their moral values and the second offering monetary rewards (Table 1). Calls to action III and IV automatically set the temperature set points to 19 °C at daytime and 16 °C at night. While the tenants could always manually adjust these set points, deviations from the initially set temperature resulted in either compensation or cost to the tenants in terms of economic incentives. The compensation or cost for saved or excess heating energy, respectively, is calculated as follows:

$$c = s\, c_{ng}\, f \sum_{t=1}^{n} \Delta T_{sp,t}\, E_t \tag{1}$$

With

c: compensation or cost in Euro

$\Delta T_{sp,t}$: deviation of set point temperature from 21°C for computing the compensation or the set point temperature from 19 °C for computing the cost of additional energy consumption

E_t: heating energy consumption in kWh

s: heating energy saving in % per °C

c_{ng}: cost of natural gas in €/kWh

f: scaling factor

t: respective time interval

By lowering the temperature to 19 °C during the day and 16 °C at night, the second economic incentive aimed to assess the tenants' unwillingness to pay and reduce the financial gain they had thus far obtained. If there was a positive deviation from these temperature specifications, the extra energy use would be charged. Calls to action were employed to evaluate tenants' load flexibility, involving specific time intervals and power thresholds. These actions, referred to as "grid bottlenecks," required the load not to exceed 2 kW or 3 kW for three hours, with a compensation of 6 Euros (3 Euros per tenant) or non-economic incentives. These intervals were typically scheduled during peak load periods, such as mornings and evenings. Compensation was calculated based on the electricity rates during the study, which amounted to 0.44

Euro/kWh (Bundesverband der Energie- und Wasserwirtschaft [BDEW], 2023). On average, a two-person household in Germany consumes 2000 kWh of electricity annually, translating to an hourly use of 0.228 kWh and an hourly cost of 0.10 €/kWh (Weißbach, 2021). For the six-hour duration of the call to action, this equated to 1.37 kWh or 0.60 €. To provide substantial but not excessive compensation for the six-week experiment, this value was scaled up by a factor of 10, following a similar approach used in prior studies (Faruqui & Sergici, 2011; Kato et al., 2016).

2.3 Demographics of participants

The two tenants, a male and a female, shared an apartment in the ESHL, both being German KIT students. Their participation in the study was entirely voluntary and not related to any mandatory degree requirements in their academic fields.

2.4 Measuring and sensor system

The power demand of every device in the building was monitored with a temporal resolution of one second during the experiment. The thermal power flow to the buildings' radiators was measured with a temporal resolution of two minutes to account for the heating consumption.

2.5 Empirical methods

Regular interviews were conducted to acquire a deeper insight into the motives and reasons for the tenants' behavior. One interview was conducted before the calls to action were sent, two interviews were conducted during the residential period, and one in-depth interview was conducted following the experiment.

2.6 Limitations

With a household comprising two persons, we recognize that the sample size of the experiment is very limited. Therefore, our findings may not be applicable to other households. However, the study design, as well as the findings may be used for reference, when designing experiments with a larger sample of households to acquire representative results.

3 RESULTS

In terms of both economic and non-economic incentives, the results demonstrate a general strong motivation to fulfill the incentivized adaption in heating and electricity consumption. However, not all of the calls to action were followed through on.

3.1 Lowering the heating set point

In the initial week with no calls to action, set points remained below 21 °C except for bedroom 2, which increased to 21 °C on December 12 at 12 a.m. During the first call to action, the tenants met the non-economic incentive by keeping the set points considerably below 21 °C. In response to the second call to action, all rooms remained below 21 °C, earning them 9.5 € in compensation. Tenant B was absent on weekdays, during the working hours, due to an internship in the first half of the experiment.

