NUDGE

Nudging consumers towards energy efficiency through behavioural science

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About

Efforts to induce energy-friendly behaviour from end-users through behavioural interventions are characterised by (i) a lack of customer personalization ("one-size-fits-all interventions"), (ii) a partial understanding about how different interventions interact with each other, and (iii) contrasting evidence about their effectiveness, as a result of rare testing under real-world conditions.

NUDGE has been conceived to unleash the potential of behavioural interventions for long-lasting energy efficiency behaviour changes, paving the way to the generalized use of such interventions as a worthy addition to the policy-making toolbox. We take a mixed approach to the consumer analysis and intervention design with tasks combining surveys and sensor data in field trials. Firmly rooted in behavioural science methods, we study individual psychological and contextual variables underlying consumers' behaviour to tailor the design of behavioural interventions for them, with a clear focus on interventions of the nudging type.

The designed interventions are compared against traditional ones in field trials (pilots) in five different EU states (Greece, Belgium, Germany, Portugal and Croatia), exhibiting striking diversity in terms of innovative energy usage scenarios (e.g., photovoltaic production for electric vehicle charging, demand reduction for natural gas), demographic and socio-economic variables of the involved populations, mediation platforms for operationalising the intervention (smart mobile apps, dashboards, web portals, educational material and intergenerational learning practices).

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Project partners

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Executive summary

The NUDGE project focuses on testing the potential of behavioural-science inspired energy efficiency interventions with real users and quantifying the respective energy-efficient behaviour change by implementing pilot trails in five different countries, with a striking diversity in terms of energy usage scenarios. In general, the trials were designed to evaluate three nudging interventions (called also NUDGE 1, 2 and 3), with the aim of supporting consumers' behavioural choices in relation to the use of energy in a predictable manner, without limiting their options. This report documents the main outcomes obtained from the events and activities held by the 5 pilots throughout the NUDGE project. In particular, it comprises an overview of the results generated from the activities conducted under the framework of Work Package 4 "Implementing energy interventions through field trials".

Brief Overview of the pilot implementation plan and results

Efficient control of heating and domestic hot water preparation for natural gas consuming boilers in Greece – GR Pilot

The Greek pilot focused on optimally tuning the operation of natural gas boilers for space heating. In total 102 participants living in five different cities in Greece were recruited. A DOMX smart heating controller was installed in all participating homes enabling the optimal management of legacy natural gas boilers through fine grained modulation control, weather compensation and scheduling, ultimately offering up to 30% of energy savings, while respecting the user comfort limits. In addition, all participants installed the DOMX App (the interface used to release the nudges) and the DOMX wireless thermostat (to optimally manage the operation of their heating system). The findings did not allow to corroborate hypotheses related to the effectiveness of NUDGE 1 (focused on providing information about the gas consumption over different intervals) and NUDGE 2 (devoted to getting feedback when a high room target temperature is defined or the user choose to disable the adaptive heating control feature) in promoting energy efficient behaviours and energy savings. In turn, by adjusting the analysis taking into consideration the days of nudge exposure (based on app usage data), NUDGE 3 (centered in sending push notifications requesting users to lowering their heating balance/heating hours in case of adequate weather conditions or congratulating them for using energy friendly settings) resulted in a small reduction in gas consumption.

Interdisciplinary project-based education on home energy consumption for children in Belgium – BE Pilot

The research conducted in Belgium aimed to promote behavioural changes in school-age children and their families through educational campaigns focusing on energy consumption aspects. Two cohorts were recruited during the academic years 2021/2022 (36 intervention students and parents + 28 control adults) and 2022/2023 (40 intervention students and parents + 33 control adults). Three specific nudges were integrated during the lessons: feedback and awareness (reinforcement), enabling social comparison and setting a common and personal goal (social influence). The lessons were combined with the activities for the visualisation of the recent energy consumption in the participant homes. Before the start of the lessons the (digital) electricity and gas meters existing in the participant homes (linked to the EnergyID platform, an openly accessible platform that is made available by a Belgian social co-operative to families, organisations, and cities) were connected to the central NUDGE platform. Five themes were specifically selected for the lessons: home gas consumption (and other ways of heating the house), electricity consumption, water use, electricity production and nudging. For the measurement of the behavioural effects of the nudges, questionnaires (pre-test and post-test) were developed. Findings showed that most children demonstrated to be interested, motivated, engaged and active during the lessons. However, the evidence collected did not corroborate significant positive impact on the knowledge, intention and motivation to save energy of the pupils and their families. Also, although gas consumption had significantly decreased after the children followed the course in the 1st cohort, this was not confirmed for the 2nd cohort. Noteworthy, the implementation of this pilot resulted in the preparation of educational booklets with important background information, tables, graphs and exercises for the children that were distributed to 150 schools in and around Leuven. This material was also translated to English and it is freely available on the NUDGE project website.

Optimization of electric vehicle (EV) charging with self-produced photovoltaic (PV) power in Germany – DE Pilot

The German pilot engaged 111 residential households having a PV-system installed from the existing customer base of MVV Energie AG in the Rhine-Neckar metropolitan area. 39 of these participants also had an EV charging station (EVCS) at home able to be connected and controlled remotely by beegy (EV group). The nudges tested in this pilot aimed to promote sustainable energy saving and optimised self-consumption in prosumer households, specifically focusing on prosumer households with EV. The nudges were delivered to participants through two nudging platforms: i) Web-Portal (all participants) allowing to visualise the energy flows at home and ii) the charging app HERMINE and subsequently "surplus charging" (only available to customers of the EV group). Motivation and the intention of the participants to save energy and optimise the use of the self-produced PV power proved to be very high throughout the project as well as customer engagement. Whilst motivation remained stable, comparing survey results throughout the field test, the intention to save energy as well as the intention to use more of one's own PV power increased significantly during the project.
According to the pilot outcomes presented in this report, the NUDGEs 1 and 2, providing "Feedback" and creating "Awareness" on key energy efficiency targets as well as "Comparisons", "Suggestions" and "Controls" to initiate efficient behaviour, resulted in a modest increase in self-consumption, typically in the range of 3-4 %. Findings also showed that the EV group responded much more strongly to the nudges, increasing its self-consumption by 10-12% (compared to the average effect of 2-3% over the full set of participants). Further, a significant reduction in household consumption was observed during NUDGE 1 and 2. Looking at NUDGE 3, the opt-in setting for surplus charging, led to a substantial 16 % increase in self-consumption among active participants in the EV group. However, NUDGE 3 led to an increase in electricity consumption (possibly associated with an increase in EV charging at home).

Healthy homes for long-lasting energy efficiency behaviour in Portugal – PT Pilot

The study implemented in Portugal aimed to promote energy savings in terms of electricity consumption while providing healthy and comfortable homes for 101 families with children. The pilot study included a comprehensive building survey and installations of smart meters in the participant homes to continuously monitor electricity consumption and the deployment of indoor air quality (IAQ) sensors to assess carbon dioxide (CO_2), airborne particles, temperature and relative humidity levels. Nudges were delivered through an app that was specifically developed for the pilot. The analysis of the datasets obtained allowed to identify factors significantly influencing electricity consumption (home dimension, occupancy, typology and construction period of the dwelling, and orientation of window glazed facades) and air quality (use of bottled gas and wood or pellets for heating, indoor smoking and the existence of physical pathologies inside the dwelling such as cracks in the walls). NUDGE 1 (providing historical electricity consumption) did not produce a noticeable effect on electricity consumption but significantly increased participants' motivation to save energy (but not their intention to do so). Interestingly, during NUDGE 2 (allowing the users to visualise indoor air quality [IAQ] data) resulted in a significant increase in the intention to save energy and in the perception of participants' self-positioning in relation to energy issues. In addition, this nudge was effective in reducing the average CO_2 concentrations, with a large percentage of participants recognising that the data provided helped them to better understand the factors that influence IAQ and that they would feel more motivated to save energy if aspects related to ensuring a high IAQ were considered. Lastly, the outcomes were not entirely clear about the effect of NUDGE 3 (focused on electricity use for heating) on electricity consumption (and on promoting behavioural changes), probably influence by the national context (i.e., of the great percentage of Portuguese families that are unable to keep their home adequately warm).

Promoting distributed self-production for local energy communities in Croatia – HR Pilot

The Croatian pilot focused on providing relevant knowledge and resources to allow consuming households to navigate evolving regulations, optimise energy consumption, increase energy-efficiency in homes, and to understand which nudges are relevant to achieve higher self-consumption and less grid dependence. For this purpose, 82 consumers having PV systems installed in their home were actively engaged, and real-time data on both electricity consumption and production was continuously monitored. A user-friendly smartphone app was specifically developed for the pilot to expose participants to nudges. Briefly, the nudges designed aimed to cultivate empathy, enhance awareness of energy usage, and encourage energy efficiency goal-setting. In general, the investigation of the effectiveness of feedback and awareness nudges (NUDGE 1 and 2) in adjusting energy consumption and production were not consistent across the different households. Nevertheless, tested goal-setting nudges (NUDGE 3) resulted in some evidence of improvements in energy efficiency. Moreover, the outcomes of the pilot also suggest that consumers tend to adapt their energy use in response to external factors, namely changes to regulatory frameworks, leading to unexpected behaviours such as increased electricity consumption during high production periods or even shutting down PV systems. Overall, the diverse nudge strategies collectively seemed to contribute to fostering energy-conscious behaviour to some extent. However, the critical analysis of the obtained results showed the need for more adaptive and personalised strategies as a priority for further studies.

Overview conclusions

The implementation of the 5 pilot trials of the NUDGE project allowed to generate real-life datasets on energy use (and PV production, where applicable) for more than one year for the 472 engaged households. Nudging interventions were mainly focused on using the real-time energy data collected with the aim of empowering the households with relevant information that they can use to comprehensively understand their consumption patterns and to identify opportunities for improvement. The exploration of data collected resulted in important insights to advance the current understanding of household energy demand

and of the effectiveness of specific nudging interventions that seemed to be easily dominated by external circumstances.

Report structure

The report first provides a brief introduction to the five NUDGE pilots and target populations that were engaged (Section 1), followed by an overview on the methodologies on what was implemented per pilot, a description of the main results and of the conclusions derived by each pilot (Section 2), and finally, Section 3 sets out final conclusion remarks derived from the execution of the five trials.

Links with other project deliverables

This report is linked to several technical deliverables namely those linked to monitoring the pilot implementation and analytics of data collected (technical documents with restricted access). An important result of the five trials is relative to nudging impacts estimation which are comprehensively discussed in Deliverable 2.3 – Final report on the evaluation of nudging interventions through pilot data, where the datasets originated from the pilot implementation are comprehensively analysed with the main goal of assessing impacts of the nudging interventions employed in the studies.

1. Introduction to the NUDGE pilots

This report is part of the Work Package (WP) 4 "Implementing energy interventions through field trials" of the NUDGE project, aiming at compiling summary information on the overall trials' implementation plan, and on the respective outcomes resulting from the implementation of the five NUDGE pilots.

The NUDGE project includes a comprehensive applied methodology focusing (i) on testing the potential of behavioural-science inspired energy efficiency interventions with real users and (ii) on quantifying the respective energy-efficient behaviour change from the implementation of five pilot trials in different European countries:

- *Efficient control of heating and domestic hot water (DHW) preparation for natural gas consuming boilers in Greece – GR Pilot;*
- *Interdisciplinary project-based education on home energy consumption for children in Belgium – BE Pilot;*
- *Optimization of electric vehicle (EV) charging with self-produced photovoltaic (PV) power in Germany – DE Pilot;*
- *Healthy homes for long-lasting energy efficiency behaviour in Portugal – PT Pilot;*
- *Promoting distributed self-production for local energy communities in Croatia – HR Pilot.*

The five pilots offer high heterogeneity and variety regarding contextual factors of the pilot participants (e.g., country, age groups, income), energy use cases (e.g., household heating, EV charging, PV production), technology/platform used for operationalising the interventions (e.g., mobile apps, web portal) and the means of measuring and communicating (e.g., human interaction, short notifications by a feedback system). At the same time all pilots implemented energy monitoring and management approaches (typically smart meters for continuous monitoring of energy consumption and – where applicable – production) and digital user interfaces (enabling the interaction with end consumers and the operationalization of the planned interventions), suited to the pilot-specific needs. In general, the execution of the pilots followed an identical three-phase time plan that includes pre-intervention (baseline data), intervention (testing of the planned interventions) and post-intervention phases (long-lasting behavioural change analysis). The intervention phase consisted of the implementation of three sequential interventions ($1^{st}/2^{nd}/3^{rd}$ intervention phases, called also NUDGE 1, NUDGE 2 and NUDGE 3) that were delivered to the users through the pilot-specific interface tools (apps, webportal).

The interventions tested in the NUDGE project were pilot-specific and designed to influence the behaviour of the engaged consumers through various nudging strategies (e.g., default settings, provision of information), aiming at inducing subtle changes to the choice architecture and guiding participants towards better (energy-efficient) and more informed decisions (without forbidding any option or significantly changing their economic incentives). To assess the effectiveness of the interventions in reaching the desirable changes, the nudging interventions in each pilot were implemented as randomized control trials, including the distribution of questionnaires at specific time points (during pre-intervention and immediately after each intervention).

The participant recruitment for the trials was driven by the defined eligibility criteria properly adjusted to the pilot-specific characteristics. The type and number of participants effectively engaged in the NUDGE project per pilot are presented in Table 1.

Table 1. Participants recruited with energy data flowing to NUDGE central platform, originally planned versus actual participation per pilot.

Country	Institute	Eligible participant description	Number of participants planned on GA	Number of participants of the trial
Greece (GR)	DOMX	Residential clients of DOMX and their families with natural gas boilers for space heating	100	102
Belgium (BE)	SPRING-STOF	School children and their families having energy meters installed in their house	50	76*
Germany (DE)	Beegy	Residential clients of MVV and their families having a PV-system connected to the beegy gateway, preferably with an EV and an EVCS at home	100	111
Portugal (PT)	INEGI	Families with children younger than 12 years-old	100	101
Croatia (HR)	ZEZ	Households with PV financed by a national initiative and supported by ZEZ Energy Cooperative	100	82

GA, Grant Agreement; PV, Photovoltaics; EVCS, Electric vehicle charging system
* 1st cohort: 36 students attended the lessons but only 22 had a digital energy meter (+ 28 control group not exposed to nudging treatment). 2nd cohort: 40 students attended the lessons (34 with a digital energy meter + 33 control group not exposed to nudging treatment).

In accordance with the Grant Agreement, in each pilot country, the target number of households to include in each trial was 100, except for the case of Belgium, for which the target was established to 50 (25 per cohort attending lessons in the academic years 2021/2022 and 2022/2023).

During the implementation of the trials, the pilots faced several difficulties, namely related to external factors caused by the COVID-19 pandemic from March 2020. The project was thus forced to adapt and change recruitment, namely due to the difficulties in scheduling home visits for installation of smart meters in participant homes and also due to the significant increase of cost of equipment. Despite specific mitigation actions which were derived and implemented, these events caused significantly higher effort and time spent on participants' acquisition for all five pilots. Despite these challenging circumstances, only in the Croatian pilot, the target number of participants needed to be reduced from 100 to 82 to keep the budget. Nevertheless, all five pilots ensured the execution of the planned trials and the successful accomplishment of their proposed objectives.

2. Individual Pilots: Overview and Main Results

2.1. The Greek (GR) pilot

2.1.1. Overview on Pilot implementation

Context and Aim

In the EU, 62.8% of the consumed energy in households is for space heating and natural gas is with 38.0% the main energy source (Sakellariou et al., 2023). In Greek homes, 57.1% of their total energy consumption is for space heating and this comes mainly from heating with oil by 46.7% of households, from renewables by 29.0% and from natural gas by 16.9%. While heating oil accounts for about half of the total energy consumed for space heating and definitely has the highest penetration in the Greek market, the market share of natural gas is continuously increasing and is primarily consumed in the big cities of Greece. Given the increasing adoption of natural gas for space heating in Greek households, the Greek pilot focused on optimally tuning the operation of natural gas boilers for space heating. The integration of the DOMX smart heating controller with legacy natural gas boilers enables their optimal management through fine grained modulation control, weather compensation and scheduling, ultimately offering up to 30% of energy savings, whilst respecting the user comfort limits.

Study design and methodology

The pilot implementation started with the recruitment activities that were split into 3 main phases: i) DOMX mailed and contacted a pool of their existing customers to inform them about the NUDGE pilot activities, ii) the research teams of collaborating energy suppliers were contacted, in order to approach users from their portfolios and iii) three existing DOMX partners heating, ventilation, and air conditioning (HVAC) installation maintenance companies were contacted, in order to promote the DOMX device and services, by explaining the benefits of joining the NUDGE pilot activities. In order to be eligible to participate in the study, participants had to meet the following criteria: They needed to have i) a natural gas boiler for space heating (OpenTherm, which is an open boiler control protocol via we can control boiler parameters or ON/OFF boilers), and ii) Wi-Fi at home. These recruitment activities resulted in 102 eligible participants across five different cities in Greece (see section 2.1.2), who have been contacted for scheduling the installation of the DOMX smart heating controller. These installations mainly took place between October 2020 and December 2022, before the start of NUDGE 2 period. The pilot population consists of various household types (single households, couples with or without children), house dwelling sizes/energy classes and peoples' age and education.

The pilot started with the pre-intervention phase for baseline data collection (room, user target, boiler, outdoor temperature, boiler consumption data and setpoints) in the first set of households recruited (n=43) which was conducted between October 2021 and December 2021. DOMX had also baseline data from the past cold season of 2020 for a subset of 30 households. After the successful installation of the smart heating controller at pilot homes, all participants installed the DOMX App and used the DOMX wireless thermostat to optimally manage the operation of their heating system. Greek pilot's intervention plan consisted of 3 intervention/nudging phases (NUDGE 1, 2 and 3), that were delivered through the app. These nudges (new app functionalities) were not removed at the end of each nudging phase. Thus, during the second intervention phase, pilot participants were exposed to both NUDGEs 1 and 2, and during the third intervention, they were exposed to NUDGES 1, 2 and 3. Briefly, NUDGE 1 was focused on providing information about the gas consumption over different intervals (week, month, year), both for space and water heating. NUDGE 2 was about getting feedback from the app when setting a high room target temperature or trying to disable the adaptive heating control feature. Finally, NUDGE 3 was focused on push notifications for nudging the users to lower their heating balance/heating hours in case of good weather conditions or congratulating them in case of using energy friendly settings.

NUDGEs and research questions

The intervention plan included the implementation of three nudging treatments, with the purpose to address and test the following research questions:

- **NUDGE 1** – *How might the access to detailed historical gas consumption data through a smartphone app impact the behaviour of residential consumers and their gas consumption?*

This nudge was mainly tested from January 2022 till March 2022 and allowed users to monitor their gas consumption at home during the intervention period. The delivery of this nudge included the introduction of new features in the app:

  - *Introduction of a new screen that allowed the users to visualise gas consumption over different intervals (week, month, year), used for both space and water heating.*
  - *The screen also visualised the consumption of the current month in comparison with the previous month.*

- **NUDGE 2 –** *How effective can just-in-time prompts be in affecting long established behaviours related with non-energy efficient habits?*

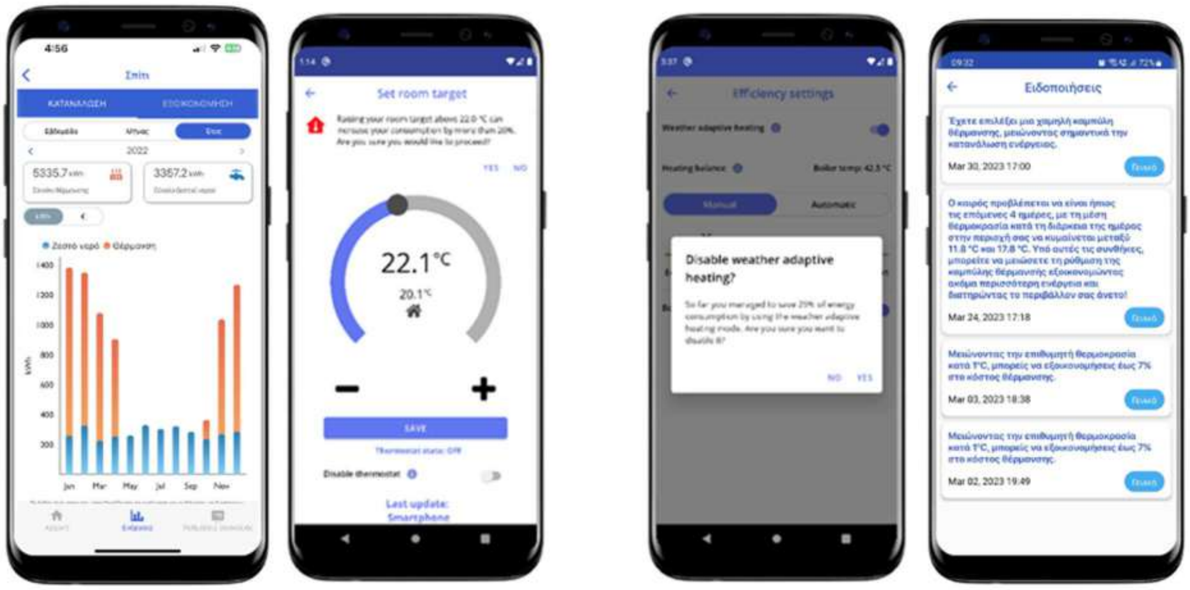
This nudge was mainly tested from December 2022 till January 2023. It informed and tried to prevent the users from applying non-energy friendly feature settings (e.g., disabling the adaptive heating control feature). The delivery of this nudge included the introduction of new features in the app:

  - *Banner with consumption feedback when setting the room target to higher temperature values than 22 °C.*
  - *Alert box reminding users of the energy consumption savings, when attempting to disable the adaptive heating control.*

- **NUDGE 3 –** *Is it possible to affect the behaviour of energy consumers through personalised energy saving suggestions?*

This nudge was mainly tested from February 2023 till March 2023, and it informed users about their interaction with the app, the things that they can improve or things that they have done well. The delivery of this nudge included the introduction of new features in the DOMX app:

- *Push notifications periodically delivered to users suggesting the adoption of energy efficient mechanisms:*
  - *switching from manual to automated control of the heating trade-off for optimal assignment based on the heating requirements of each household*
  - *lowering the target temperature (applicable to ON/OFF boilers as well)*
  - *Congratulating for users' eco-friendly behaviour and energy consumption reduction*
  - *Urging them to use lower heating balance/reduce heating hours under mild weather conditions.*



NUDGE 1 NUDGE 2 NUDGE 3

Figure 1. Nudges in the DOMX app for the Greek pilot.

2.1.2. Participant Households

A total of 102 households were equipped with the DOMX heating controller in the GR pilot. The GR pilot included participant households in five different cities: Thessaloniki (n=83), Volos (n=11), Athens (n=6), Kalampaka (n=1) and Karditsa (n=1). The approximate location of the participant households is presented in Figure 2.