"Now I have set the temperature in my room to 18.5 °C when I am not at home during the day, but I know if I would sit and work at my desk all day, it would feel a bit fresh." (Tenant B, interview 2, translated from German)

Tenant B noted that the lower room temperatures in the bedroom were acceptable since most activities took place in the living room in the evening. Following voluntary set point reductions during the first two calls to action (I and II), calls to action (III and IV) all gave default set points of 19 °C during the day and 16 °C at night. Figure 1 depicts the third call to action (III), including the set points, measured indoor and outdoor temperatures, and heating demand. The set points in both bedrooms were lowered below the upper limit of the call to action, which is an interesting reaction given that this behavior was not monetarily rewarded. Neither tenant stated their intention to behave in this manner throughout the interviews. The main room's set point was only ever raised from 19 to 20 °C on January 22 in the morning. The excess heat cost of increasing the temperature set point by 1 °C was calculated for the time period of the active set point morning to evening (10 pm) on 22 January, and amounted to 1.4 Euro.

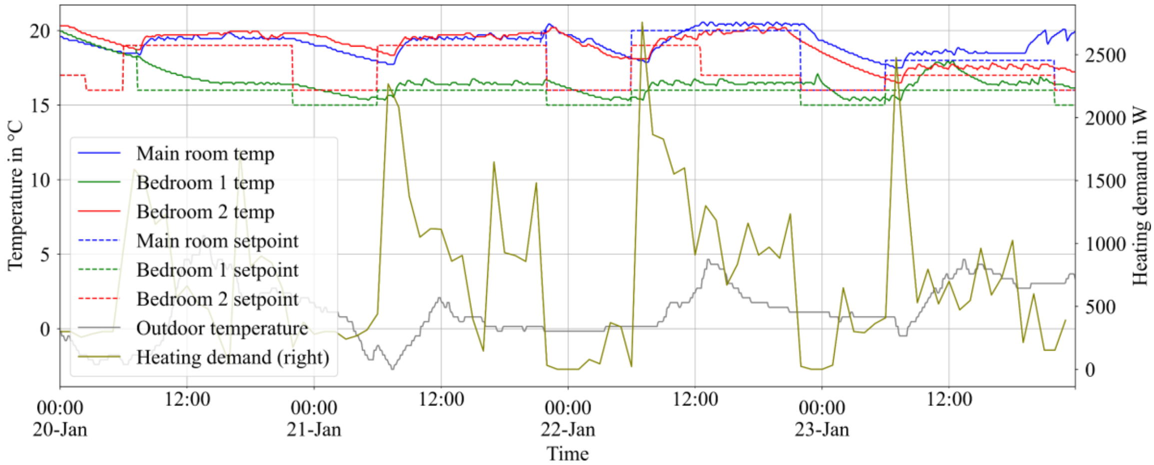

Figure 1 - Temperature et points, measured indoor and outdoor, temperature in °C, as well as heating demand in W for the heating call to action III

The set point was decreased the next day to 18 °C so no further cost for excess heating occurred. Tenant A described the temperature in the main room as:

"For me, this is still comfort temperature. I think we still have 19 °C in the living room, and with a sweater or something similar, this is totally acceptable." (tenant A, interview 2, translated from German)

Call to action IV was unsuccessful, as the bedroom 1 set point temperatures, initially below the target, were adjusted, with daytime increasing by 1.5 °C and nighttime by 1 °C. Out of the four calls to action, two went unmet in the final third of the residential phase, with no comments from the tenants during interviews, leaving the motive for overriding and raising temperatures unknown. Call to action III, with economic incentives, posed comprehension challenges due to a lack of detailed information on the incentive, eventually prompting a temperature increase, possibly due to discomfort, and then a 2°C reduction the following day. The fourth non-economic call to action did not lead to a reduction in temperature. Factors like decreased activity or falling outside temperatures could have played a role. This contrasts with the tenants' claims of efficient heating management and adaptability during the interviews. The absence of direct feedback on the dashboard, unlike electricity-related actions, may have made heating-related calls to action less prominent for the tenants.

3.2 Flexibility provision in electricity consumption

On eleven days, the tenants received calls to action for flexibility in the event of a grid bottleneck. Table 2 shows four calls to action related to economic incentives and seven to non-economic ones.

Table 2 - Calls to action to shift or reduce load in specific time intervals

No.	Incentive E: economic N: non-economic	Duration 3 hours per interval 2 intervals per day		Incentive achieved (Y: yes, N: no)
1	N	6 am – 9 am	6 pm – 9 pm	N
2	N	6 am – 9 am	6 pm – 9 pm	N
3	E	6 am – 9 am	6 pm – 9 pm	Y
4	E	6 am – 9 am	6 pm – 9 pm	Y
5	N	9 am – 12 pm	9 pm – 12 am	Y
6	N	12 pm – 3 pm	5 pm – 8 pm	Y
7	N	8 am – 11 am	8 pm – 11 pm	Y
8	E	12 pm – 3 pm	5 pm – 8 pm	Y
9	E	8 am – 11 am	8 pm – 11 pm	N
10	N	12 pm – 3 pm	5 pm – 8 pm	N
11	N	8 am – 11 am	5 pm – 8 pm	N

The tenants responded to the call to action six times, achieving three out of four economic incentives and receiving 18 Euros in compensation. Figure 2 illustrates successful load shifting.

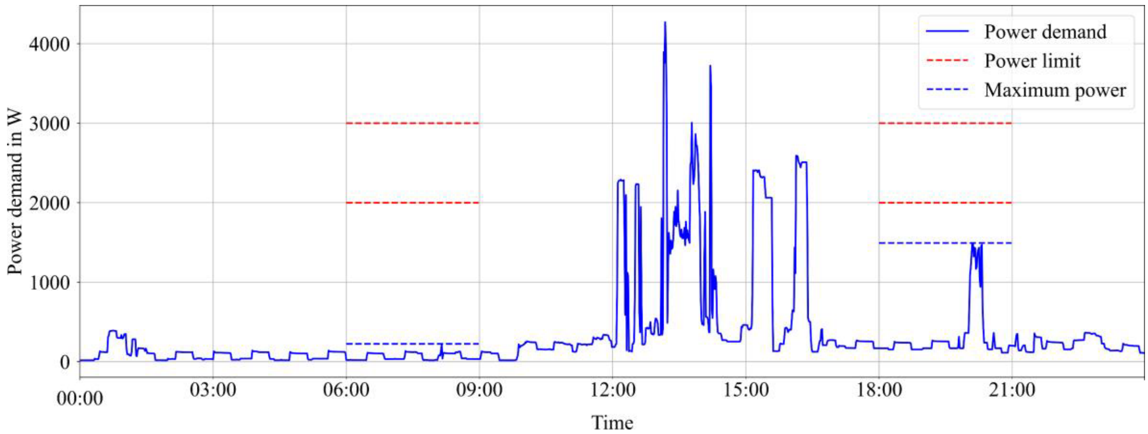

Figure 2 - Call to action representing successful load shifting by the tenants of the Energy Smart Home Lab

Interviews revealed diverse reasons for the remaining five call-to-action failures. The first grid bottleneck call to action encountered a dashboard programming error, falsely indicating a threshold breach at 4 pm, though the interval started at 6 pm. This led the tenants to believe they had already failed, causing them to disregard the threshold. The subsequent call to action, occurring on a Sunday, was unintentionally ignored, as Tenant B had scheduled the washing machine to run at a peak of 2.15 kW, coinciding with the action's start. On two other days (the 9th and 10th grid bottleneck call to action), tenant B declared not to have had another time slot available that day to transfer activities such as running the dishwasher or the tumble dryer. The last grid bottleneck was breached due to the 'apple pie incident'.