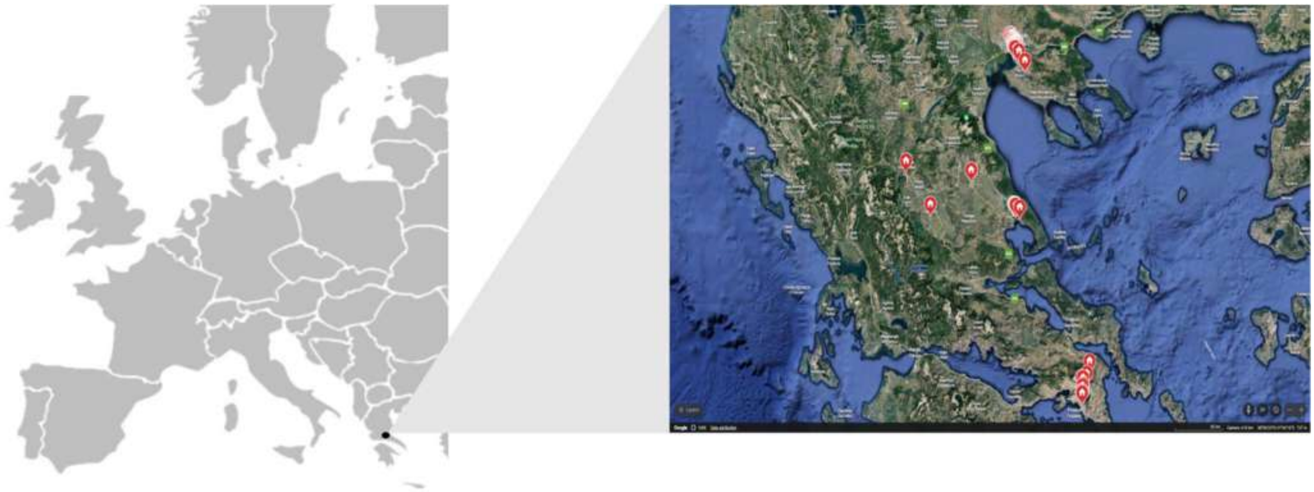


Figure 2. Location of households for the Greek pilot in the North and centre region of Greece.

Surveys were developed in order to capture relevant data about the characteristics of the households, such as the period of building construction, energy class, house size, boiler type and gas tariff. Regarding the Greek pilot, the information on their household characteristics is presented in Table 2.

Table 2. Summary of the results collected through surveys on the characteristics of the households participating in the GR pilot.

Household characteristics	***n* (%)**	**Mean (Min – Max)**
Period of construction	--	
1946 - 1960	2 (2.3)	
1961 - 1980	29 (33.3)	
1981 - 1990	21 (24.1)	
1991 - 2000	11 (12.6)	
2001 - 2010	21 (24.1)	
2011 – 2015	2 (2.3)	
2016+	1 (1.1)	
Energy class	--	
A+	2 (4.3)	
A	3 (6.4)	
B+	7 (14.9)	
B	2 (4.3)	
C	8 (17.0)	
D	15 (31.9)	
E	9 (19.1)	
F	1 (2.1)	
Dwelling size (m^2)	--	86.4 (30.0 – 300.0)

20 - 39	1 (1.0)
40 - 59	15 (15.2)
60 - 79	31 (31.3)
80 - 99	25 (25.3)
100 - 119	14 (14.1)
120 - 139	6 (6.1)
140 - 159	4 (4.0)
160+	3 (3.0)
Boiler type	--
Opentherm	84 (82.3)
ONOFF	18 (17.6)
Gas Tariff	--
Fixed	35 (52.2)
Dynamic	32 (47.8)

Not all participants answered all questions

According to data presented in the table:

- More than a half of the participants who answered this question (57.4%) live in buildings constructed between 1961 and 1990, whereas 36.7% live in buildings completed between 1991 and 2010, and only 3.3% live in more recent dwellings (built after 2011).
- As for the households' energy classes, there are 9 energy rating categories (A+, A, B+, B, C, D, E, F, G, A+ being the highest and most efficient) which are determined by a range of values based on the estimated total primary energy consumption of the building. Most of the households (51.0%) have D or E energy classes, and only 25.6% have B+ or higher classes.
- Most of the residences (56.6%) present dwelling size between 60 and 99 m^2 and 27.2% are larger than 100 m^2.
- The great majority of the participant households (82.3%) have Opentherm boilers, whereas only 17.6% of the boilers existing in the participant homes are of the type "ON/OFF".
- Around half of the GR users (52.2%) have a fixed gas tariff while the remaining (47.8%) have a dynamic one.

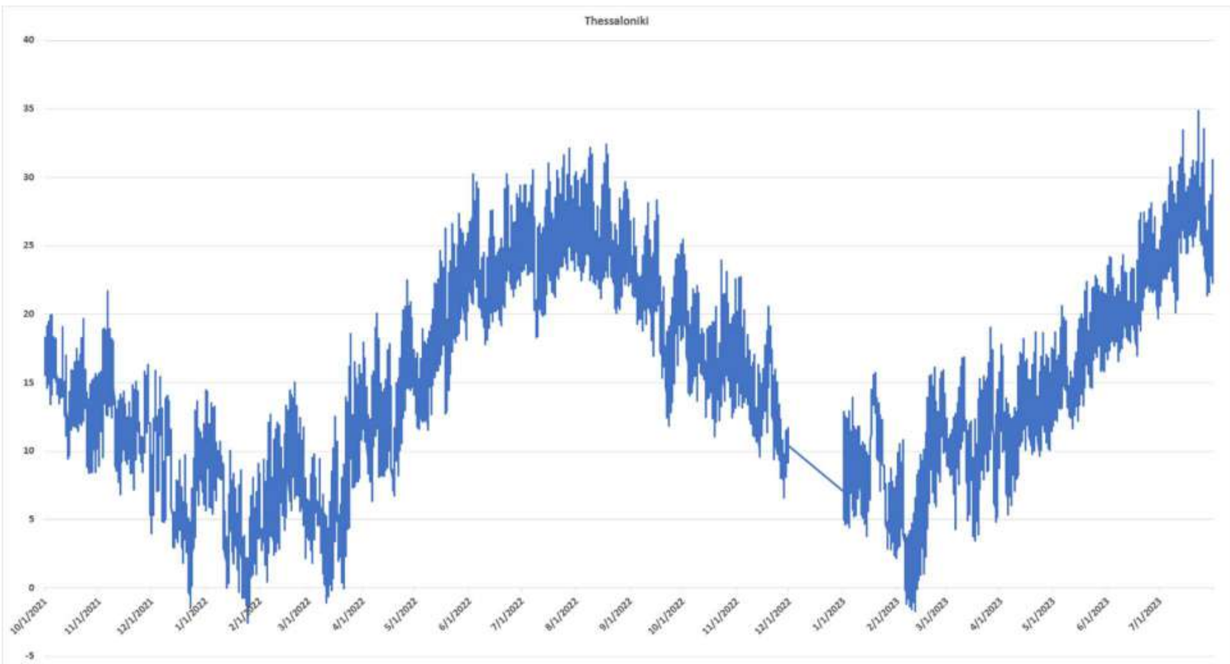
2.1.3. Climate and Meteorological data

The climate in Greece is predominantly Mediterranean. However, due to the country's geography, Greece has a wide range of micro-climates and local variations. The Greek mainland is extremely mountainous, making Greece one of the most mountainous countries in Europe. The cities of Volos, Karditsa and Kalampaka are located in central Greece, while Athens is located in the southern part. To the West, the climate is generally wetter and has some maritime features. To the East, it is generally drier and windier in summer. The northern areas of Greece (Thessaloniki) have a transitional climate between the continental and the Mediterranean climate. Finally, the southern areas have a predominantly Mediterranean climate.

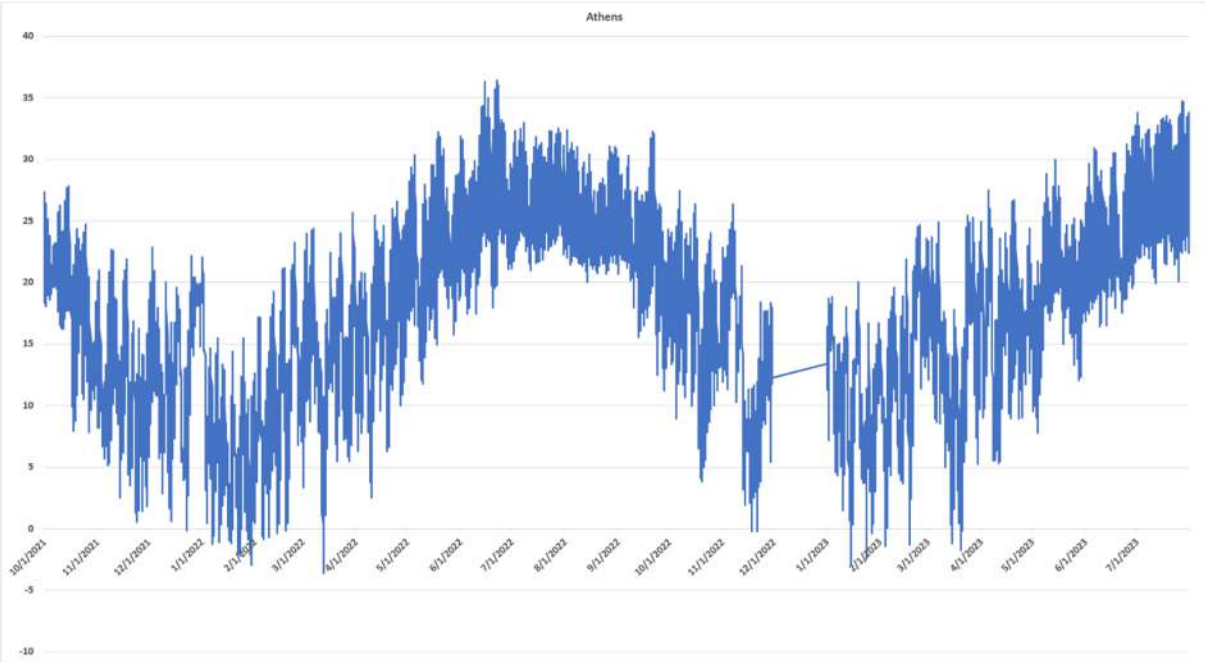
The **pre-intervention phase of the GR pilot** for collection of baseline data had a duration of **3 months (from October 2021 to December 2021)**, **NUDGE 1** period had a duration **of 3 months (from January 2022 to March 2022)**, **NUDGE 2** period had a duration of 2 months **(from December 2022 to January 2023)** and finally **NUDGE 3** period had a duration of 2 months **(from February 2023 to March 2023)**. Table 3 presents some basic metrics for the local outdoor temperature registered during baseline and relevant intervention periods. Meteorological data acquired from Copernicus is presented below in Figure 3 for the three cities with the largest number of pilot users. Ambient air temperature data for December 2022 was not available in Corpenicus platform.

Table 3. Ambient temperature evolution for the 3 cities considered in the GR pilot during the relevant study periods.

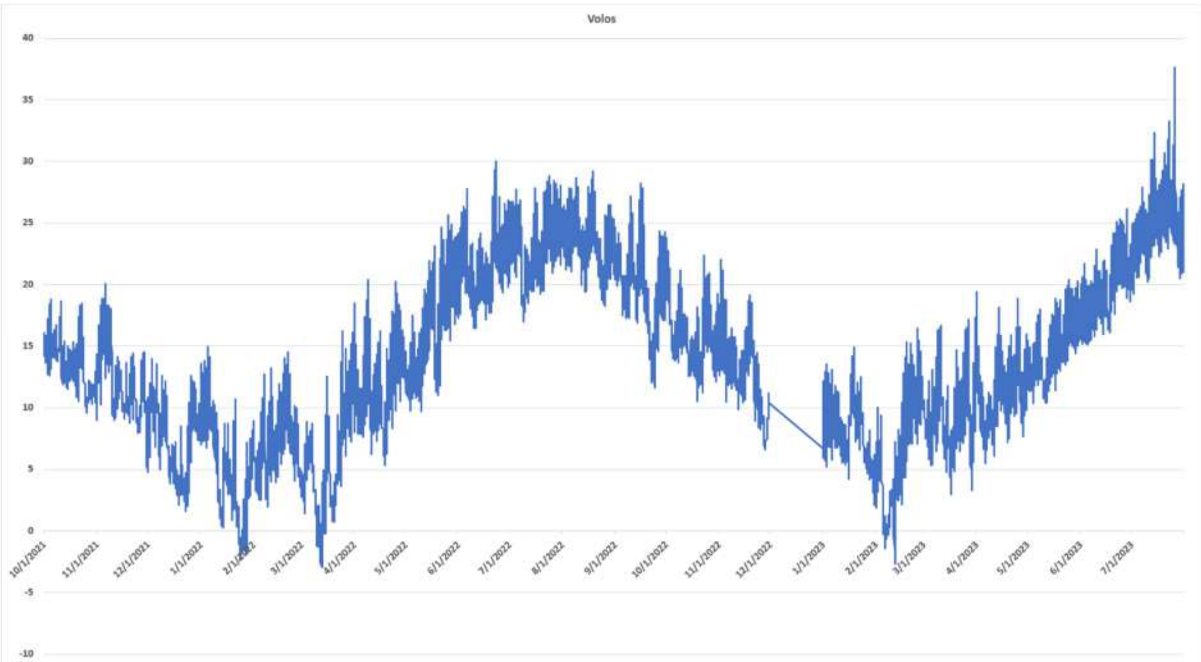
City	Ambient Temperature [Mean (Min – Max)] (°C)			
	Pre-intervention	NUDGE 1	NUDGE 2	NUDGE 3
Thessaloniki	11.4 (-1.4 – 21.7)	6.6 (-2.5 – 18.6)	8.7 (2.1 – 15.7)	9.0 (-1.7 – 19.0)
Athens	13.7 (-0.1 – 27.8)	9.5 (-3.5 – 25.6)	9.4 (-2.9 – 20.0)	12.7 (-1.7 – 25.4)
Volos	11.1 (1.6 – 20.0)	6.1 (-2.9 – 16.1)	8.1 (2.0 – 14.8)	8.1 (-2.6 – 17.3)



(a) Thessaloniki



(b) Athens



(c) Volos

Figure 3. Ambient air Temperature in Thessaloniki, Athens and Volos from October 2021 until July 2023 (data from the Copernicus project platform, with a gap (no data available for December 2022).

2.1.4. Main Results from the Pilot Implementation

The aim of this first level analysis is to derive a high-level understanding of the heating habits of pilot households, without considering the implementation of nudging. We start our analysis by considering all pilot data gathered during the winter season of 2022/2023. In Figure 4, we illustrate the evolution of the total power consumption of natural gas boilers from all pilot homes and the average outdoor temperature across all considered locations. We observe that the first requests for space heating appeared at the end of October 2022, while the last requests were observed at the end of April 2023 – resulting in a typical heating period of 6 months. For the rest of this section, we focus on the heating period of 6 months, lasting from November 2022 to April 2023. In addition, we focus on four parameters: a) energy consumption, b) thermal comfort, c) user controlled heating parameters and d) the achieved energy savings, which are detailed in the following subsections, respectively.

Figure 4. Evolution of the total power consumption of natural gas boilers (blue line) and the average outdoor temperature across all pilot homes (red line), for the entire heating season of 6 months.

Energy consumption

The identification of the energy consumption profile of end consumers is a key part of energy management. Household operations change over time as occupants move in and out of a property, and as different heating practices are adopted over different days of the week. For the rest of this section, we focus on two metrics, which are detailed below:

- **Heating demand:** It denotes the number of hours per day, during which heating has been **requested**. This metric is computed indirectly by tracking the variations of the target temperature and is reported for both Opentherm and ON/OFF boilers. The overall heating demand (in hours) is then the sum of those intervals over a given period of interest (e.g., one month) and it is particularly useful for characterising the heating demand practices of residential building consumers on a daily basis.
- **Energy consumption:** It is calculated (in kWh) as the integral of instant boiler power (kW) and is reported only for Opentherm boilers. The total energy consumption can be split across the two main

cases of space heating and hot water preparation. For this pilot, we only focus on space heating, so we focus on intervals where the energy is being consumed for heating the building.

In Figure 5, we plot the distribution of the average daily heating demand (in hours) for all pilot homes. The majority of pilot homes (51 households) request between 6 and 12 hours of space heating on a daily basis, while a smaller set of pilot homes (25 households) request 14 - 22 hours of space heating on a daily basis. Finally, three homes use more than 22 hours of heating each day, which denotes that they do not turn their heating off during periods of inactivity or absence (e.g. sleep).

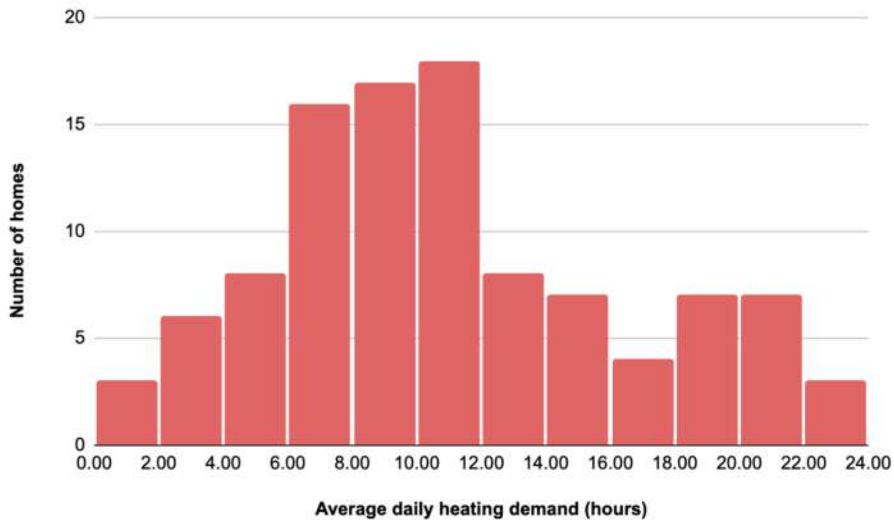


Figure 5. Distribution of average daily heating demand across pilot homes.

The most common indicator used to benchmark performance for household space heating for EU countries is the energy consumption per m^2 (to correct for differences in dwelling size). In order to calculate the above metric for the pilot homes, we have to downsize the set of pilot homes under consideration, by focusing only on Opentherm boilers that report their instantaneous boiler power consumption. In addition, we use the data provided through the end user surveys regarding the dwelling size of pilot homes. In Figure 6, we plot the distribution of the average yearly energy consumption (in kWh) used for space heating per m^2 across the 64 pilot homes that are equipped with an Opentherm boiler. It is clear that the majority of pilot homes (48 households) consume between 9.5 and 37.5 kWh/m^2 during the whole heating season. In addition, a smaller set of pilot homes (nine households) require 37.5 to 65.63 kWh/m^2 on a heating season basis, while only two homes consume more than 65.63 kWh/m^2.

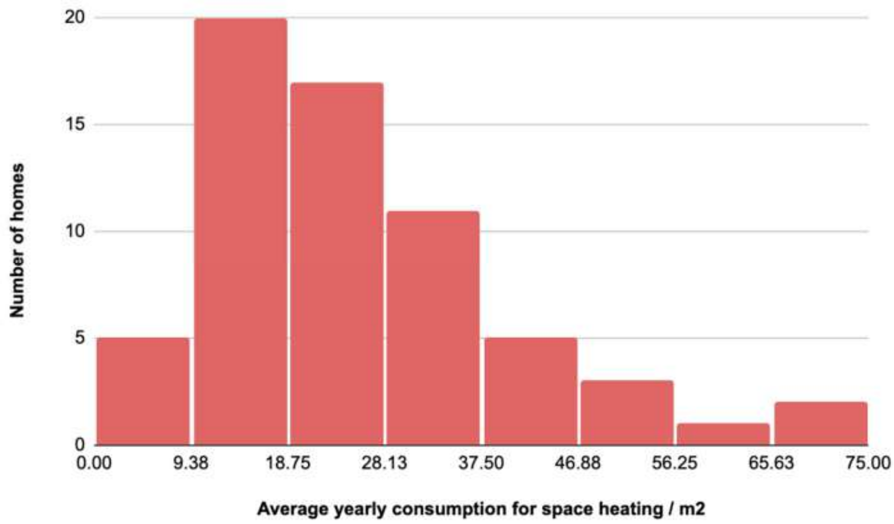


Figure 6. Distribution of average yearly gas consumption (kWh/m²) across pilot homes.

Thermal Comfort

Smart thermostats aim to increase the efficiency of heating systems, by providing the exact amount of heat required for maintaining a comfortable environment and not delivering excess heat. However, targeting energy savings, these systems often fail to achieve a comfortable thermal environment for the inhabitants. Therefore, it is important to understand the factors that contribute to thermal comfort. We assume that users perceive thermal comfort when the current indoor temperature is within +/-1.0 degree of the target temperature. In order to evaluate the thermal comfort experience by pilot users, we use the following notion of thermal comfort:

- **Thermal comfort:** It is calculated as the percentage (%) of time during which the current indoor temperature is within +/-1.0 degree of the target temperature. This metric is only calculated, during periods that heating demand is requested.

In Figure 7, we plot the distribution of the average daily thermal comfort (%), as calculated across pilot homes (both Opentherm and ON/OFF boilers). It is evident that 49 homes achieve more than 90% of thermal comfort on a daily basis, while more than 74 homes achieve their thermal comfort limits more than 80% of their heating demand duration. Only a small subset of 6 pilot homes did not manage to achieve acceptable performance in terms of thermal comfort (<70%).

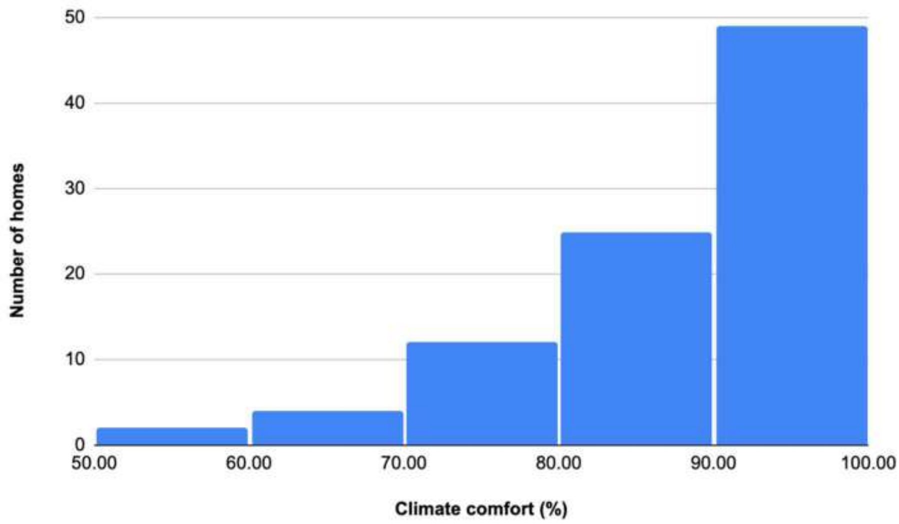


Figure 7. Distribution of the achieved thermal comfort across pilot homes.

The energy efficiency mechanism that is applied for Opentherm boilers can assist users to achieve significant energy savings. The user is also able to calibrate the operation of the algorithm to match their heating preferences, by setting the value of 10 to prioritise comfort through instant heating response – or by setting the value of 1 to maximise energy savings through gradual heating response.

As a consequence, the achieved climate comfort can be impacted by variations of the heating balance settings. In Figure 8, we use a scatter plot, to illustrate the relationship between the achieved thermal comfort and the heating balance setting, across all pilot homes. It is shown that the majority of pilot homes are able to maintain a high thermal comfort value, while different heating curve settings are applied. In addition, a decreasing trend is observed for the achieved thermal comfort across increasing values of heating balance, which is counter intuitive. However, this effect can be explained due to room temperature overshooting that frequently occurs under high heating curve settings, which results in higher boiler temperature values and higher room temperature increase rates. The aforementioned effects validate the ability to maintain the thermal comfort of end users and even improve it when applying the energy efficiency mechanism of DOMX that is applicable to Opentherm boilers.

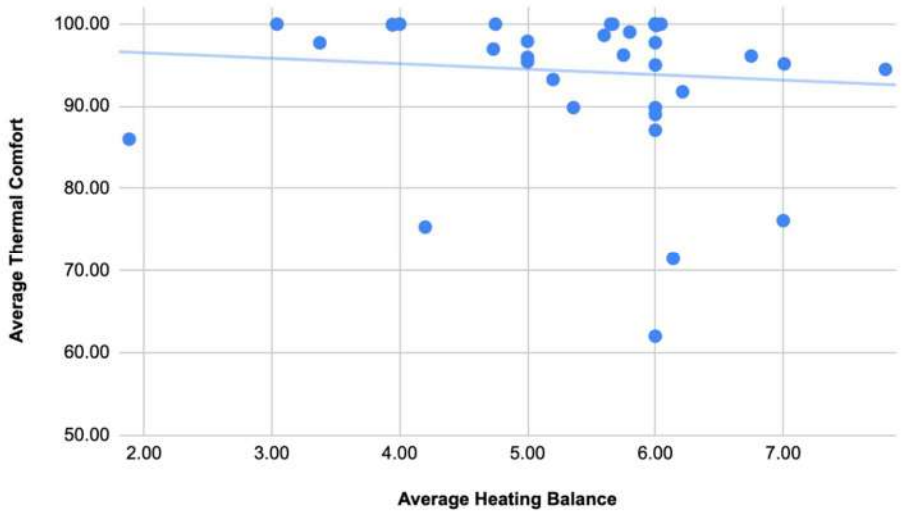


Figure 8. Distribution of achieved thermal comfort across different heating balance settings.

User controlled heating parameters

A rather commonly followed advice for energy saving suggests a reduction of the target temperature during periods of inactivity. Especially, during the night, lowering the thermostat by a few degrees can lead to substantial energy savings without compromising the achieved climate comfort.
Based on this fact, many end users reduce their target temperature during the night, in order to save energy and ultimately money on their heating bills.

In Figure 9, we plot the distribution of the average target temperature excluding hours of inactivity (e.g., night), across all pilot homes. We observe that the majority of the Greek pilot homes (70 households) employ a room target temperature between 20 °C and 22 °C. Only a small subset of homes follows a different approach, by using less than 20 °C or above 22 °C for their average room target temperature, thus assisting in the identification of households rather interested and not interested in energy conservation, respectively.

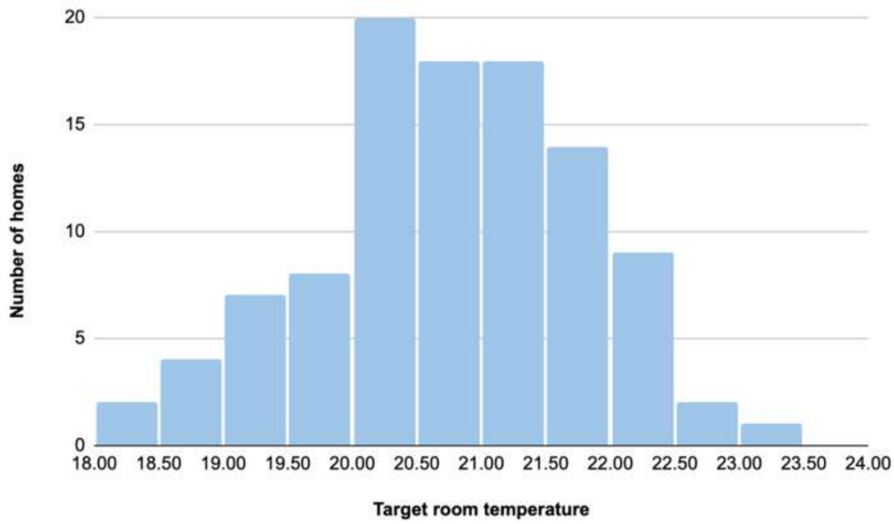


Figure 9. Distribution of average daily target room temperature across all pilot homes.

In Figure 10, we plot the distribution of the average target temperature difference between day and night modes, across all pilot homes. We observe that the majority of the Greek pilot users follow the aforementioned energy saving tip and lower their target temperature during periods of inactivity, between 0.5 and 6.5 degrees, while only a small subset of 7% maintain a fixed target temperature across 24 hours on a daily basis. This initial finding suggests that the Greek pilot users have high potential for adopting interventions related with the adaptation of their root target temperature, considering that most pilot users are keen on adjusting their target temperature.

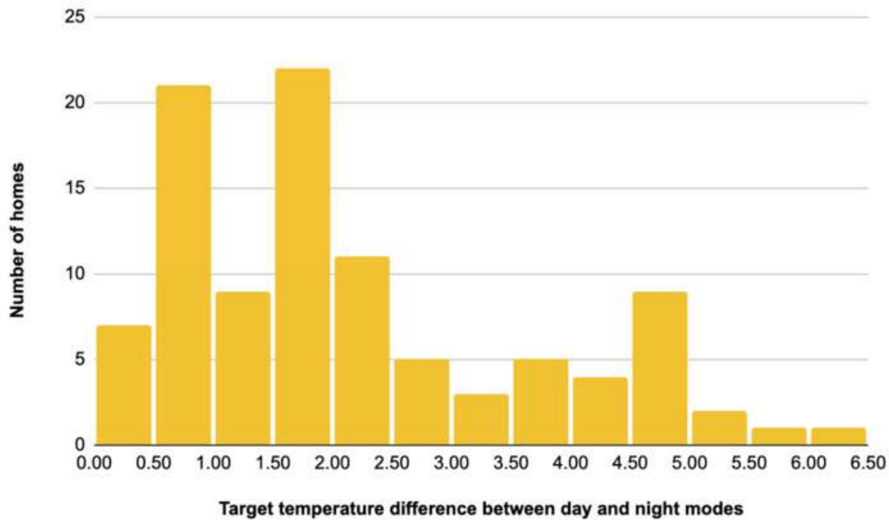


Figure 10. Distribution of the average target temperature difference between day and night modes, across all pilot homes.

Variation of user-controlled heating parameters during the heating season of 2022/2023

The three interventions that were designed for the Greek pilot took place during an unprecedented energy crisis for the EU. During the heating season of 2022/2023, the domestic consumption of natural gas has been reported to decrease by nearly 34%, compared to the corresponding quarter of 2022, according to the country's natural gas transmission system operator (DESFA). In this section, we focus on characterising the impact on heating behaviour change of pilot participants. Thus, we calculate the weekly average of the target temperature and heating curve values for all pilot users across the entire heating season of 2022/2023. In Figure 11, we clearly observe a decreasing trend for the average target temperature, starting with the value of 23.64 °C in November 2022 and reaching the value of 20.85 °C (as average over the last two months of March and April 2023).

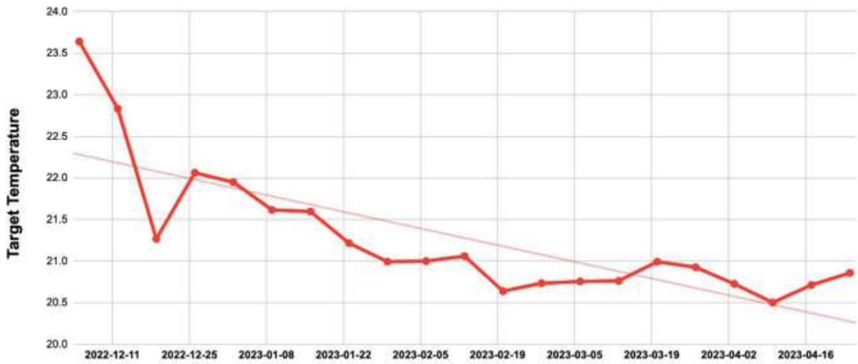


Figure 11. Evolution of the weekly average of the target room temperature (in °C) for all pilot users across the entire heating season of 2022/2023.

In Figure 12, we clearly observe a decreasing trend for the average heating balance, starting with the value of 5.39 in November 2022 and reaching the value of 4.75 as average in April 2023. It is important to note that the behaviour change in terms of both the target temperature and heating curve parameters is related to both the nudging interventions and overlapping effects (e.g. energy crisis).

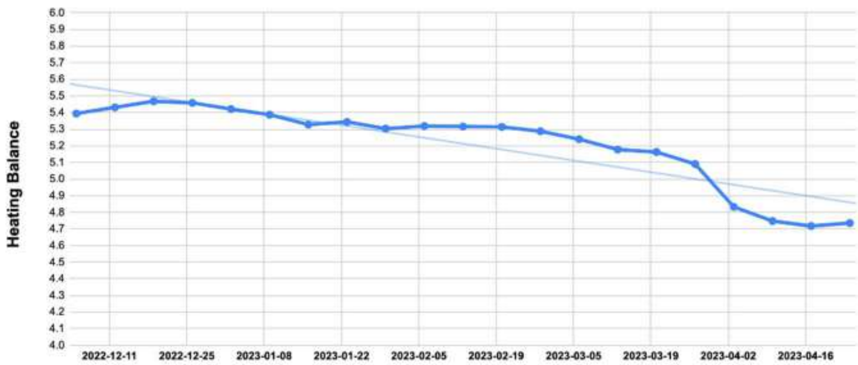


Figure 12. Evolution of the weekly average of the heating balance for all pilot users across the entire heating season of 2022/2023.

Energy savings

Traditional heating systems in Greece employ a constant outlet temperature (typically in the range of 65-80 °C), regardless of the indoor, outdoor conditions and the user specified room target temperature. The inability of traditional heating systems to match the heating needs of the building under consideration with the prevailing outdoor and indoor conditions, the habits and preferences of the users and the performance of each building/heating system combination, directly affects the achieved performance and energy efficiency of the heating system, resulting in excess energy consumption and costs as well as in reduced thermal comfort.

A typical configuration for natural gas boilers in Greece considers the application of the boiler outlet temperature of 65 °C. Contrary to the typical "baseline" mode of heating operation, the DOMX controller uses a sophisticated algorithm to control the boiler activation patterns and to adapt the actual temperature of the boiler's outlet temperature, directly affecting the boiler's load of operation. The followed approach considers as input the user specified target temperature, the varying indoor temperature, the prevailing outdoor conditions, along with the given building's response to heating requests, towards dynamically adapting the boiler's operation to deliver the exact amount of heat required to properly heat the building under consideration, while respecting the user's comfort limits. Apparently, the potential for energy savings increases as the average outdoor temperature increases, as the boiler is able to transfer the required level of heat while operating under low load and return temperature levels. Considering the Greek climate, the winter season can be characterised by mild weather conditions, thus providing high potential for energy savings.

In order to properly capture the impact of the various parameters affecting energy consumption in residential heating scenarios, a custom evaluation methodology has been designed by applying commonly adopted Measurement & Verification (M&V) principles. In addition, a data analysis pipeline has been developed, using established clustering techniques, in order to extract comparable 24h periods between the two modes (baseline and energy saving mode) and produce gas consumption evaluation reports. Having applied the aforementioned clustering approach for the Greek pilot homes, out of the 84 homes equipped with Opentherm boilers, 40 of them provided enough baseline data for achieving a minimum confidence threshold. In Figure 13, we plot the distribution of the achieved energy savings as estimated for the 40 homes, which show that the majority of pilot homes achieve energy savings between 15% and 35%. This energy savings potential is a typical benefit of DOMX users that can be achieved irrespective of the application of nudging. Even users that never use the DOMX smartphone application are able to efficiently heat their household and achieve both energy savings and thermal comfort, by providing only their room target preferences through the simple DOMX wireless thermostat.

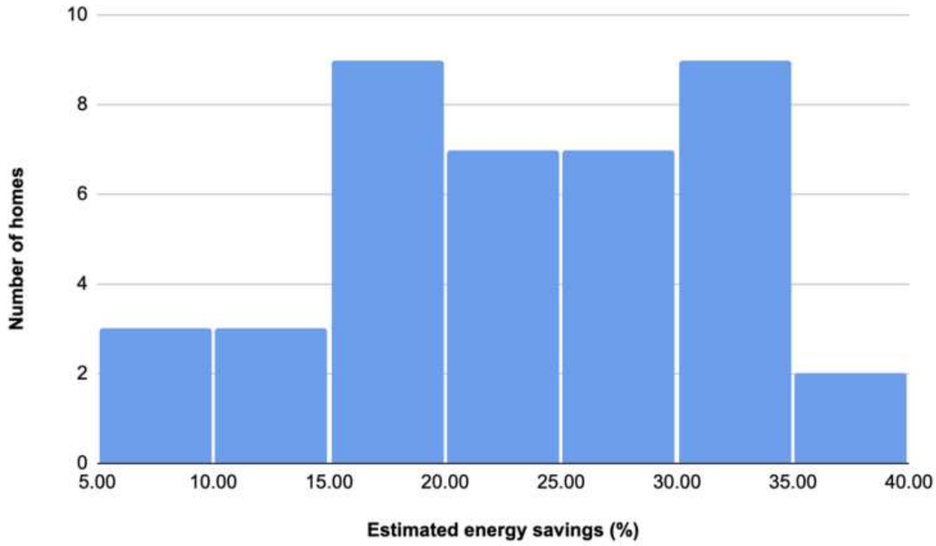


Figure 13. Distribution of achieved energy savings (%), between the baseline and energy saving mode of DOMX across all pilot homes.

The energy efficiency mechanism that is applied for Opentherm boilers can assist users to achieve significant energy savings. The achieved energy savings are impacted by heating balance variations. In Figure 14, we use a scatter plot, to illustrate the relationship between the achieved energy savings and the heating balance setting, across all pilot homes. As expected, a decreasing trend is observed for the achieved energy savings across increasing values of heating balance.

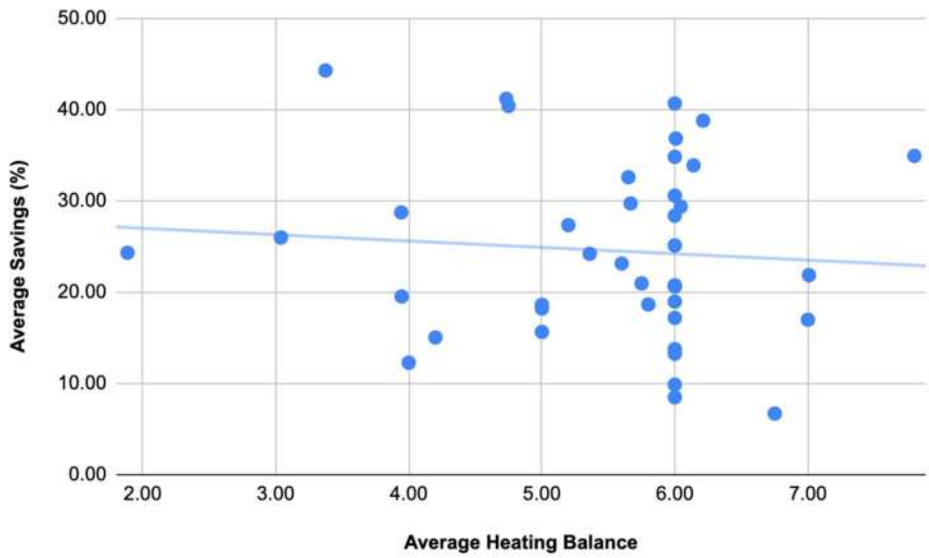


Figure 14. Distribution of achieved energy savings across different heating balance settings.

Main outcomes on the interaction of the participants with the mobile app

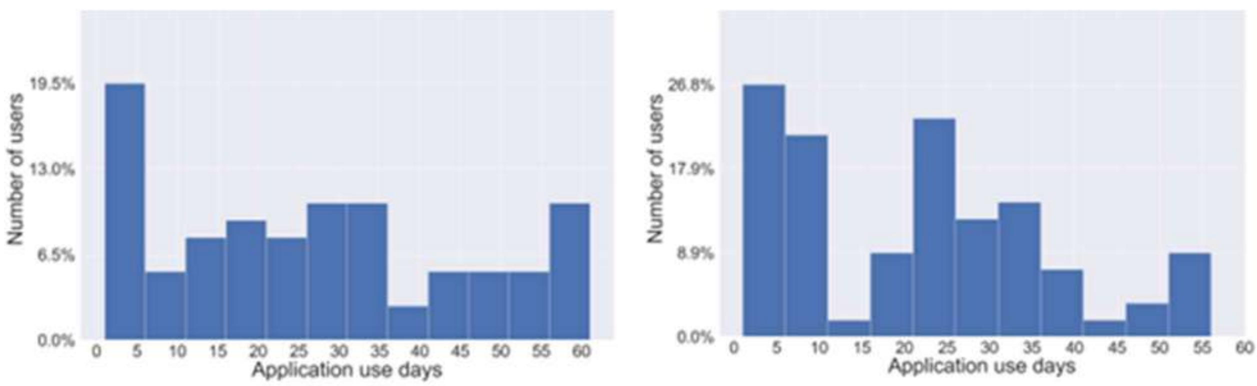
DOMX App has been available on both Play Store and App Store since November 2020. Via the App, the users can remotely control their boilers, have an overview about (indoor and outdoor) temperature, boiler temperatures, boiler faults and gas consumption data. The interaction of the users with the application is reflected in log files, which record events (e.g., launch of the App, access to certain pages). The logging process started just before the second nudge period (October-November 2022), so no app data for the NUDGE 1 were logged.

Based on the recorded data, participants from 77 and 76 different households interacted at least once with the app during the second and third intervention period, respectively. Hence, almost a quarter of the pilot participants had no interaction with the app (and, as consequence, no exposure to nudges). The three most popular app activities are presented in Table 4.

Table 4. Distribution of event entries in the DOMX App logs across all GR pilot participants.

Intervention	Main screen	App launch	Set room target
NUDGE 2	39%	28%	13%
NUDGE 3	41%	28%	12%

Interesting is the way the engagement with the DOMX App varies across the pilot participants. We measure the engagement of each participant in distinct days of interaction with the DOMX App. Specifically, almost every third user interacts with the mobile app 20-40 days (or 2-4 days weekly) in both intervention periods. Likewise, common across the two periods is the portion of participants (1 out of 5) who only rarely (less than once per week) interacts with the App. On the contrary, in the third intervention period, we found clear evidence of fewer "devoted" users than in the second intervention period, namely users who interact with the App daily.



(a) NUDGE 2 (b) NUDGE 3

Figure 15. Distribution of days of interaction with the DOMX mobile app across the GR pilot participants.

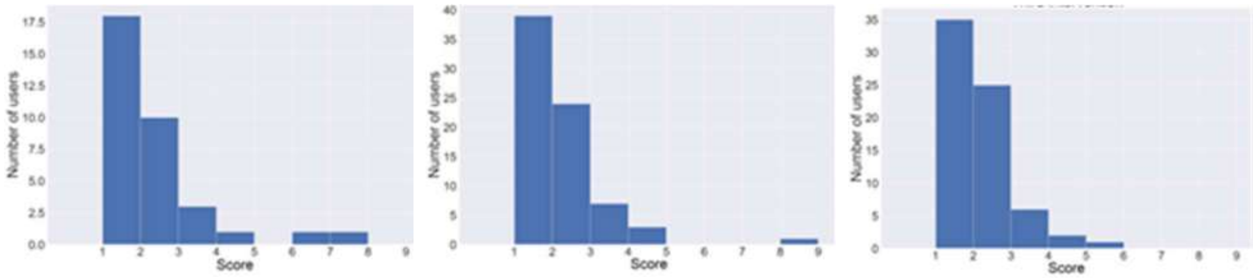
After each intervention period the GR pilot participants were first asked to rate the app along several properties (see Table 5). Low numbers indicate positive ratings whereas high numbers indicate negative ones. Overall, the participants who responded to the question appear to have a clearly positive view of the app. They find the app easy to use, with an average 1.9 rating (score) over the three survey waves, time saving (2.3 average score) and supportive (2.1 average score). Moreover, the participants appear to find the app easier to use and more intuitive in the course of time, which may indicate a learning effect, but also more interesting, which is counterevidence against fatigue effects but may be caused by more and more changes and new features in the app.

Table 5. Average ratings of the DOMX App properties along the 3 waves of pilot surveys.

Question items	2nd wave* (n=34)	3rd wave* (n=73)	4th wave* (n=69)
intuitive:cumbersome	2.2	2	1.9
relevant:irrelevant	1.9	2.2	1.8
supportive:disabling	2.2	2.1	1.9
easy:difficult	2.4	1.8	2
clear:confusing	2.1	2.2	2.3
interesting:uninteresting	2.3	2.2	1.9
time saving:time consuming	2.6	2.2	2
enabling control:forcing me to relinquish control	2.6	2.2	2
creating opportunities:restricting opportunities	2.4	2.6	2.4
adaptable to my needs:unadaptable to my needs	2.2	2.9	2.4
comprehensible:incomprehensible	1.9	2.1	2
easy to use:hard to use	2	1.9	1.8
Total	2.2	2.2	2

*data from questionnaires administered after NUDGE 1 (2nd wave), NUDGE 2 (3rd wave) and NUDGE 3 (4th wave)

The positive assessment of the participants about the DOMX App is confirmed in Figure 16, which plots the distribution of ratings given to the app by the users throughout the intervention periods. These distributions are heavily right skewed.



(a) 2nd wave (n=34) (b) 3rd wave (n=73) (c) 4th wave (n=69)

Figure 16. Distribution of app ratings at 1-9 scale according to the responses of GR pilot participants in the three post-intervention surveys.

2.1.5. Concluding Remarks on Pilot Outcomes

Before diving in the outcomes of the nudging interventions implemented for the Greek pilot, it is important to shed light on two important aspects. First, we need to remark that all three interventions that were designed for the Greek pilot actually took place during an unprecedented energy crisis for the EU. In the wake of Russia's invasion of Ukraine (February 2022) and a surge in wholesale energy prices, natural gas demand in the European Union fell in 2022 by 13% (Zettelmeyer et al., 2022). The rise in energy commodities, especially natural gas, triggered record prices and high volatility during both the last quarter of 2022 and the first quarter of 2023. More specifically, between August and December 2022, Greece's natural gas consumption was at -18.2% compared to the five-year average (eKathimerini, 2023), while in the Jan-March 2023 period, the domestic consumption of natural gas decreased by nearly 34%, compared to the corresponding quarter of 2022 (OT, 2023). Based on the above facts, it is made clear that the majority of Greek households adapted their space heating habits to reduce their energy consumption. As a consequence, the impact of all three nudges has been superimposed by the aforementioned energy crisis for the EU and the underlying behaviour change of Greek consumers towards energy consumption reduction.

Second, it is important to consider the inherent ability of the DOMX smart heating solution to generate significant energy savings (up to 30%), while running in the background in a fully transparent way to the end users. The energy saving functionality is set up during the initial system's installation and commissioning phase, it is enabled by default and constantly adapts to their varying comfort limits (target temperature, heating curve) and to the prevailing outdoor conditions. Even users that never use the DOMX smartphone application are able to efficiently heat their household and achieve both energy savings and thermal comfort, by providing only their room target preferences through the simple DOMX wireless thermostat. Based on the above, we understand that the Greek pilot users of the DOMX solution are able to achieve significant savings without requiring any interaction with the controller or the app. As a result, the Greek pilot participants are characterised by low motivation for interacting with a smartphone application, given the fact that they already experience significant energy savings and thermal comfort through a solution that does not require any interaction from them.