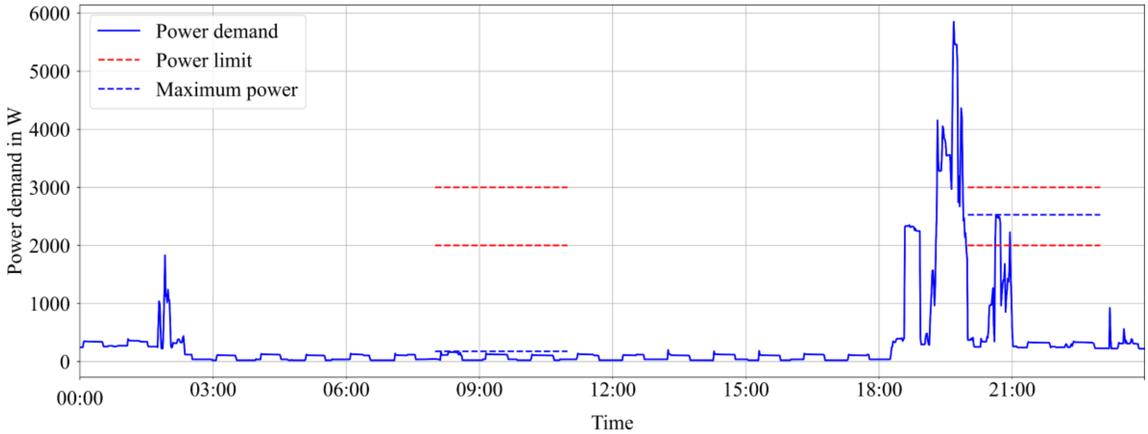

Figure 3 - Call to action 11 representing failed load shifting in the second time interval of the grid bottleneck by exceeding the 2 kW threshold with a peak power of 2.5 kW

Tenant A intended to bake an apple pie, preheating the oven before 5 pm (the threshold start time) to finish baking the apple pie with the oven switched off, and utilizing the residual heat during the interval. Because of growing doubts about the plan's feasibility, the oven was restarted, forcing it to reach its peak power of 2.1 kW and surpassing the 2 kW power threshold (Figure 3). Tenant A stated that regardless of the economic or other sorts of incentives presented, they were generally interested in following the calls to action:

"For me, the financial incentive had no bearing and I always attempt to follow through on the calls to action." (Tenant A, interview 3, translated from German)

Tenant B, on the other hand, contended that transferring load under bottleneck conditions would be motivated more by economic rather than non-economic incentives. Both sides acknowledged the challenges associated with the timing of the bottlenecks, citing kitchen usage (e.g., the stove and oven) as the main impediment, particularly in the evenings:

"The hours between 6 and 9 am and 6 and 9 pm are challenging when one is the entire day away. To prepare meals in the morning and set the oven to cook so that dinner is ready when one arrives home requires a lot of forethought and effort." (Tenant B, interview 3, translated from German)

Four of the five failed calls to action, featured non-economic incentives, while one involved economic incentives. Because seven non-economic and only four economic incentives were tested, and since both tenants would, ultimately, influence the decision of the one household they represented, it is impossible to say with certainty whether the economic or non-economic incentives worked better. Though findings suggest a preference for economic incentives, tenant responses were significantly influenced by contextual factors, such as the presence of guests.

3.3 Guidelines for future experimental designs

From the lessons learned during this experiment, we derived the following guidelines to support and improve future experiments in living labs that examine comfort levels and energy consumption behaviors of residential consumers:

1. Start with a reference period (without incentives)
2. Check for economic, as well as non-economic incentives
3. Check for compensation, as well as cost schemes
4. Account for temperature change inertia (e.g., long-term residential phase of at least eight weeks, incentive schemes over multiple days)
5. Adequate user interface for real-time feedback and easy interaction
6. Adequate data gathering equipment
7. Adequate sample size

Starting with a reference period is crucial to enable tenants to acclimate to the new living conditions and establish their daily routines. This period enables unaltered observation of energy consumption, facilitating adjustments to planned incentives. If early observations reveal e.g. deviations from standard load profile, incentive timing should be adapted. Recognizing the significance of non-economic incentives, studies emphasize that household decisions are not solely economically driven (Parrish et al., 2020). Real-time feedback empowers tenants to monitor and improve their energy consumption behavior.

4 CONCLUSIONS

In a two-month field study, two occupants resided in the Energy Smart Home Lab and received calls to action involving economic and non-economic incentives to adjust their electricity and heating demand. Analysis of recorded data, encompassing electricity and heating demand along with temperature settings, was supplemented by regular interviews to uncover motivations for their behaviors. The results indicate a genuine willingness to conform to incentivized changes in energy consumption, encompassing both economic and non-economic incentives. Lowering heating demand did not significantly disrupt the tenants' comfort, but during the final third of the study, temperature settings were raised despite continued claims of compliance with heating calls to action, indicating a preference for comfort over incentives. Not all of the calls to action on electricity consumption were heeded, as well. Some calls to action for electricity usage were ignored due to social commitments, pre-existing schedules, or unnoticed notifications. As this study examined only one household, its findings may not be universally applicable, necessitating further research with a more diverse sample for representative results.

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