Taking the above facts under consideration, we next summarise the main conclusions derived with regards to the three research questions:

NUDGE 1 – How might the access to detailed historical gas consumption data through a smartphone app impact the behaviour of residential consumers and their gas consumption?

NUDGE 1 was implemented from January 2021 till February 2022 and allowed users to monitor their gas consumption, as split between space heating and hot water preparation. The focus of this first intervention has been on informing consumers about their daily consumption and to help them understand where their consumption comes from (space heating/ hot water preparation). This feedback and awareness intervention was expected to trigger initial behaviour changes in short-term and thus was decided to be introduced first. Considering that the number of participating households during the first intervention period was limited to 40 and given the limited availability of sufficient baseline data, it was not possible to apply the data analysis methodology that was proposed to isolate the effect of nudging from the overlapping effects of the energy crisis. As a result, it is not possible to accept or reject the main hypothesis of our research question on whether the access to detailed historical gas consumption data through a smartphone app can impact the behaviour of residential consumers and their gas consumption.

However, given the positive feedback from households that received the new functionality, we understand that the nudging intervention has been well received by the majority of participants. In addition, we expect that this first nudge that was still available during the second and third interventions, might have contributed in assisting consumers to understand the impact of applying energy efficient settings for space heating in the long term, thus impacting the recorded behaviour change for the two subsequent nudges.

NUDGE 2 – How effective can just-in-time prompts be in affecting long-established behaviours related with non-energy efficient habits?

The second intervention is a confrontation nudge that has been realised through just-in-time prompts and was implemented between December 2022 and January 2023. The focus has been on changing the long-established behaviour of consumers that is related with the application of non-energy efficient habits. Specifically, when the user tries either to set the room target temperature higher than 21.50 Celsius or disable the weather adaptive-heating feature, an alert box is trying to prevent him/her from accomplishing the action. In the Greek pilot, nudges are not removed once they are introduced, thus implying that during the second intervention period, pilot participants are exposed to both NUDGEs 1 and 2.

Based on the analysis of recorded events by the DOMX mobile app, 25 households were identified to have no interaction with the application, and consequently, they were not exposed to the second nudge. Therefore, these 25 households have been considered as a potential control group, where no nudges are applied, for the analysis of the pilot's sensor data. The two groups, control and intervention, that were exposed to the second nudge, exhibit similar variation. Overall, when looking into how the target room temperature has been adapted, we do not observe any clear differentiation across the two groups that could be interdependent with the impact of the second intervention on the behaviour change. Concluding, it has not been possible to isolate the effects of nudging from other overlapping effects (e.g. energy crisis) in the behaviour change of pilot participants.

<u>**NUDGE 3 –** Is it possible to affect the behaviour of energy consumers through personalised energy saving suggestions?</u>

The third nudge consisted of personalised messages that were delivered to pilot participants through push notifications in the DOMX app. Based on the initial analysis of the effect of NUDGE 3, a small increase has been identified in the heating time and natural gas consumption. However, by modifying the treatment's group population based on the days of nudge exposure that occurred from the pilot's mobile application data analysis, a small reduction in gas consumption for the treatment group was detected. The specific observation was also verified from the detailed analysis that focused on isolating the impact of nudges from overlapping effects (e.g. energy crisis), which captured approximately 3% reduction in consumption effect for the treatment group.

In addition, the impact of the third intervention on changing the behaviour of pilot users with respect to their heating balance configuration was also investigated. Through this analysis, it was verified that the introduction of the third intervention had a clear impact on pilot users that were using the app and decided to reduce their heating balance: Their heating balance changed from the average value of 5 to the value of 4.5 and maintained this drop till the end of the heating season.

Focusing on the pilot users that reduced their heating curve, a subset of 12 users have radically reduced their heating curve setting upon the introduction of the respective push notification, from the average value of 4.63 (last week of March) to the value of 2.98 (second week of April). The application of a custom Measurement and Verification approach has also been executed by DOMX to quantify the impact of the behaviour change for these 12 homes on energy consumption. This process resulted in a subset of 6 homes that had enough comparable baseline data and resulted in energy consumption reduction of 16.12% that has been calculated as the weighted mean average for 32 comparable baseline-intervention pairs of days between March 2023 and April 2023.

2.2. The Belgian (BE) pilot

2.2.1. Overview on Pilot implementation

Context and Aim

The aim of this pilot was to study the behaviour of 10 to 14 years old children and their families related to their energy consumption. We wanted to measure the effect of a series of five lessons / nudges for children on energy combined with visualisations of the own home energy consumption. We expected intergenerational learning from the students to their families by talking about the lessons and analysing the energy consumption on the platform. The design of the study, combining lessons and using a platform with visualisations of the consumption at their own home, made this pilot unique.

As the expertise of SPRING-STOF is dedicated education for gifted children, all participants were gifted children. Course material that is adapted to their special needs is rarely available in Belgium. However, the course material is designed to be used for all children in STEM education (12-16 years old) to enable a broader impact in the validation phase.

Study design and methodology

Different *materials* were developed and installed for the intervention. Five themes were selected for each of the lessons: gas consumption at home (and other ways of heating the house), electricity consumption at home, water consumption at home, electricity outside (production) the house and nudging. For each lesson, a booklet was made with relevant important background information, tables, graphs and exercises for the children. Each child received a booklet, worked in the booklet during the lesson and took the booklet home. Children were encouraged to show what they have learned in their own class and school.

In each lesson, the content of the lesson was combined with analysing and interpreting visualisations of the energy consumption as tracked by EnergyID, an openly accessible platform that is made available by a Belgian social co-operative to families, organisations, and cities. Before the start of the lessons, a family member of each child had to connect the (digital) electricity and gas meter with the EnergyID-platform and the NUDGE group. We checked that the meters were correctly connected and data was sent to the NUDGE platform. During the two months before the start of the lessons, several failures were solved.

For the measurement of the effects of the nudges, a questionnaire (pre-test and post-test) was developed. The questionnaire consisted of the same set of questions as for the other pilots plus supplemental questions to measure the knowledge of the participants.

Two cohorts of participants were selected. A first cohort of schools and children to be included in the intervention group were selected from September until December 2021. Eight schools demonstrated interest in organising the series of five lessons in their school for a group of gifted children. However, a high number of children did not have any digital meter at home to assess energy consumption. Thus, the three schools with children having digital meters were selected to host the lessons. All lessons were given by Ellen Vandewalle herself. A fourth class was composed at SPRING-STOF with individual children coming from 8 different schools. In this way, 36 children (22 with a digital meter and 14 with an analogue meter) were selected to attend the series of five lessons in the school year 2021-2022. In the school year 2022-2023 a new cohort of schools and children were selected from June until November 2022. By then, more families had a digital meter at home. Six schools were interested to participate, of which five schools with children having digital meters were selected. For the second cohort 40 children (34 with a digital meter and 6 with an analogue meter) attended the series of 5 lessons in school year 2022-2023. Only the participants with a digital meter were able to send data to the central NUDGE platform.

NUDGEs and research questions

Three specific nudges were selected to change the behaviour of the children and their families. The teaching and learning activities were developed to work specifically on these nudges. The main nudge was *reinforcement: feedback and awareness*. Through the lessons we informed the children about energy consumption in general and their energy consumption at home based on their own data in the dashboard. During the lessons we worked at different levels: increasing knowledge, understanding, applying, analysing, evaluating and finally creating behavioural change (with an emphasis on analysing, evaluating and creating). These insights were linked to the feedback from the data in the dashboard on their own consumption to raise awareness of energy consumption within the child and the family.

We further strengthen intergenerational learning through assignments from lessons in which the children worked with the dashboard to study and optimise their consumption at home.

The second nudge that was selected was *social influence*: enabling social comparison. In the lessons we compared different households with each other to analyse and evaluate which behaviour had which effect on energy consumption. Within the group of children taking the lessons, we compared the different consumptions - the effect of solar panels, the effect of the size of your house, the effect of the way you heat your home, etc. Good practices were discussed and exchanged. The children took these comparisons home to discuss further with the family. Three lessons ended with suggestions to reduce energy (gas and electricity) and water consumption.

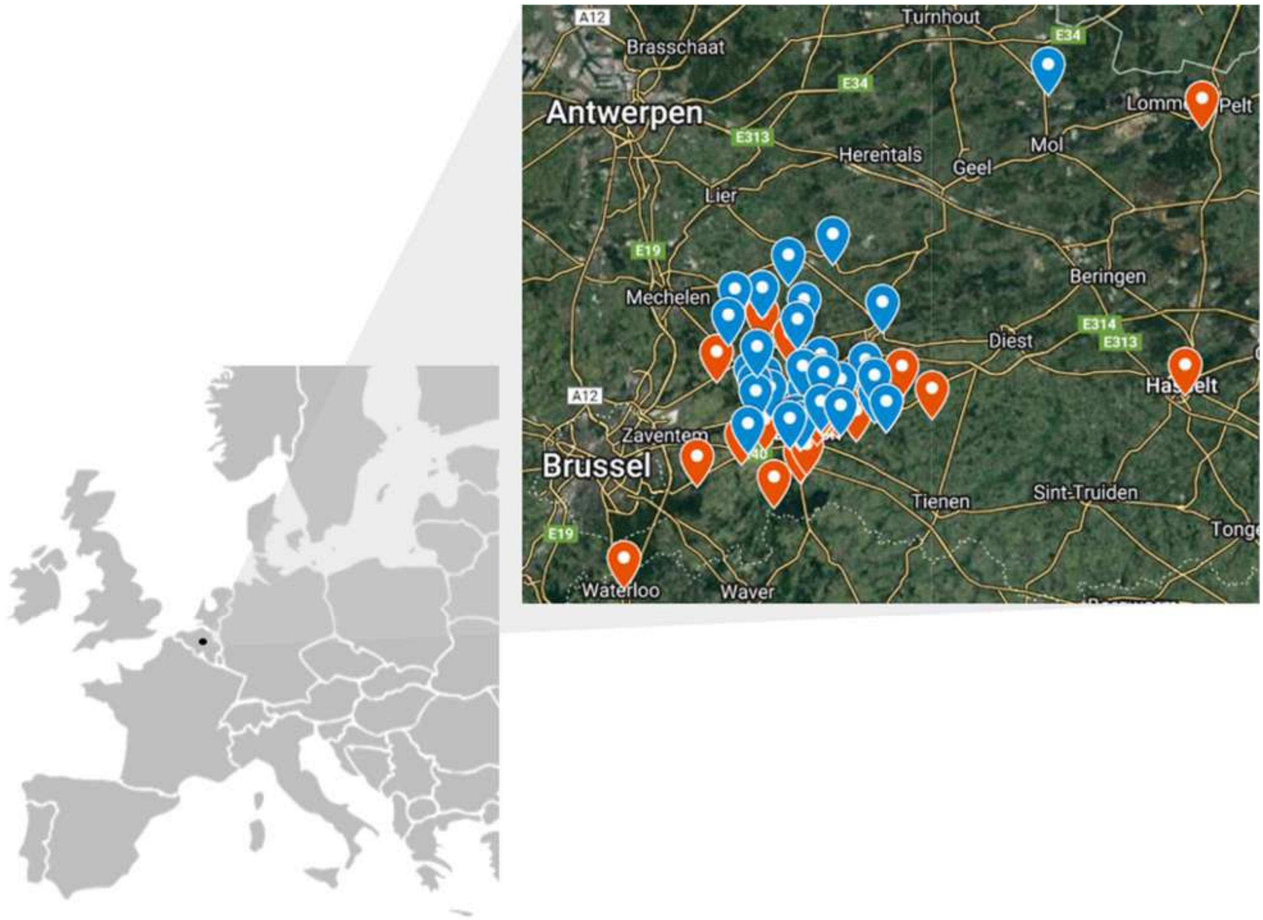
In the third nudge we stressed the *social influence*: at the end of three lessons, we set a common and a personal goal to reduce their energy and water consumption (e.g., lowering the heating temperature at home by 1 degree) and to leverage public commitment. All nudges were discussed in parallel during the five lessons.

We formulated the following research questions to measure the effect of the nudges through the lessons and the EnergyID-platform:

- *Does the knowledge about energy consumption of children and their families increase?*
- *Does the intention of children and their families to save energy increase?*
- *Does the motivation of children and their families to save energy increase?*
- *Do the children and their families have a lower gas consumption?*

2.2.2. Participant Households

All participant schools were selected in and around Leuven, in the province Flemish-Brabant in the centre of Belgium. Most participating households (n = 70) with connected meters are also situated in and around Leuven, as shown in Figure 17. Three participants live in the province Antwerp in the North of Flemish-Brabant (15-50 km from Leuven), one participant is living in the province Walloon-Brabant, in the south of Flemish-Brabant (30 km from Leuven) and two participants are living in Limburg, in the east of Flemish-Brabant (45-60 km from Leuven).



Note: Cohort 1: red; Cohort 2: blue

Figure 17. Location of households of families with children engaged for the Belgian pilot in the region of Leuven (Central Region of Belgium, Northwestern Europe).

Regarding the Belgian pilot, 32 out of the 36 participants of the intervention group provided information on a number of household's characteristics, as presented in Table 6. From these 32 participants, 17 participants had a digital meter. The data is relative to the participant house that works as primary residence.

Table 6. Household characteristics of the participants of the intervention group based on data in EnergyID.

Household characteristics participants	**Cohort 1:** ***n (%)***	**Cohort 2:** ***n (%)***	**Total:** ***n (%)***
Central heating system	32 (100)	34 (100)	66 (100)
Natural gas	26 (81)	26 (76)	52 (79)

Heating oil	4 (13)	2 (6)	6 (9)
Electricity	2 (6)	2 (6)	4 (6)
Pellets	0 (0)	2 (6)	2 (3)
District heating	0 (0)	1 (3)	1 (2)
Other	0 (0)	1 (3)	1 (2)
Additional Heating	32 (100)	34 (100)	66 (100)
None	24 (75)	25 (74)	49 (74)
Electricity	6 (19)	4 (12)	10 (15)
Firewood	1 (3)	4 (12)	5 (8)
Pellets	1 (3)	0 (0)	1 (2)
Other	0 (0)	1 (3)	1 (2)
Warm water	32 (100)	34 (100)	66 (100)
Natural gas	25 (78)	24 (71)	49 (74)
Heating oil	4 (13)	2 (6)	6 (9)
Electricity	3 (9)	5 (15)	8 (12)
District heating	0 (0)	1 (3)	1 (2)
Other	0 (0)	2 (6)	2 (3)
Cooking	32 (100)	34 (100)	66 (100)
Electricity	25 (78)	27 (79)	52 (79)
Natural gas	6 (19)	7 (21)	13 (20)
Propane	1 (3)	0 (0)	1 (2)

n (%) refers to the total number of respondent families and respective percentage in the valid cases

Most BE pilot participants (79%) use natural gas in a central heating system and 74% are heating warm water with natural gas as well. Most of the participants don't have an additional heating system. In case they have an additional heating system, this is most often electrical heating (15%) and firewood (8%). Most households are cooking with an electric hob (79%).

The characteristics of the 76 children from the intervention group who attended the lessons are presented in Table 7. The gender and age are based on the questionnaire that the children completed. The class group and number of lessons attended are registered by the teacher.

Table 7. Characteristics of the children of the intervention group attending the lessons.

	All Participants		Cohort 1		Cohort 2	
Child characteristics	**n (%)**	**Mean (Min – Max)**	**n (%)**	**Mean (Min – Max)**	**n (%)**	**Mean (Min – Max)**
Sex	76 (100)		36 (100)		40 (100)	

Male	56 (74)		27 (75)		29 (73)	
Female	20 (26)		9 (25)		11 (0,28)	
Age	76 (100)	12 (9 – 15)	36 (100)	12 (9 – 15)	40 (100)	12 (10–14)
Class group	76 (100)		36 (100)		40 (100)	
Class group 1			13 (36)		6 (15)	
Class group 2			10 (28)		8 (20)	
Class group 3			6 (17)		8 (20)	
Class group 4			7 (19)		9 (23)	
Class group 5			/		9 (23)	
Number of lessons attended	76 (100)	4.9 (3 – 5)	36 (100)	4.8 (3 – 5)	40 (100)	4.9 (4 – 5)
Frequency of consulting EnergyID-dashboard by the child	75 (100)		36 (100)		39 (100)	
Min. 1x/week	10 (13)		4 (11)		6 (15)	
3x/month	9 (12)		3 (8)		6 (15)	
2x/month	16 (21)		7 (19)		9 (23)	
1x/month	19 (25)		7 (19)		12 (31)	
once	17 (23)		14 (39)		3 (8)	
never	4 (5)		1 (3)		3 (8)	

After attending the lessons, the children estimated how many times they consulted EnergyID themselves. The frequency varied, as shown in Table 7 and Figure 18. Because of the low frequency for a number of children in the first cohort, during the lessons of the second cohort more time was spent on the consultation of the graphs in EnergyID. This resulted in a more frequent consultation of EnergyID in the second cohort.

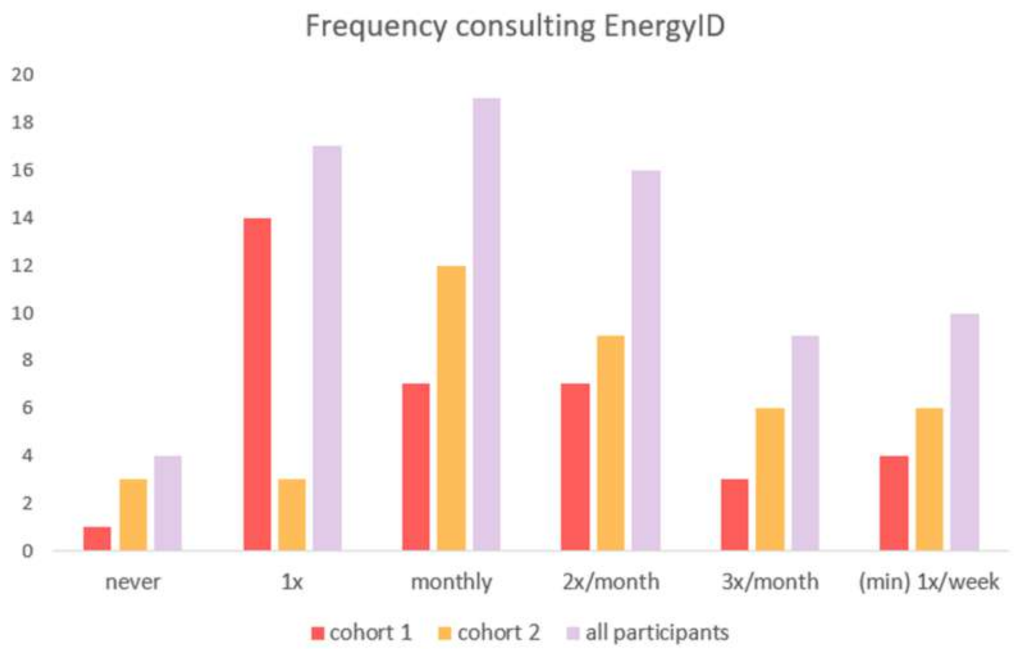


Figure 18. Frequency of consulting the graphs in EnergyID reported by the children of the intervention group in the questionnaire (post-test).

The characteristics of the families of the children of the first and second cohort and the control groups who completed the questionnaires (pre- and post-test, without outliers) are represented in Table 8. For most variables, the characteristics were similar. In cohort 1, we can observe more male versus female participants in the intervention group. In cohort 2, male and female were the same in the intervention group. In both control groups, there were more female than male participants. The average age in the four groups was 40 to 43 years old. There were on average 4 people in a household. They stayed averaged 4 to 5 days at home. More days of homework in the first cohort might be due to the COVID-19 pandemic.

Table 8. Characteristics of the families of the intervention group and the control groups.

	Cohort 1 - Intervention	***Cohort 1 - Control***	***Cohort 2 - Intervention***	***Cohort 2 - Control***
Sample (outlier excluded)	30	22	32	23
Stated being female	10	14	16	16
Stated being male	20	8	16	7
Average age (SD)	43.27 (5.49)	41.41 (3.51)	41.75 (3.23)	40.22 (4.52)

Average living area in m² (SD)	225.7 (104.96)	253.82 (93.96)	216.28 (133.21)	228 (188.86)
Number of persons in household	3.90	4.00	3.75	3.91
Average days per week being mainly at home	5.57	5.39	4.17	4.70

Additional data about the houses of the participants were gathered through the EnergyID platform, as presented in Figure 19, 20, 21 and 22. These questions were not mandatory for the participants to complete. Therefore, a lower number of participants has completed these questions. Although the data is not fully representative, the percentages can provide an impression of the distribution of the prevalence of some characteristics in the intervention group. Because of the low number of participants, the participants of both cohorts are represented together.

Figure 19. Pie chart of percentage owners in comparison with tenants for the participants of the intervention group.

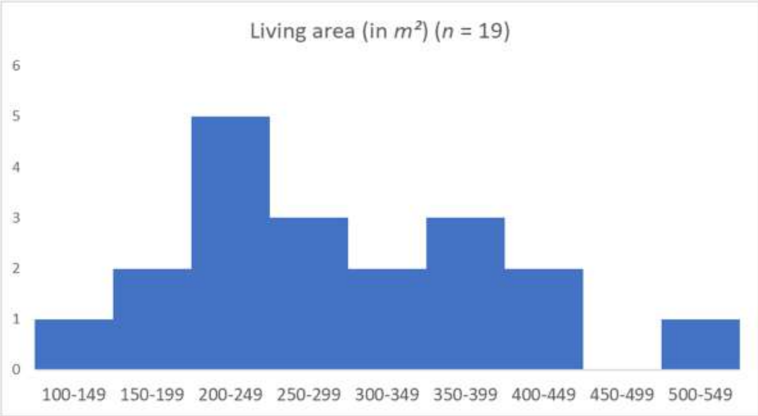


Figure 20. Right: Histogram of the living area of the participants of the intervention group based on EnergyID.

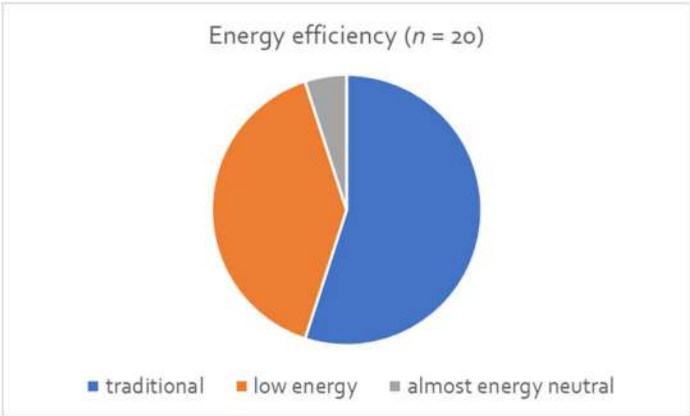


Figure 21. Pie chart of the energy efficiency of the house of the participants of the intervention group based on EnergyID.

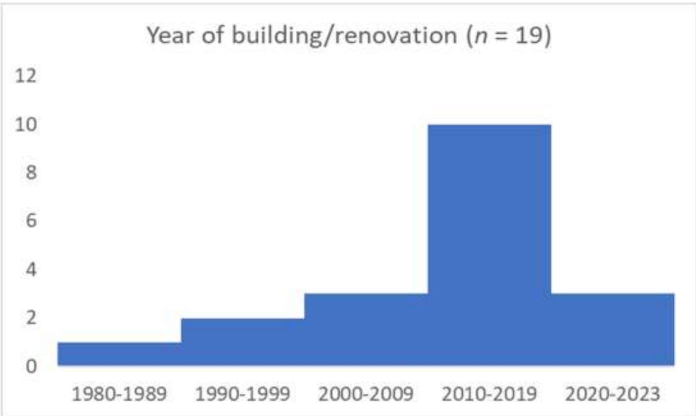


Figure 22. Histogram of the year of building or renovation (if applicable) for the house of the participants of the intervention group based on EnergyID.

2.2.3. Climate and Meteorological data

The climate in Belgium is a mild maritime climate characterised by moderate temperatures. The average Belgian temperature is 10.2 °C. July is the warmest month with an average temperature of 18.1 °C, while January is the coldest month with an average temperature of 3 °C. The average annual precipitation for Belgium is 910 mm/year. On average, the most precipitation falls during winter and the least during spring. Most precipitation falls in December (average 100 mm) while April is the driest month (average 50 mm) (www.meteo.be/nl/klimaat). The climate is similar for the locations where the participants live (in the centre of the country).

The pre-intervention phase of the Belgian pilot for the collection of baseline data had a duration of approximately 3 months, the intervention took about 5 months and post-intervention endured 3 months. For the **first cohort** conducted in the academic year 2021/2022, the pre-intervention phase lasted from November 2021 to January 2022. The lessons with the nudges started in February 2022 and lasted until June 2022. The post-intervention phase endured from July until September 2022. For the **second cohort** conducted in the academic year 2022/2023, the pre-intervention phase lasted from September to November 2022. The lessons with the nudges started in December 2022 and ended in May 2023. The post-intervention phase started in June 2023 and ended in August 2023. Meteorological data acquired from Copernicus for the period from November 1st, 2021 until August 8th, 2023 is presented in Table 9 and Figure 23 for the city of Leuven where most of the pilot participants live.

Table 9. Ambient temperature evolution for the city considered in the BE pilot during the relevant study periods.

	Ambient Temperature [Mean (Min – Max)] (°C)		
City	**Period**	**Cohort 1**	**Cohort 2**
Leuven	Pre-intervention:	5.7 (3.8 – 9.6)	13.2 (2.5 – 29.4)
Leuven	Intervention:	11.6 (-3.3 – 30.7)	8.2* (-4.1 – 23.3)*
Leuven	Post-intervention:	19.0 (5.6 – 36.8)	19.1** (9.9 – 30.4)**

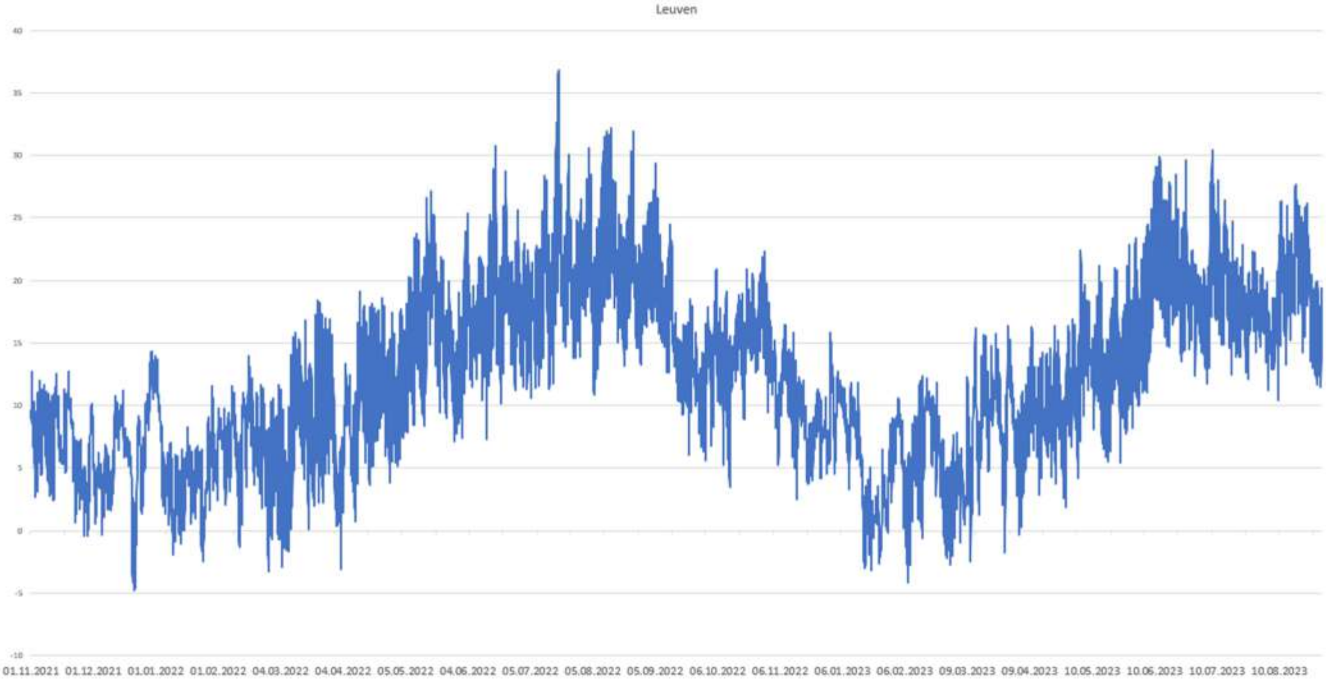


Figure 23. Ambient air temperature in Leuven from October '21 until March '22 (data from Copernicus project). (The weather data of December '22 is missing in the Copernicus project.)

As observed in Figure 23, the outdoor temperature in the region of Leuven during the period from November 1st, 2021 until July 31st, 2023 mostly ranged between –5 °C and 30 °C, with a mean temperature of 12°C and only few days going below –4 °C or above 30 °C. The lowest temperature was -4.8 °C on December 22nd, 2021 and the highest temperature 36.8 °C on July 19th, 2022. During winter, there were a number of weeks with temperatures below 0 °C and during summer, there were exceptional heat waves with temperatures above 30 °C (most of them in 2022).

2.2.4. Main Results from the Pilot Implementation

In the Belgian pilot we have put forward four research questions addressing the impact of the energy course / the nudges) on the knowledge level, the intention and the motivation to save energy among pupils and parents. These related results were based on survey data administered by the pupils and their family.
For the fourth research question, the gas consumption of the participating families was analysed based on the EnergyID data.

Knowledge based on survey data

To measure the knowledge, both for the pupils attending the lessons and for the parents, the survey data administered before and after the energy course were analysed. The results did not prove that the knowledge increased after the intervention.
For knowledge, the test scores of the parents were significantly lower after the energy course compared to before (see Figure 24).

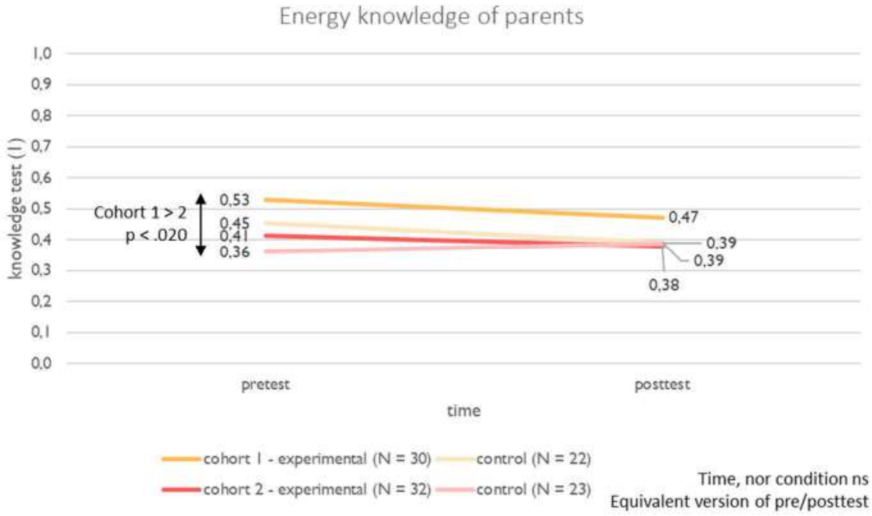


Figure 24. Energy knowledge among parents (N = 107).

The test scores of the pupils for knowledge remained unchanged between pre- and post-test (see Figure 25).

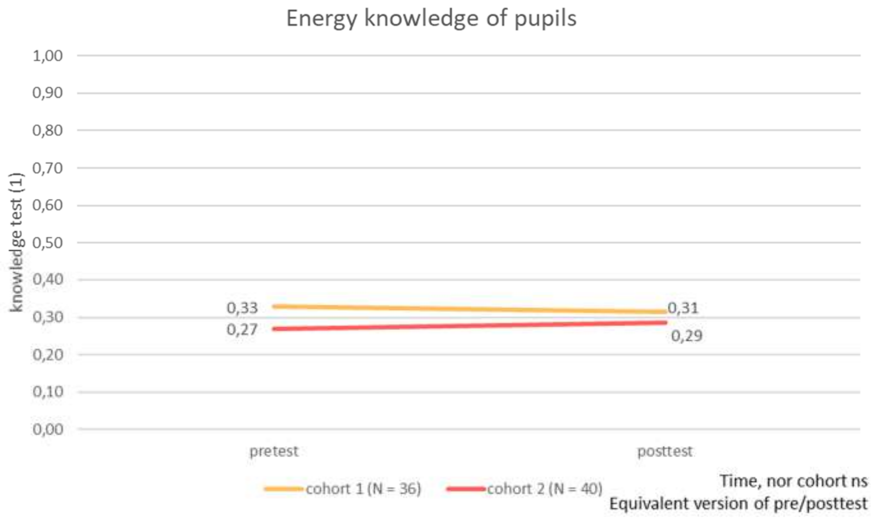


Figure 25. Energy knowledge among pupils (treatment group only, N = 76).

There might be different explanations for these surprising results. Since all children were gifted children, most of the parents were highly educated and already well informed about their own energy consumption and energy related challenges in general. This high 'start level' can be one of the reasons that explains the increase in their knowledge thanks to the course was limited. Before the energy course, we observed that the test scores of the parents were already higher than those of the pupils (see Figure 26), which limited the intergenerational learning.

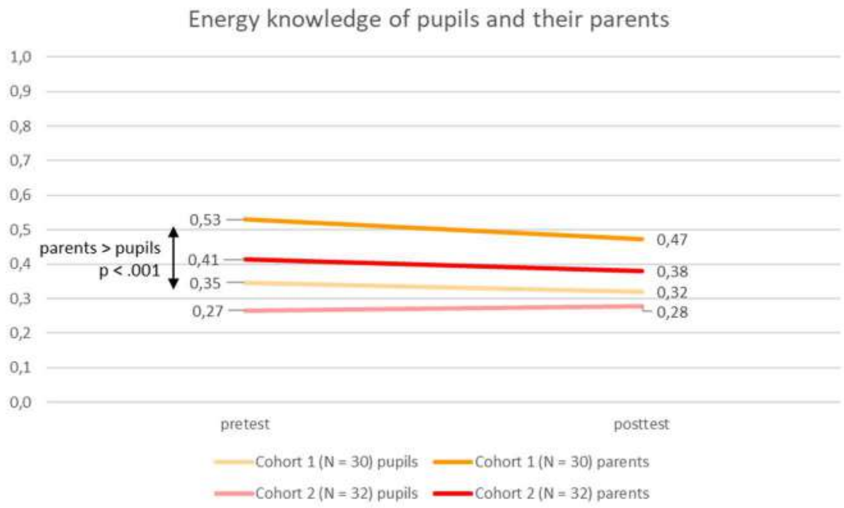


Figure 26. Energy knowledge among pupils and their parents (treatment group only).

Moreover, the knowledge post-test was perceived as more difficult than the knowledge pre-test, both by the children and the parents.

Intention and motivation to save energy based on survey data

The intention and the motivation to save energy was measured with several questions evaluated on a 5-point Likert scale in the survey. The survey data administered before and after the energy course were analysed and compared (where possible). The results did not prove that the intention and motivation to save energy increased after the intervention.
The intention to save energy was significantly lower for both parent groups after the energy course compared to their intention before.

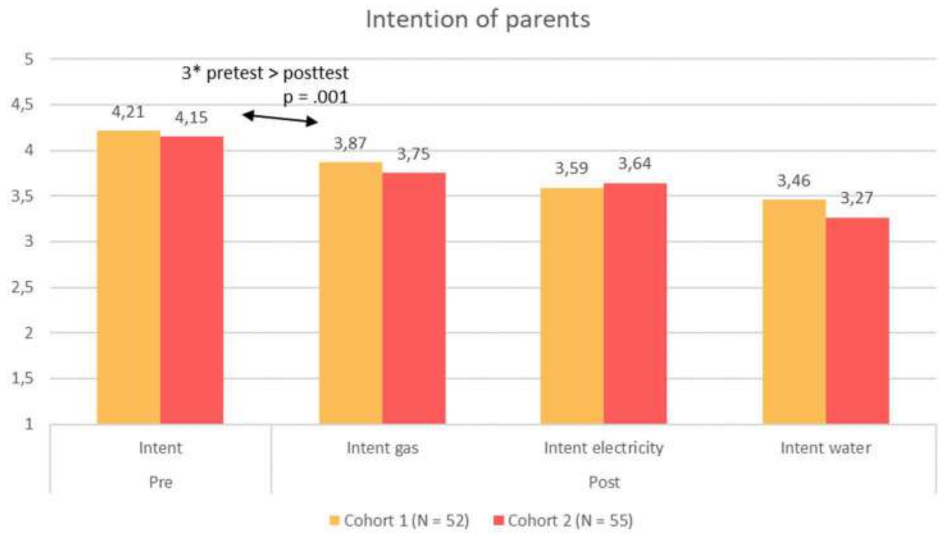


Figure 27. Intention to save energy among parents (pre- and post-test, N = 107).

It must be mentioned that the intention to save energy in the pre-intervention survey had been asked on a general level, whereas intention in the post-intervention survey had been asked in relation to a specific energy source (gas, electricity and water). Therefore, it is uncertain whether this decrease is due to the ability of respondents to better assess their specific intention or if it is a result of the intervention.

For the pupils, intention was not measured before the intervention.

The motivation to save energy showed similar surprising results: a lower score in the post-test compared to the pre-test for the parents of the intervention group (see Figure 28). For the pre-test, the treatment group scored significantly higher than the control group.

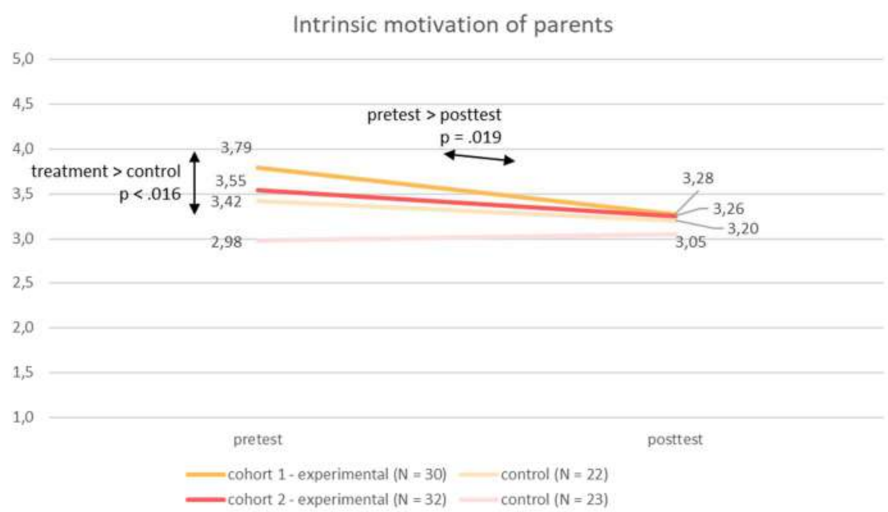


Figure 28. Intrinsic motivation among parents (N = 107).

A significantly lower score in the post-test compared to the pre-test was also observed among the pupils (see Figure 29).

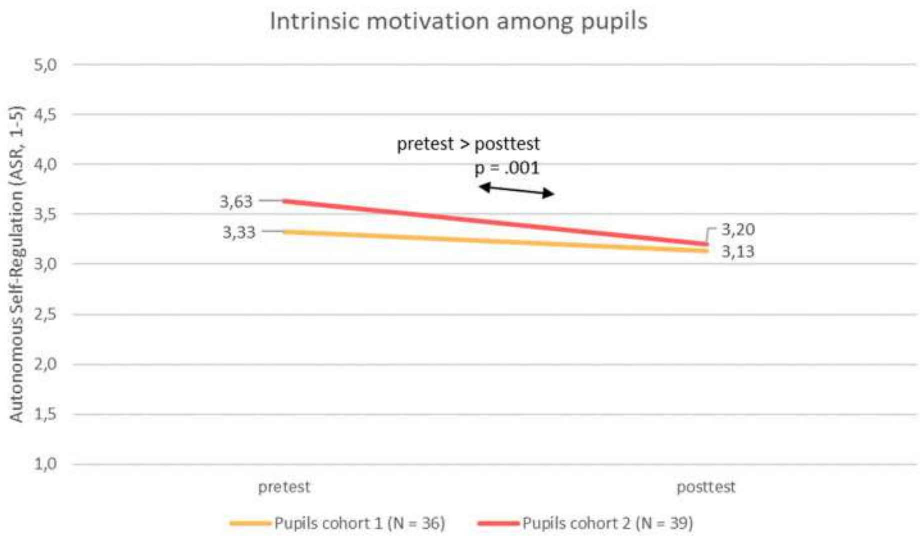


Figure 29. Intrinsic motivation among pupils (N = 75).

The most probable explanation for these surprising results might be the extreme rise of the energy prices "forcing" households to cut their energy consumption during (or for cohort 2 even before) the intervention period, as explained in general in 2.2.4.4. Children and parents might be not motivated and not intending to reduce even more after all these efforts.

Gas consumption based on data of EnergyID

The fourth research question has been substantiated by gas consumption data before, during and after the intervention period. For cohort 1 (n = 36) 16 households with digitally available gas data were analysed, while in cohort 2 (n = 40) 25 households with gas consumption information were followed. When we look at the gas consumption data for the entire measured period, we can observe peaks in winter consumption, especially during the Christmas period, and in April, probably because of easter holidays. Median daily consumption across both cohorts was 41.58 kWh, which is lower than mean Flemish consumption for an average family (64 kWh). Consumption during the measured winter period is much higher: for the first cohort we measured a median daily consumption of 193.54 kWh and for the second cohort 91.85 kWh (see Table 10).
In Figure 30, we can observe a significantly lower mean and median daily consumption for cohort 2 compared with cohort 1. A reasonable explanation could be that the intervention period of cohort 2 was during the 2022/2023 energy crisis.

It is also remarkable that several participants had extremely high values. This might be caused by owning a swimming pool, a sauna, or a large, poorly insulated home that requires more heating during the colder months. These themes were discussed and confirmed during the lessons as well.

Table 10.: Description of gas measurements in cohort 1 and cohort 2

	Cohort 1	**Cohort 2**
Participants	16	25
Earliest date of the lesson	February 7th, 2022	December 2nd, 2022
Latest date of the lesson	February 18th, 2022	January 9th, 2023
Mean daily consumption	203.50 kWh	117.187 kWh
Median daily consumption	193.53 kWh	91.852 kWh
HDD (base of 23°C)	16.84	17.15

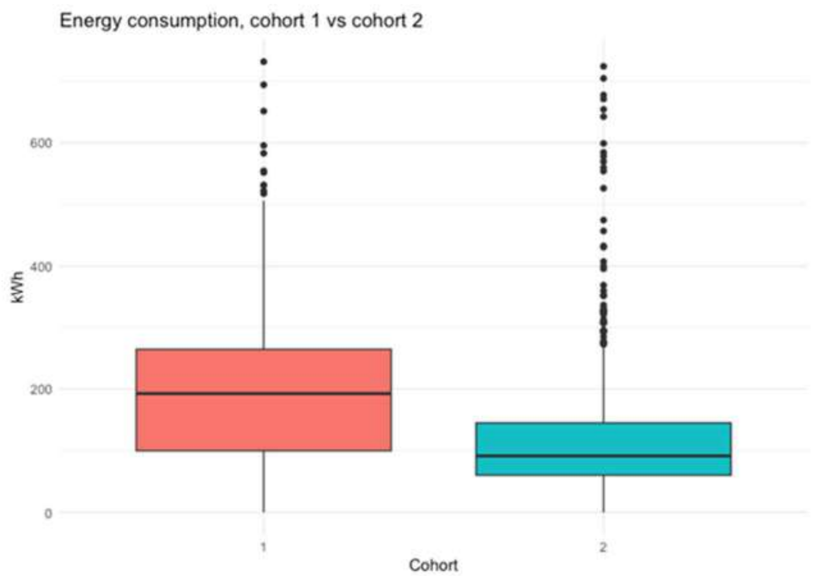


Figure 30. Comparing consumption during the six week measurement period for cohort 1 and cohort 2.

The gas consumption in the two- and three-week period after the intervention was compared to the two- and three-week period preceding the intervention. For cohort 1, the results showed that the gas consumption had significantly dropped after the children followed the courses compared to before the intervention. This result was in line with our expectations and may explain why motivation and intention to further reduce was lower, as targets were already achieved.

Results were different with the second cohort. We observed a higher gas consumption after the intervention for the second cohort compared to before the intervention. This may be explained by the fact that, before the start of the pretest of the second cohort, the highest price increase for gas was noticed. This can explain the low gas consumption for the second cohort before the start and an increased gas consumption after the course because the prices normalised and the hard efforts were difficult to maintain.

Further possible explanations might be that the results of cohort 1 are the result of generally higher energy use during the 2021/2022 winter, when compared with the 2022/2023 winter, whereby participants in cohort 1 saw more scope for energy reduction. We can observe that the mean consumption for cohort 2 is significantly lower during the overall measurement period. However, we also note that for cohort 1, the post-intervention temperature was higher and for cohort 2 the temperature was lower. It is possible that the real-world impact of consumption could not be completely muted by controlling for heating days and normalisation of the data.

Another explanation of different results might be caused by the different starting dates for both cohorts. For the second cohort, the post-intervention period encountered the Christmas season, which is typically a period of increased consumption, while for cohort 1 this period fell in the pre-intervention period. For the first cohort, Spring started in the post-intervention period, with corresponding higher temperatures.

General explanation of the results

Also, for other parameters in this study, hard conclusions were difficult to draw. The extreme fluctuations of the prices (prices up to 10 times of the 'normal' prices) for electricity and gas during this study undoubtedly had a very important effect on the energy consumption, awareness as well as the knowledge of both children and parents about energy in general. This effect was not foreseen, nor studied, but definitely impacted the families in this study in some unpredictable way.

Before the start of the pretest of the first cohort, there was a small price increase for gas, but before the start of pretest of the second cohort, the highest price increase for gas was noticed.

During the lessons, it was remarkable that for the first cohort, most children were enthusiastic in lowering temperature at home and did lot of efforts. For the second cohort, most children mentioned already really low heating temperatures and argued that this could not be lowered anymore. These price increases might also explain the intention and motivation to save energy before the start of the intervention. The intention and motivation might have decreased because of lower energy prices and the hard work it takes to maintain all the efforts. In conclusion, the price of energy might be the strongest nudge that overruled all other nudging effects.

2.2.5. Concluding Remarks on Pilot Outcomes

It was difficult to prove in facts and figures that the course including reinforcement and social nudges had a positive impact on the knowledge, the intention and motivation to save energy of the pupils and their families. As expected, the gas consumption had significantly decreased after the children followed the

course in the first cohort. Unfortunately, this result could not be confirmed with the second cohort. However, this may be due to the overwhelming effects of the energy crisis on cohort 2.
Despite these confusing and unexpected results, we could "feel" a very positive vibe during the course. Most children were interested, motivated, engaged and active during the lessons. They were asking questions out of the scope of the course, they were thinking, reflecting and discussing energy-related questions at high level. They enjoyed meeting peers during the lessons, other children with the same interest.
We saw one of our pupils talk to the European Parliament on July 29th, 2022. He impressed us, his parents, his teachers and the participants of the meeting in the way he fluently spoke to the audience with a broad knowledge of the complex topics he was talking about.
The city of Leuven helped to distribute the course material to 150 schools in and around Leuven, enabling a further dissemination to teachers and children. We promoted the course materials to different energy-related events in cooperation with the city of Leuven. The course material is translated to English as well and available on the NUDGE project website.

2.3. The German (DE) pilot

2.3.1. Overview on Pilot implementation

Context and Aim

In Germany, there are about 40 million buildings, thereof 12.9 single-family houses and 3.2 million two-family houses. These 16.1 million houses are potential prosumer and a target market for privately owned residential PV systems (Wirth et al. 2023)

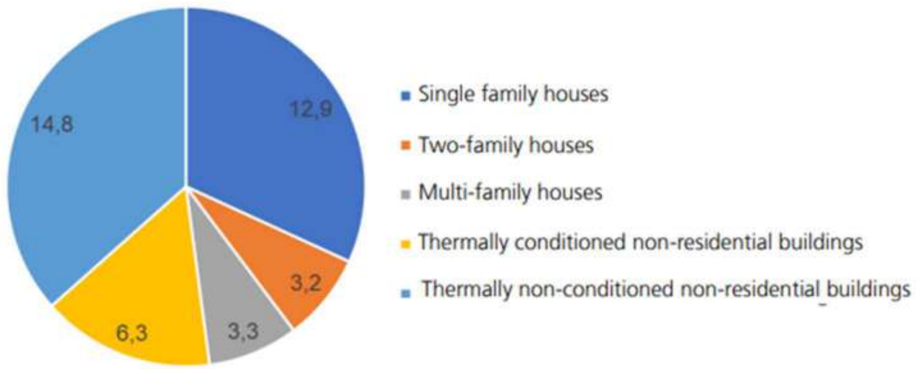


Figure 31. Building stock in Germany.

However, while in rural districts the majority of single- and two-family houses are suitable for setting up a photovoltaic system due to typically larger dimensions and less shading properties, in urban areas the potential is limited to about one half of these single- and two-family houses. Therefore, the target market of residential PV systems in Germany is 11.7 million single and two-family homes (SolarServer,2021). At the end of 2020, 1.3 million photovoltaic systems were installed on single- and two-family homes in Germany (E3/DC, 2021). Since then, the PV market has grown very rapidly, from a total of 2 million PV systems installed on roofs and ground in 2021 to 3 million in May 2023. Two thirds are roof-top PV systems and one third grounded systems. (Heise, 2023; Statistisches Bundesamt (Destatis), 2023). We estimate that the total number of PV systems on single- and two-family homes has reached 2 million by mid 2023. This would represent a market penetration of 17 % of all potential residential homes. The penetration is highest in Southern Germany and lowest in Eastern Germany homes (SolarServer,2021).

In addition, the number of electric vehicles (EV) in Germany has grown exponentially during the three project years. The number of Battery Electric Vehicles (BEV), meaning EVs which are fully electric with rechargeable batteries and no gasoline engine, grew from 136 617 in 2020 to 1 170 630 in July 2023 – see Figure 32, plotting the number of electric vehicles from 2006 until October 1st, 2023. In addition, there were 887 300 Plug-In-Hybrid vehicles on July 1st , 2023 (Statista, 2023). This total figure of electric vehicles in Germany is expected to increase to 14 million by 2030 (Nationale Plattform Zukunft der Mobilität, 2021).

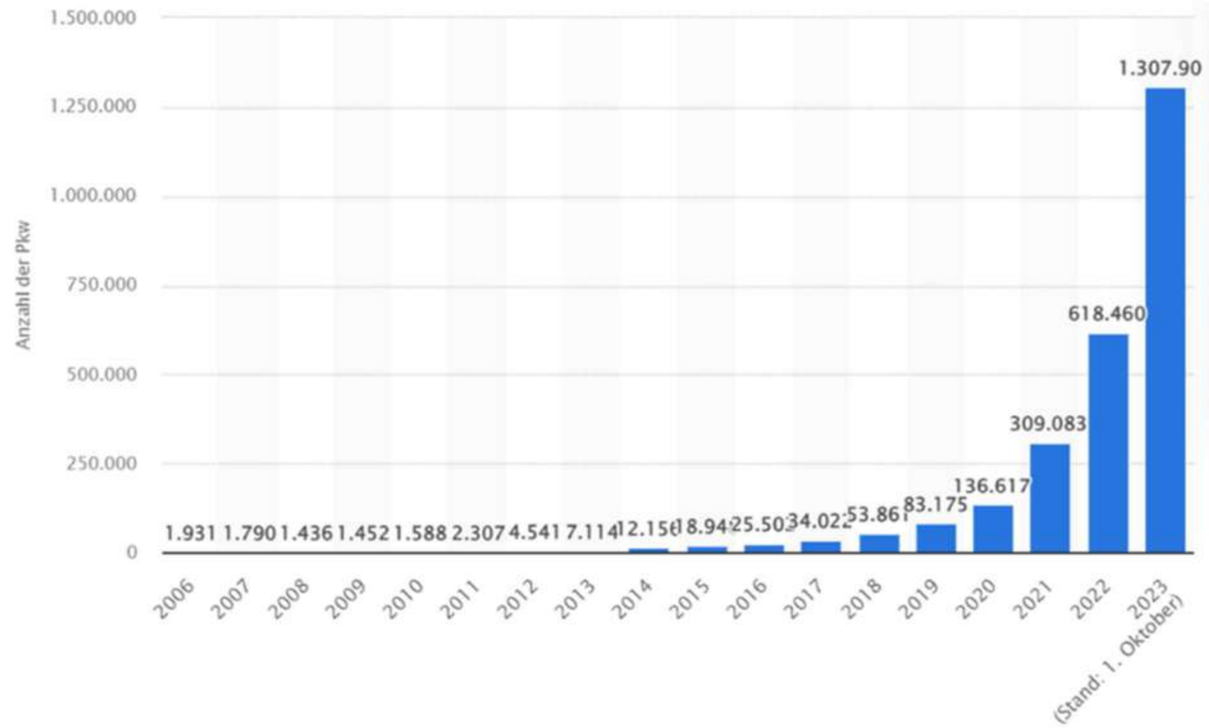


Figure 32. Rising number of electric vehicles (BEV) in Germany 2006 – 2023.

Households with PV systems generating their own solar power present a large group with a high potential to buy an EV. This is also incentivised by regulatory measures. Just recently, on September 26th, 2023 a special subsidy named "Solarstrom für Elektroautos" offered up to 10 200 Euro for the purchase and installation of a comprehensive decentral energy solution, including a charging station, a PV system and a local battery storage. A total of 300 million EUR were budgeted by the Federal Ministry for Digital and Transport for this. After just one day, the budget was completely allocated, with 33 000 approved applications (Statista, 2023). For that growing number of prosumers with EVs in Germany, it is important to optimise their energy balance – by reducing their power consumption, i.e. by reducing their remaining demand for power from the grid and by optimising their autarky and self-consumption rate, taking advantage of self-produced PV power. The growing number of e-vehicles (EV) offers both a challenge and an opportunity in that context. The challenge is the additional energy demand of the EVs and the opportunity is the flexibility potential of this new power consuming entity.

Within the group of German pilot households, the energy demand for EV charging has been rising by 71% from 2021 to 2022 and by another 21% in the first 8 months of 2023 compared to the same period in 2022.

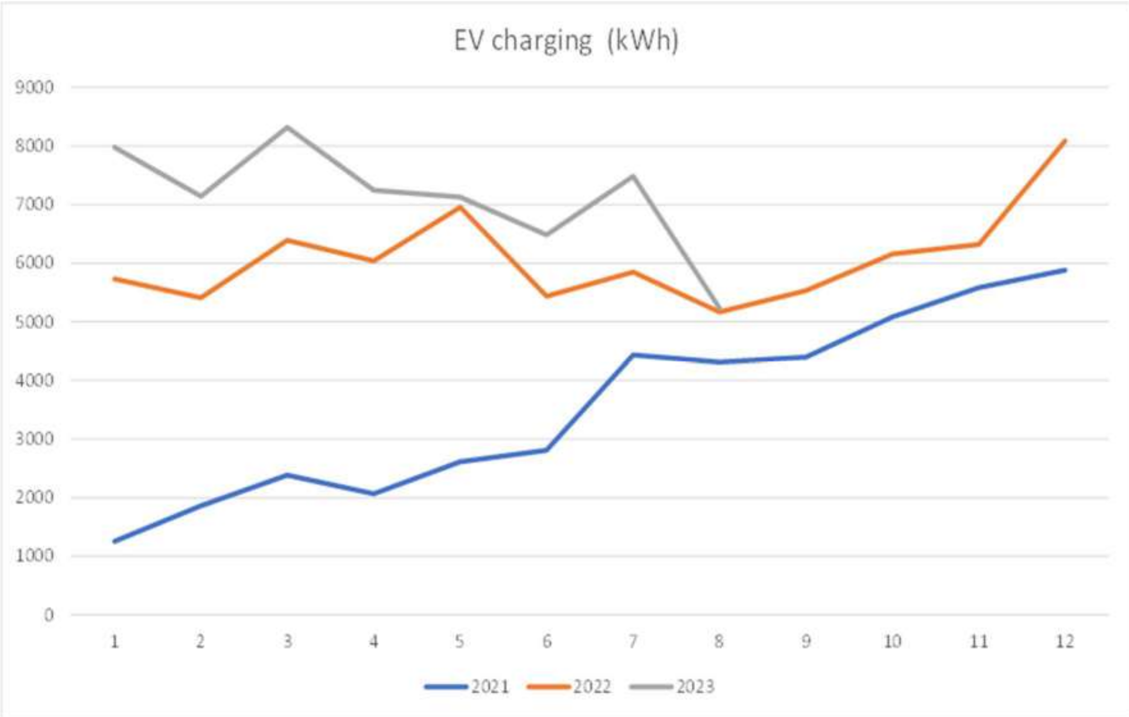


Figure 33. Growing energy demand of German pilot households for charging e-vehicles at home (Charging energy of 82 pilot HH, excl. HH with non-intergated EVCS)

With this in mind the NUDGE pilot in Germany aimed to test the effectiveness of specific nudges to promote sustainable energy saving and optimised self-consumption in prosumer households, specifically focussing on prosumer households with e-vehicles.

Study design and methodology

The DE pilot sought 100 residential households from the existing customer base of MVV Energie AG in the Rhine-Neckar metropolitan area. As a prerequisite, all participating households needed to have a PV-system, enabling them to produce their own solar energy, with or without a battery. In addition, at least 50 participants should have an EV charging station (EVCS) at home that is able to be connected and controlled remotely by beegy. Thus, the target for the pilot customer recruitment was a total of 100 participating households, equally allocated to the EV-group (50 participants) and the PV-group (50 participants).

More than 400 customers of MVV were contacted in five recruiting waves. The pilot reached the recruitment target of 100 households by October 2021 with a total of 102 pilot households, equally split into 51 EV and 51 PV households. Participants in the EV group were entitled to receive a specific EV charging app. However, during the following provisioning process of the app, it was discovered that not all 51 EV households did fulfil all technical prerequisites. Several EVs did not provide 3-phase charging and further PV-installations had more than one inverter. Therefore, 22 EV households had to be transferred to the PV group. Further recruitment activities were initiated, to add additional households to the EV group (5th recruiting wave). As a result, by February 2022, we had a total of 111 pilot households, split into 39 EV and 72 PV participant

groups. The participants of both groups were randomly divided into two similar sized sub-groups (EV1 and EV2 as well as PV1 and PV2).
The German pilot was ready to start the pre-intervention phase in October 2021, when the engagement of 102 pilot households was completed. The pre-intervention phase ran for 5 months, until February 2022.
Following the pre-intervention phase, the intervention plan for the German pilot consisted of the implementation of three sequential interventions (1st/2nd/3rd intervention phases, called NUDGE 1, NUDGE 2 and NUDGE 3) – followed by a post-intervention phase, concluding the field trial.

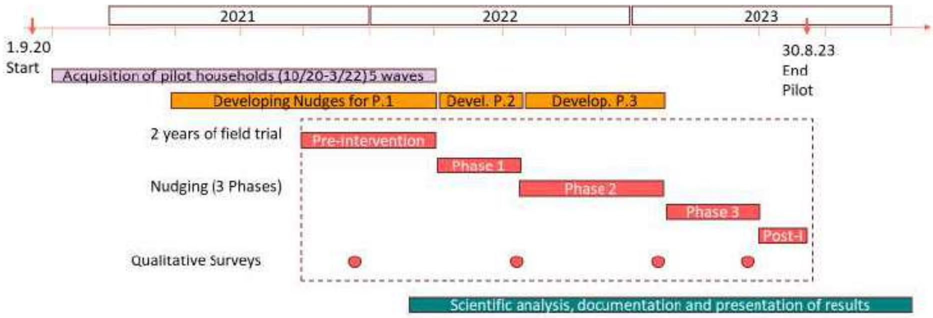


Figure 34. Timeline of the German pilot.

The intervention in each nudging phase occurred in two periods (period 1 and period 2) following a crossover trial design, ensuring that all participants were exposed to the nudging treatment.

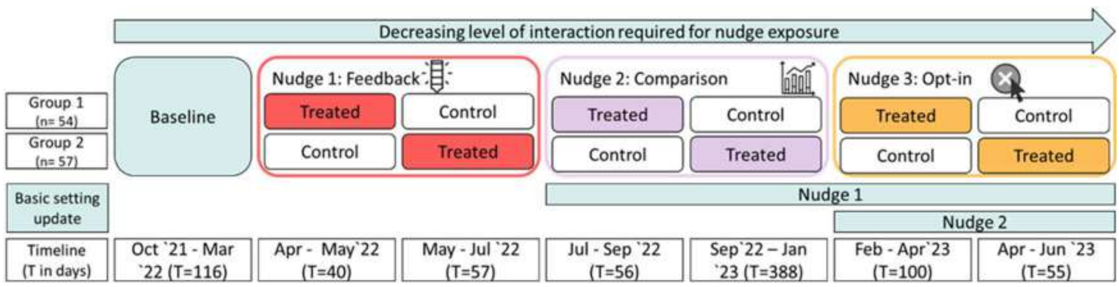


Figure 35. Intervention plan of the German pilot.

NUDGEs

In the German Pilot, we decided to focus on the following "positive" nudges

- *Facilitate – by providing **Feedback** and increasing Awareness (for the energy efficiency)*
- *Confront – in a positive sense by "**Comparison** and Suggestions"*
- *Reinforce – by enabling "control" and thru **Opt-In** for an automated optimization by setting **defaults***

Usage data and qualitative customer feedback from the initial nudging phase(s) were used to adapt the design of the nudges for subsequent phases.

The nudges were delivered on two nudging platforms in the German pilot: All participants had access to the Web-Portal, visualising the energy flows at home. In addition, customers of the EV group got access to the charging app HERMINE.

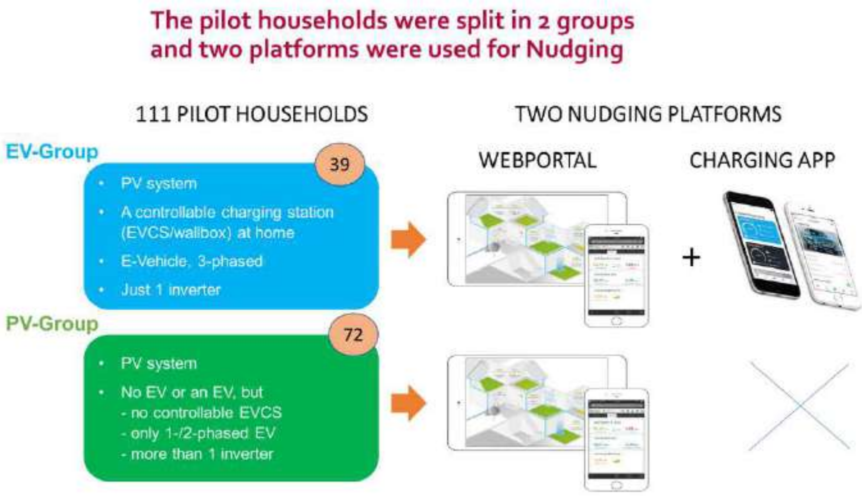


Figure 36. Grouping of the German pilot customers with applicable nudging platforms.

The following nudges were offered to the German pilot households on the Webportal:

- *Phase 1 applied **"Feedback & Awareness"-**Nudges that provided inwebformation on central target metrics (KPIs) on the dashboard. In addition, „Perceived Control"-Nudges were used, enabling customers to enter individual tariff information for calculating individual savings.*
- *Phase 2 focused on "**Compare, Control & Suggest"** Nudges, providing comparisons of energy data for different periods and suggestions for shifting energy consumption depending on the PV forecast.*
- *In Phase 3, **"Feedback" & "Compare"-**Nudges were further extended, thru monthly and annual energy reports on the personal energy balance (available as downloads).*

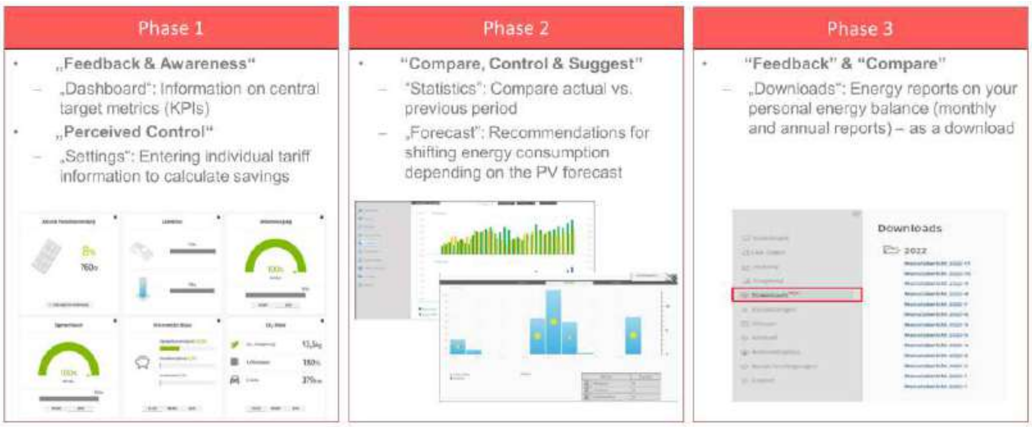


Figure 37. Nudges on the Webportal.

On the charging App, similar types of Nudges were provided during Phase 1 and Phase 2:

- **"Feedback & Awareness" and "Perceived Control" thru** Improved user-friendliness (usability and controllability) and better information (additional information, improved visualisation)
- **"Compare, Control & Suggest":** Personalised savings (analogous to the web portal) and the display of the planned and actual charging schedule
- In Phase 3 a new type of Nudge was realised for EV-charging. **"Default (Opt-In)" to Reinforce** an alternative charging behaviour: Solar surplus power charging was offered as a new charging mode on the web portal. This option can be selected as a default setting for any future EV-charging.

Figure 38. Nudges on the Charging App.

Research Hypothesis

The overall hypothesis of the German pilot is that implementation of Nudges on the Webportal and the Charging App will allow the users to reduce their overall energy consumption and optimise self-consumption of their own solar power. As described in D2.3, the German pilot did address the following three research hypothesis with regards to the effectiveness of such nudging interventions and the differences between the three nudges:

DE1: *Nudges are effective in increasing the self-consumption of participants.*

The web portal allows customers to shift their consumption or increase it during hours of self-generated electricity (surplus). Additionally, the charging app can automatically increase the EV's usage of self-generated electricity within the settings defined by the user.

DE2: *Nudges are more effective in increasing the self-consumption of participants with controllable electric vehicles than of the ones without.*

DE3: *Nudges are (also) effective in reducing the overall electricity consumption of participants.*

2.3.2. Participant Households

The pilot households were recruited mainly in the city of Mannheim and its neighbouring area. Homes of 103 participants were located within a 50 km radius around the city centre of Mannheim. The other 8 participants were located further away, with the biggest distance being 250 km.
The approximate location of participating households is presented in Figure 39.

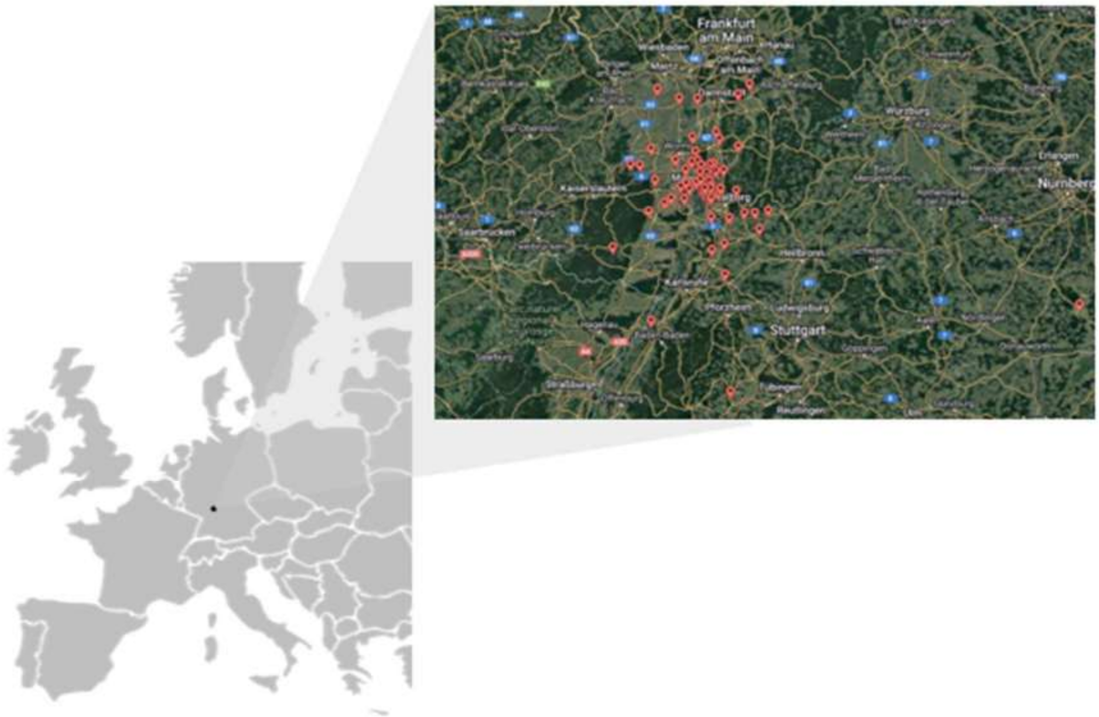


Figure 39. Location of households engaged for the German pilot in the region of Mannheim (South Western part of Germany).

The participating pilot households occupied primarily single detached houses (based on 105 responses to the initial survey):

- *Single-family home: 54%*
- *Semi-detached house: 15%*
- *Terraced house: 21%*
- *Other: 10%*

The most relevant characteristics of the 111 participating households in the German pilot are the components of their decentralised energy system. As previously referred, all of the participant homes had a PV system installed. Two homes actually had two PV systems, which were measured by two separate meters. Overall, The PV-systems have a total capacity/maximum output of 906 kWp. The average capacity per system was 8.16 kWp. Only 13 PV-systems went beyond 10kWp, which is the typical threshold for residential PV systems. The largest installation had a max. output of 19.47 kWp. Moreover, 98 households have installed a battery storage together with their PV-system. This is a penetration of 88% of installed PV systems. The installed batteries have a total capacity of 610 kWh. The average capacity per battery is 6.84 kWh. The two largest batteries have a capacity of 12.8 kWh.

Sixty-six pilot households have installed an EV charging station (EVCS), which can be connected to the beegy Gateway and thus may be actively controlled. These EVCS are of the following types: 48 Keba P30-c, 6 Keba x-series and 12 Webasto Next. The EV charging app can only support the charging of EVs in 3 phases. Another prerequisite is that the PV-system shall only have one inverter. Therefore, only 39 of these 66 households were enabled for smart EV charging.

Further, 10 participating households also have an EVCS that were not connected to the beegy Gateway, because they either do not provide a technical interface or because the type of EVCS has not been integrated into the Energy Management Platform. Therefore, the penetration of EVCS (and thus EVs) reached 68 % in the participating households (n = 76).

Nineteen participating households reported having a heat pump installed. Nevertheless, Heat pumps were not individually connected to the beegy Energy Management System, and, therefore, were not visualised separately in the Web Portal. They may however contribute to the total energy consumption, if they are not separately connected to the grid and thus measured separately.

As mentioned above, the pilot households were grouped into four sub-groups.

- *EV1 and EV2 have a PV system, with or without a battery and an EVCS which is connected and which enables smart charging of an EV.*
- *PV1 and PV2 have a PV system, with or without battery – but no connected EVCS.*

The technical installations of these four sub-groups are described in the table below:

Table 11. Summary of the relevant components installed in the homes of the 4 sub-groups of the German pilot.

Participant sub-groups		EV1	EV2	PV1	PV2	Total
Number of households		18	21	36	36	111
Components						
	PV system	18	21	36	36	111
	Battery	17	19	28	34	98
	EVCS					
	- connected	18	21	16	11	66
	- others	0	0	2	8	10
	Heat pump	3	3	6	7	19

2.3.3. Climate and Meteorological data

The climate in the region of the city of Mannheim is rather warm and sunny. Located in the warmest summer region in Germany, the "Rhine shift", temperatures rise up and above 35 °C in summer.

Climate in this area has mild differences between highs and lows, and there is adequate rainfall year-round. Due to the Rhine River, humidity in summer is high. In winter, snow is rare, even in the coldest months. The Köppen Climate Classification subtype for this climate is "Cfb" (Marine West Coast Climate/Oceanic climate).

Meteorological data is not stored for pilot households. Instead, meteorological data was taken from the Copernicus project and is presented below in Figure 40. The figure plots the temperature on the y-axis and the days on the x-axis – from October 1st, 2021 until July 31st, 2023.

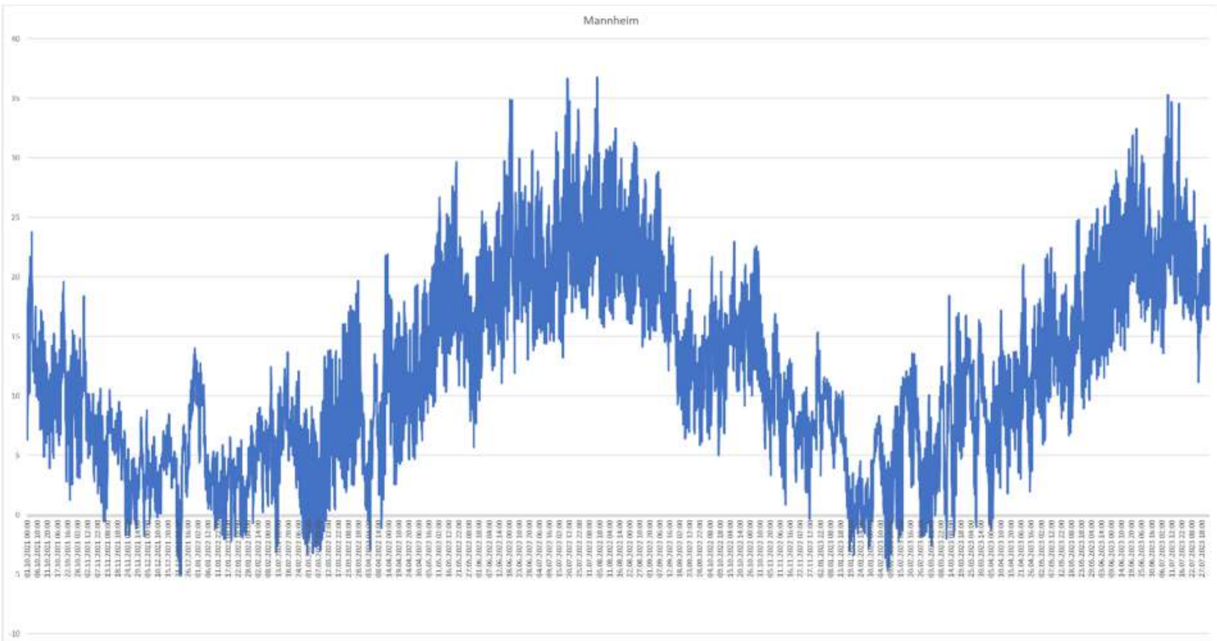


Figure 40. Ambient air Temperature in Mannheim from 1st October '21 until 31st July '23 (data from Copernicus project).

For the time period October 1st, 2021 – July 31st, 2023, the outdoor temperature in the Mannheim region during Winter (1.12. - 28.2) ranged between –5 °C and 15 °C and during Summer (1.6. - 1.9) between 10 °C and 37 °C (see Table 12).

Table 12. Ambient temperature evolution for the cities considered in the DE pilot during the relevant study periods.

City	Ambient Temperature [Mean (Min – Max)] (°C)			
	Pre-intervention	NUDGE 1	NUDGE 2	NUDGE 3

Mannheim	5.9 (-5.1 – 23.8)	15.9 (-3.0 – 34.9)	13.4 (-4.7 – 36.8)	11.5 (-2.6 – 28.9)

Source: https://commons.wikimedia.org/wiki/File:Pvgis_solar_optimum_DE.png

Figure 41. Yearly global irradiation (kWh/m²) across German territory.

The Mannheim region is located in the Southern part of Germany, and benefits from high solar radiation (see Figure 41). Solar radiation and thus the potential for the generation of solar energy with PV systems is subject to seasonal variations, with peaks in the summer months and lows in winter. Daily weather conditions then determine the effective value of solar radiation within the seasonal pattern.

The surface solar radiation (SSR) in the Mannheim region during the field test is plotted in Figure 42, as an average of the typical peak hours (12:00 and 14:00 hrs). The radiation value is expressed in J/m2 per hour.

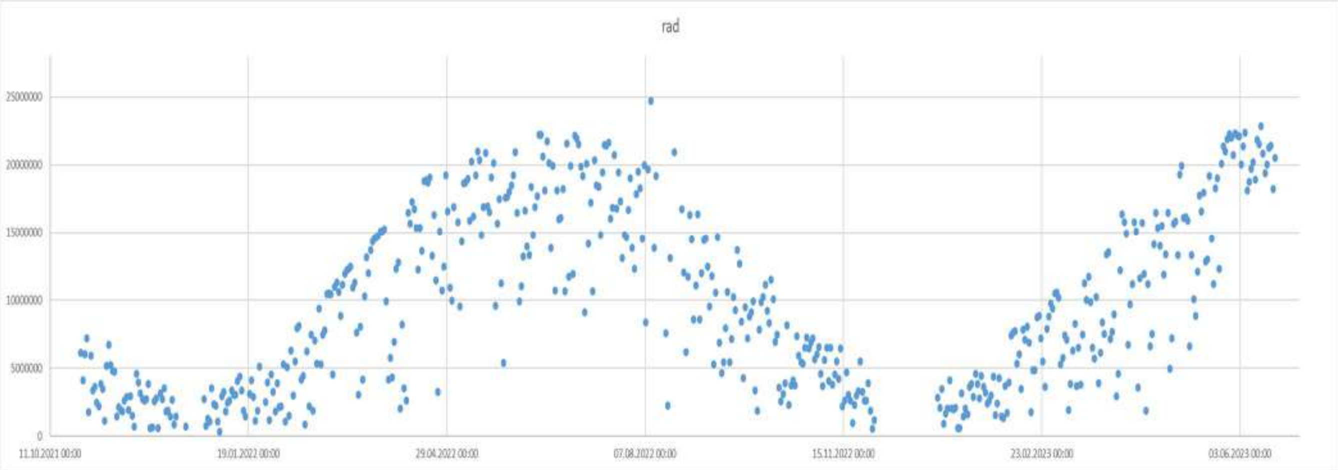


Figure 42. Solar radiation in Mannheim region during the field test (SSR in J/m2 per hour) - as an average of 12:00 hrs and 14:00 hrs values).

Table 13. Solar radiation in the DE pilot area (Mannheim) during the relevant study periods.

City	Solar Radiation [Mean (Min – Max)] (SSR in kW/m²)			
	Pre-intervention	NUDGE 1	NUDGE 2	NUDGE 3
Mannheim	915 (0 – 2190)	369 (2 – 2451)	871 (1 – 2408)	691 (2 – 2441)

2.3.4. Main Results from the Pilot Implementation

Pre-Conditions

Customer engagement

The German pilot households showed a very high interest and engagement in the project during the entire field-trial. Only one household did quit the project in 2022 – and therefore was not counted in any of the statistics and results. All other 111 households maintained their participation during the project.
This engagement also resulted in very high response rates to all four surveys, with a record high in the first survey.

- *Pre-intervention survey (December 2021): 105 (95%)*
- *Post-intervention surveys surveys*
  - *Wave 1 – First post-intervention survey (July 2022 after NUDGE 1): 90 (81%)*
  - *Wave 2 – Second post-intervention survey (Dec 2022 after NUDGE 2): 95 (86%)*
  - *Wave 3 – Third post-intervention survey (June 2023 after NUDGE 3): 87 (78%)*

Customer motivation and intention

Motivation and intentions were monitored through three consecutive surveys, after each nudging phase. The results showed that there was a significant decrease in motivation to save energy after NUDGE 1, followed by an increase after NUDGE 2. No significant difference in motivation was found in the wave-1-3 comparison. The intention to save energy increased significantly after NUDGE 1 and 2, and thus also increased significantly in the wave 1-3 comparison. Intention to use more of one's own PV electricity increased significantly after NUDGE 1 and remained approximately at this level after NUDGE 2; resulting in a significant increase from wave 1 to wave 3.

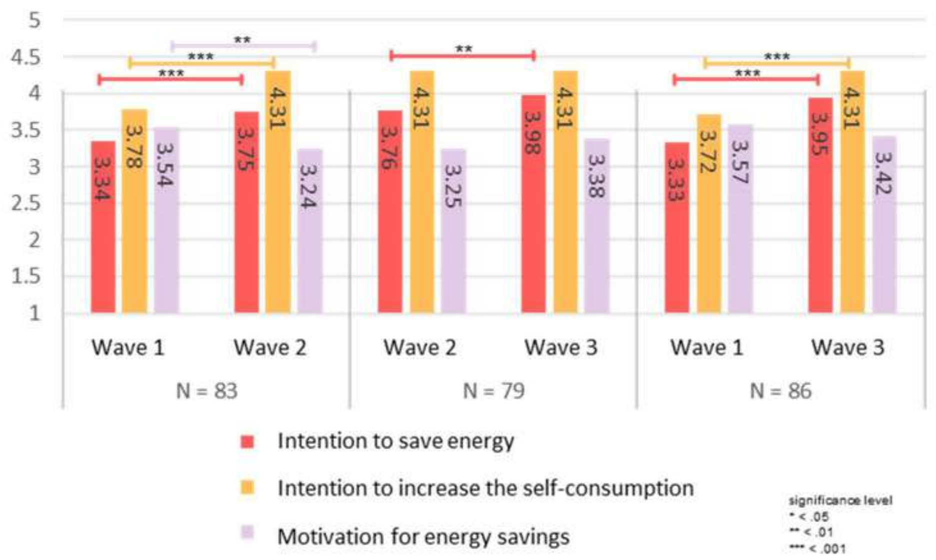


Figure 43. Intention and motivation to save energy reported by pilot customers during post-intervention surveys.

Technical limitations to disclose

The use of the nudging tools as well as the data collection were affected by some technical problems.
On the web portal, we experienced various interruptions of the data transfer to the central data platform. These interruptions were mainly due to a loss of connectivity between the local beegy gateway and the internet router of the customer. Such interruptions were constantly monitored, but resetting the connection took time, in some cases up to several weeks. Another problem were "spikes" in energy data, resulting from these interruptions. These problems were mitigated as much as possible during data analysis through extrapolation and "smoothing".
On the charging app HERMINE, we experienced problems with one type of wallbox. A new software stack resulted in compatibility issues and meant that charging was no longer possible. We therefore had to deactivate the charging app HERMINE for five customers during approx. five months. No energy data could be transmitted during this period.
The strongest restriction was the technical incompatibility of the charging app with non-integrated wallboxes, e-vehicles or PV-system components. Some wallboxes installed at pilot households have not yet

been integrated with the beegy gateway and therefore cannot be measured nor controlled by the charging app. As a result, we had to exclude 10 households from using the charging app.
In addition, as already mentioned above, several e-vehicles did not provide 3-phase charging and/or the PV-system had more than one inverter and/or more than one wallbox. Therefore, 27 households with integrated wallboxes could still not use the charging app HERMINE.
All these 37 households with EVs were transferred to the PV group. The PV group therefore had 72 participants.

Use of the Nudging tools

The Webportal was used regularly by about two thirds of all customers. However, the usage (and thus visibility of nudges) varies depending on the different pages/nudges.

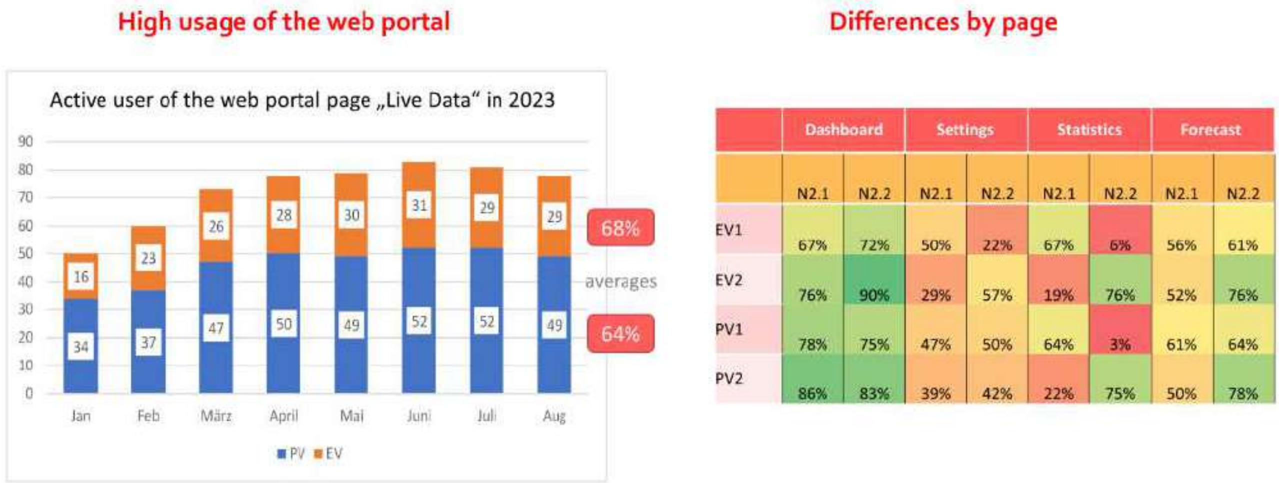
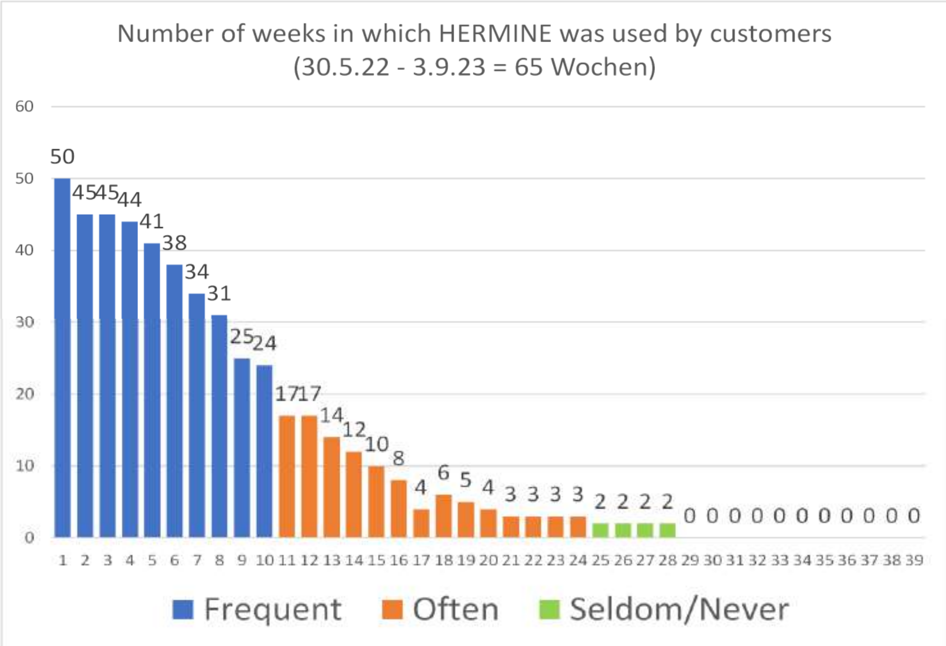


Figure 44. Use of the Webportal (overall) and of its various sub-pages.

The Charging App, called HERMINE, was only used by approx. 25% of the customers that were provisioned for this service. The acceptance and use of the service continued to decline throughout the project. Only 7.6 customers (out of 39) did use the app on average per week. These were mainly approx. 10 "heavy users" that regularly used the app for optimising the charging of their EV at home.

- 39 households provisioned for HERMINE
- 10 frequent users



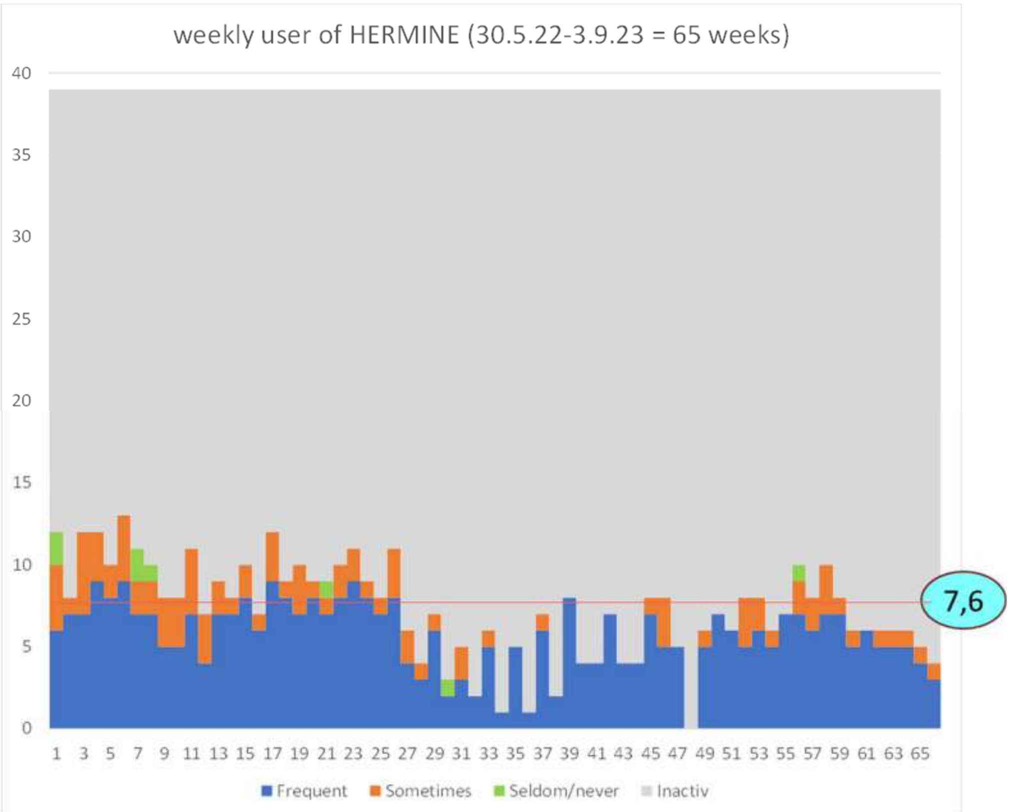


Figure 45. Use of the charging app HERMINE by user and by week.

Based on customer feedback and effective usage data, we decided to develop and introduce an alternative charging method as NUDGE 3, the so called "surplus charging."
Adaption and use of this alternative charging method was much higher. Over 2/3 of qualified customers from the EV2 group did use surplus charging during the third Nudging phase.
Different usage pattern can be observed:

- *"Switching on/ activating surplus charging only once as a "default";*
- *Multiple/continuous switching on/off depending on charging requirements and PV forecast.*

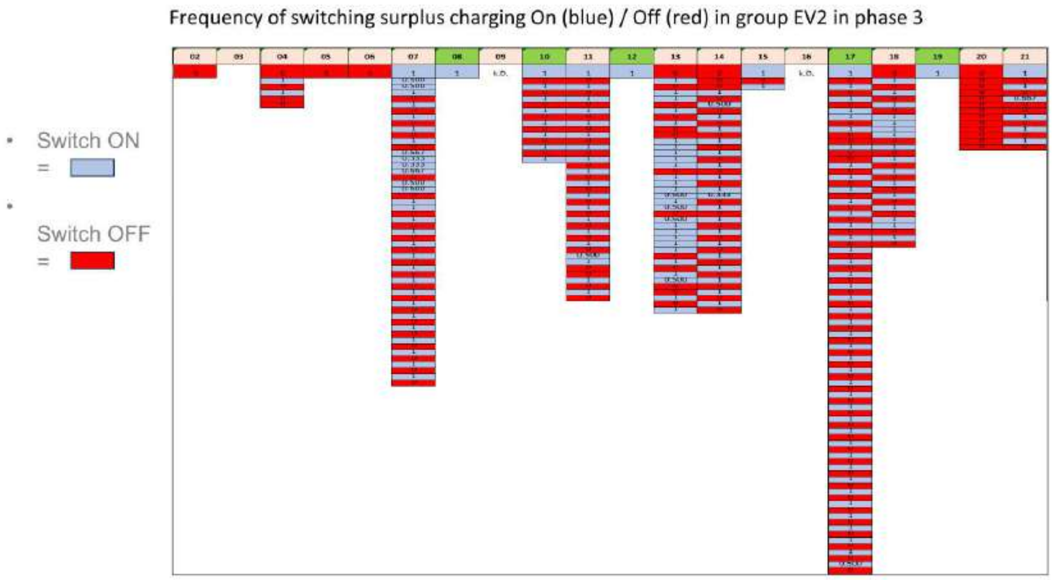


Figure 46. Use of Surplus Charging.

Nudging effect on energy consumption and self-consumption

The aim of the nudges was to reduce energy consumption and increase self-consumption. The measured results differ between the two groups.

Nudging effects in Group 1
NUDGE 1 and 2 have a positive effect on self-consumption and autarky. We find small, positive treatment effects regarding these two self-consumption indicators. The reported coefficients for autarky indicate that the nudging treatments increased autarky by ca. two percentage points. Since autarky is measured on a scale from zero to one, it is useful to put this estimate in relation to the mean autarky rate in the sample, which is an autarky rate of 0.55. At this level, the 2-point improvement corresponds to an increase of 3.8% on average. Regarding self-consumption, the coefficients can be interpreted directly as changes in percent due to the logarithmic transformation. Self-consumption increased by 2.9% due to NUDGE 1 and by 2.8% due to the NUDGE 2.

With regards to household consumption, both NUDGEs 1 and 2 also led to a significant reduction in household consumption. NUDGE 1 led to a reduction by 3.9% on average, NUDGE 2 to a reduction by 5.2% (again, household consumption was log-transformed). Taken together, the results indicate that households managed to increase self-consumption and simultaneously decrease household consumption with the nudging intervention.

	Autarky (0 to 1)	Self. consum (%)	Household consum (%)
Nudge 1	+ 4%	+ 3%	- 4 %
Nudge 2	+ 4%	+ 3%	- 5 %
Nudge 3	0	+ 11%	0

- Nudges 1 and 2 fit together :
  - Autarky **+ 2 points**, or otherwise: approx. 4% increase of the average
  - Own consumption + **3%**, but imprecise (not significant)
  - Household consumption **– 4-5%**
- **Nudge 3 has a different effect (not unexpected):**
  - No effects on autarky and Household cons.
  - **+11%** in own consumption
  - Nudge 3 had no electricity saving target

Figure 47. Change of consumption behaviour in Group 1.

NUDGE 3 had no effect on the autarky rate. By contrast, the nudge has a strong positive effect on self-consumption, which increases by 11.1%. We interpret this result as suggestive of additional charging during NUDGE 3.

Nudging effects in Group 2

For NUDGE 1 the treatment effects are unexpectedly negative. Autarky decreased by 3 points, and self-consumption decreased by 6.8%.

For NUDGE 2 the treatment effects are positive. The estimated increase in autarky by 1.4 points corresponds to a 2.3% increase relative to the sample mean (0.60). Self-consumption increased by 2,6%. These results are only slightly smaller than for group 1, indicating that the treatment worked similarly for both groups.

For household consumption, the NUDGE 1 coefficient is positive but not significantly different from zero. For NUDGE 2, the effect is unexpectedly negative, indicating a 2.8% decrease for group 2 relative to group 1.

By contrast, the treatment effects for NUDGE 3 are negative for both self-consumption indicators. Autarky decreases by 2.4 points (or 4% relative to sample mean). Self-consumption decreases by 15.7%, which is a substantial drop that does not conform to expectations. The result for NUDGE 3 on household consumption is close to zero and insignificant, which aligns with group 1.

Interpretation of unexpected results for Group 2

We conducted a number of robustness checks to rule out that the unexpected results for Group 2 are driven by outliers or other changes from individual households but found that the sign of the effect remains stable. Therefore, the most likely explanation is the order of treatment in the design and the chosen measurement method (differences-in-differences).

We believe that the measurements of the second group are impacted by long-term effects for the first group. For example, if the first group adopted new habits regarding their energy-saving behaviour, this would impact the results for Group 2 as the measured treatment effect says whether the treated group changed more (or less) than the other group, not whether they changed at all.
Therefore, we have more confidence in the results of the first group because these households can be compared to those that have never seen the treatment.

Deepdive on NUDGE 3
We investigated adoption of NUDGE 3 and its effect on charging behaviour for both groups.
For Group 1, the results support the hypothesis that the default nudge allowed users to substantially increase self-consumption after activating the smart charging.

- Consumption patterns shifted throughout the day when consumers activated the default nudge. The active participants have substantially higher self-consumption during the midday peak, indicating that they indeed did shift their consumption. The coefficients indicate that self-consumption increases by ca. 16% when the smart charging feature is activated. The shift occurs only during the midday window. There is no evidence that the default nudge has any effect during the evening.
- Surprisingly, there is also a simultaneous increase in total consumption by a similar amount.
- However, the caveat is that only few users took advantage of this option in the first place. Surprisingly, many consumers did not take advantage of the offer at all or activated it rather late in the intervention phase.

- Do participants with activated „solar power charging shift their consumption to the sunshine hours?
- Do they achieve higher self-consumption than without Nudge 3 "surplus charging"?

	Autarky (0 to 1)	Self con-sumption (%)	Total consumpt. (%)
Midday	0	15-17%	13-16%
Analysis	• Comparison: active users and non-active users in group 1 with hourly data • Approximately half of the users activate the feature during the nudging period • Midday is considered from 11:00 till 15:00		

Midday:
- No change in the level of autarky
- **Strong increase** in self-consumption AND total electricity consumption by approx. + 15%
- Higher self-consumption arises from shifts within the course of the day

Figure 48. Change of consumption behaviour initiated by NUDGE 3 "surplus charging".

For Group 2 the results are inconclusive. Autarky shows small, negative effects during the midday peak in the range of 3 to 4 percentage points. By contrast, there are small, positive effects for the hours after midday (12:00 – 24:00 hrs) in the range of 1 to 3 percentage points. For self-consumption, we find that self-consumption increased by 4.85% during the midday peak, but by 12.2% during the PM hours. In contrast to group 1, we do not find any differential development between the active and the non-active EV households in group 2. For total consumption there is a solid increase of 16.4% during midday, and a smaller, but still significant increase of 8.5% during the PM window.

To interpret the findings, the key difference between the groups is the timing of the intervention, which has two implications.

- First, there is more opportunity for self-consumption during the PM window for Group 2 without the nudge, as Group 2 was nudged in early summer (20-April – 13 June) which offers longer sunny hours and higher radiation. The Group 2 households therefore were already close to full autarky, so it appears the effect of the nudge is smaller and at least partially diverted to an increase in overall consumption.
- Second, there is a possibility of learning effects. Even though Group 1 did not have access to the smart charging feature anymore it is still possible that users adapted their charging behaviour manually. We expect learning to be of minor importance in NUDGE 3.

Time and group dependent effects

The results described above give the average effect over the entire treatment period. We analysed whether the nudge effect changes over the study period for both groups.

Time dependent effects: The results of the analysis do not support either fatigue or delay in the nudge effect on autarky and self-consumption. Overall, the results match for both groups. We found no evidence for common patterns in the time series that would match with fatigue effects or delayed onset. The results are similar for household consumption

The conclusion from the event study is that the NUDGE 3 works continuously over the intervention period.

Sub-Group dependent effects: We also investigated the differences between the EV and the PV groups, unique to the German pilot. Fitting to the previous results, there is a common pattern in Group 1 for the effects of NUDGEs 1 and 2. The EV group responds much more strongly than the PV group. The EV group increases self-consumption by 10-12%. Compared to the average effect of 2-3% over both groups, this is a sizable difference. The results thus suggest that the small average effects mix the null result for the PV group with sizable treatment effects for the EV group.

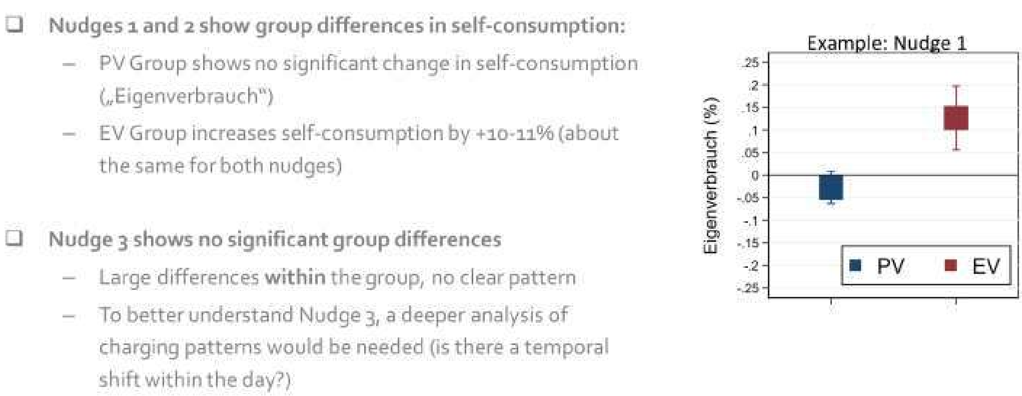


Figure 49. Change of consumption behaviour: Comparison between EV and PV groups.

For NUDGE 3 there are no significant differences between the PV and the EV group. The low activation rate of the default is a likely explanation for this result.

For Group 2, the analysis produces mixed results. The results for NUDGE 1 are the reverse of Group 1. In turn, for NUDGE 3, the EV group responds more in autarky, but less in self-consumption.

The analysis of household consumption indicates that in Group 1 the PV group slightly increased their household consumption – which is not in line with expectations and may reflect rebound effects. The EV group, however, shows a significant decrease in household consumption.

For Group 2, there is again no evidence for sub-group differences during NUDGE 1. For NUDGE 2, it appears that the PV group does not respond, while the EV group increases household-consumption. This reveals that the positive effect in the main result is driven by the EV sub-group. For NUDGE 3, the results are the exact opposite to group 1. This may be explained by changes in policy frameworks and electricity prices during the intervention period, especially after the turn of the years 2022/2023, leading the control group and the treatment group to adopt different trajectories.

Overall, the results do not show a clear pattern across nudges and groups. It appears that household consumption is relatively more idiosyncratic across time than the two self-consumption indicators.

Commercial Effect

The commercial effect of the Nudging is driven by the two targeted improvements

- reduction of the household energy consumption
- increase of the self-consumption of PV solar power

First indication of a positive effect from nudging is the aggregate metering data form 82 pilot households, for which we do have complete meter data from 2021 till present and which do not include EV-charging thru non-integrated EVCS. These 82 households did reduce their yearly household energy consumption 2,5 % in 2022, compared to 2021.

However, we also see a rebound effect in 2023. The household energy consumption rose again by 3,4% during January - August 2023 compared to the same time period in 2022 – mainly due to a peak in March 2023, which may be due to heating devices (heat pumps, etc.) not differentiated/ separately measured.

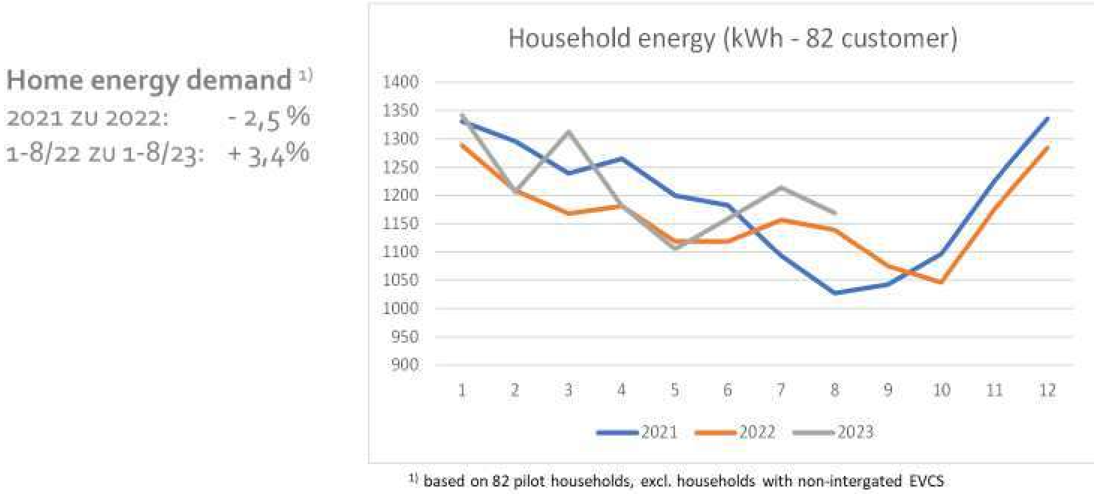


Figure 50. Change in home energy demand between 2021, 2022 and 2023.

More differentiated analysis, excluding other external factors, provides further insight into the reduction of household consumption and – in addition – to the additional savings from shifting energy demand in order to increase self-consumption. According to the analysis, self-consumption rose by 3% - driven by NUDGEs 1 and 2 on the web portal and the charging app HERMINE. The alternative charging method "surplus charging" (NUDGE 3) led to an even higher increase of 15% in self-consumption. These savings can be translated into savings in kWh and/or EUROs – assuming average energy volumes and prices. The cumulated annual saving is 200 EUR (resulting from surplus charging and reduced home consumption).

- Example calculation with average values
- Assumptions: Electricity costs: 30 ct/kWh, feed-in tariff: 10 ct/kWh
- Customers can calculate their individual saving values on the web portal

	Self-Consumption		
Savings	Webportal & HERMINE (Average)	Surplus charging (if activated)	Overall consumption
in %	3%	15%	5%
in kWh p.a.	117	586	298
in EUR p.a.	**23**	**114**	**87**

Figure 51. Savings in energy cost from nudges.

The effects mentioned above have been calculated as an average across the entire participants group. The effect may be much higher for individual customers, based on their current energy consumption and individual behaviour in optimising, triggered by the nudges. We would expect such higher impact especially for those customers that proved to be "high frequency" users of the nudging tools, namely the web portal and the two EV charging solutions.

2.3.5. Concluding Remarks on Pilot Outcomes

The analysis suggests the following conclusions with regards to the three research questions:

Hypothesis – DE1: Nudges are effective in increasing the self-consumption of participants.

According to the results presented above, NUDGEs 1 and 2, providing "Feedback" and creating "Awareness" on key energy efficiency targets as well as "Comparisons", "Suggestions" and "Controls" to initiate efficient behaviour, resulted in modest self-consumption increases, typically in the range of 3-4 percent.

Hypothesis – DE2: ***Nudges are more effective in increasing the self-consumption of participants with controllable electric vehicles than of the ones without.***

We investigated the differences between the EV and the PV groups for the effects of NUDGEs 1 and 2. The EV group had controllable electric vehicles, whilst EV charging in the PV group could not be controlled.
The EV group responded much more strongly to the nudges than the PV group, increasing its self-consumption by 10-12%. Compared to the average effect of 2-3% over both groups, this is a sizable difference.

Looking at NUDGE 3, the opt-in setting for surplus charging, leads to a substantial 16 percent increase in self-consumption among active participants in the EV group, which have a controllable electric vehicle and have activated the surplus charging.

The surplus charging benefit results from an "automated" shift of energy demand for EV charging into hours with PV surplus. This means that households with controllable electric vehicles exhibit more pronounced effects compared to those without such vehicles.

DE3: ***Nudges are (also) effective in reducing the overall electricity consumption of participants.***

Both NUDGEs 1 and 2 led to a significant reduction in household consumption of electricity. NUDGE 1 led to a reduction by 3.9% on average, NUDGE 2 to a reduction by 5.2% (again, household consumption was log-transformed).In contrast, NUDGE 3 led to an increase in electricity consumption, which we associate to an increase in EV charging at home.

Overall conclusions

Our findings strongly suggest the effectiveness of nudges in establishing new energy consumption routines, especially when dealing with flexible and high-consumption components like EVs. To maximise the effect of nudges, we recommend implementing nudges that require minimal user interaction and energy literacy. Even among our self-selected and motivated participants in the German pilot, acceptance and use of nudging tools were decreasing if they required frequent manual interaction.

Finally, it is important to consider that consumers can strongly influence, respectively optimise, their energy balance by investing in integrated decentral energy solutions, namely a PV system combined with a battery storage, an EVCS and /or a heat pump.

A PV system that is dimensioned according to the expected demand of the household, will generate sufficient energy to cover more than 30% of energy demand. The households in the German pilot reached an autarky rate of 33% on a yearly average.

If a battery is combined with the PV system, the autarky will reach more than 60%. As pictured in Figure 52, the households in the German pilot which have an integrated battery, reached an autarky rate of 62% on a yearly average – versus only 33% at households without a battery. The self-consumption rate of the two types of prosumers in the pilot was 36% without battery and 49% with an integrated battery.

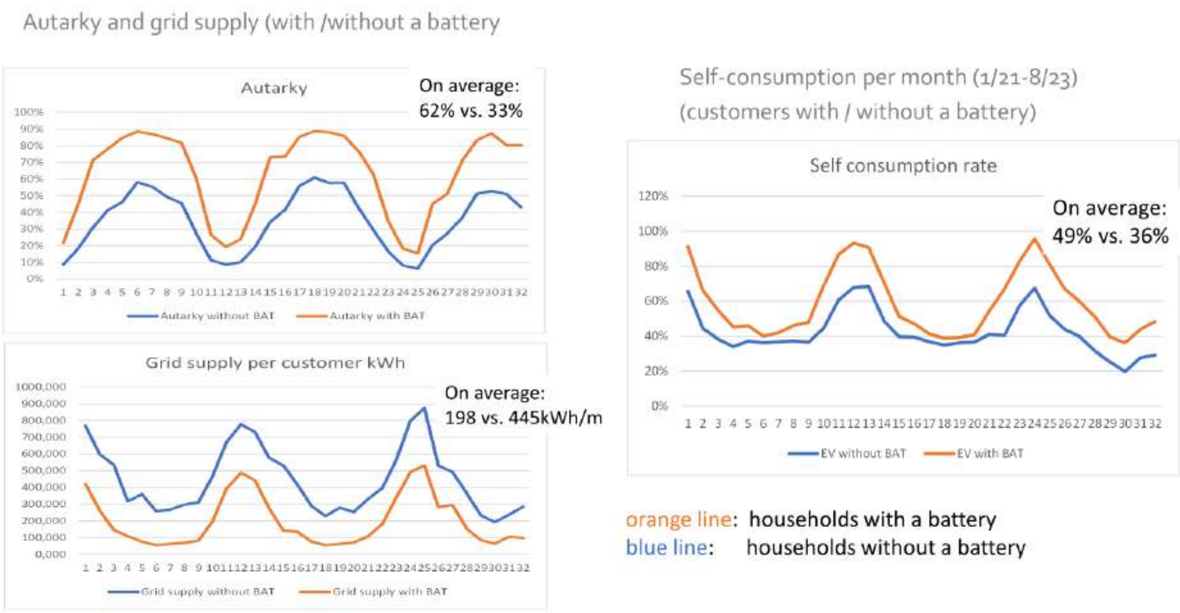


Figure 52. Impact of a battery storage on self-consumption and autarky.

A combination of an EV and/or a heat pump creates additional demand for electricity. However, as demonstrated in the pilot, this also provides flexibility for (automated) demand shifting into surplus hours, which again increases both autarky and self-consumption rate.

These investments have a substantial and long-term effect on the energy balance of residential customers. Such investment decisions should therefore also be strongly nudged. These kinds of nudges would support and further promote such investment decisions in the "PV-capable" market of the 12 million residential single- or double-family houses in Germany, as described above.

2.4. The Portuguese (PT) pilot

2.4.1. Overview on Pilot implementation

Context and Aim

According to Eurostat, in 2018, Portugal was the fifth country in the European Union where people could not afford to keep their homes adequately heated, with about 19% of the Portuguese population living in a situation of energy poverty, well above the European Union average of 7% (Eurostat, 2019; Horta et al., 2019). Studies conducted in the last few years in Portugal also showed that a high percentage of children is living in homes with unhealthy environmental conditions, due to dampness, darkness, cold and excess noise (RAND Europe, 2019), and also with insufficient ventilation rates and high air pollution levels (Canha et al., 2020; Gabriel et al., 2021). Based on this background, it is crucial to develop strategies that properly reflect the character, identity and needs of local homes and residents to effectively tackle the current energy, thermal comfort and indoor air quality (IAQ) problems. In particular, there is a research gap on developing regional assessments to establish actions to promote active citizen participation and to achieve such multidisciplinary (energy and non-energy) benefits. With this in mind, the NUDGE pilot study organised in Portugal aimed to test the effectiveness of specific nudges to promote long-term energy savings in building energy use while providing healthy and comfortable homes for families with young children.

Study design and methodology

The extensive works for pilot implementation started on July 2021 with the recruitment activities that included: i) a wide dissemination campaign namely through publications in the INEGI's newsletter, website, and social media accounts; ii) email/phone contacts to families with young children that participated in a previous project with INEGI; and iii) contacts at the main umbrella organisation for school parents' associations (National Federation of Parents' Associations (CONFAP)) and the Portuguese Consumer Defence Association (DECO), which has agreed to disseminate information related to the NUDGE pilot to reach a wider network of potential participants to the study. In order to be eligible to participate in this study, participants had to meet all of the following criteria: i) to be a family with young children (from newborns to up to 12 years of age at the time of the recruitment); ii) to live in the district of Porto or nearby; iii) to have Wi-Fi at home; iv) do not plan to move to a new home in the next 12 months; and v) to be properly informed on the study aims and provide a signed informed consent. The recruitment activities resulted in 101 eligible participants, who were then contacted for scheduling visits for interview, building survey and smart electricity meters' installation works (Shelly EM and 3EM devices). These home visits were conducted from July 2021 to April 2022.

The pilot was considered to be ready to start the pre-intervention phase when the energy meters deployment was completed in 70% of the target homes (70 out of 100) by the end of December 2021. For the execution of the cross-over trial, the technological user's interface (App Nudge.it) was developed. All the participants were invited to install the pilot-specific app during March-April 2022. The intervention plan for the pilot consisted of 3 sequential interventions (1st/2nd/3rd intervention phases, called NUDGE 1, NUDGE 2 and NUDGE 3) that were independently delivered to the users through the pilot-specific app. The participants were randomly divided into two similar sized groups (Group 0 and Group 1) and the intervention program occurred, for each nudge, in two periods (Period 1 and Period 2) following a crossover trial design,

ensuring that all participants were exposed to the nudging treatment. Briefly, in Period 1, Group 0 consistently worked as the control and Group 1 as the intervention group, and in Period 2, Group 1 worked as the control and Group 0 as the intervention group.
The nudges to test in the PT Pilot were designed and implemented to cover different energy and health-related matters: NUDGE 1 was focused on providing information on the recent history of energy use, NUDGE 2 on indoor air quality (IAQ) and NUDGE 3 on heating related aspects. For allowing the execution of NUDGE 2, a modular Internet of Things (IoT) architecture based on low-cost sensors for assessing carbon dioxide (CO_2), particulate matter ($PM_{2.5}$ and PM_{10}), temperature and relative humidity was specifically developed and tested to collect real-time IAQ data in the participant homes. 84 out of 101 NUDGE Portuguese participants (40 from Group 0 and 44 from Group 1) were available to receive a second home visit for IAQ sensors installation. For the PT pilot, electricity consumption, air quality parameters levels and indicators of the app usage (number of openings of the app and new data requests), were the data that was continuously acquired throughout the study. During pre-intervention and after each intervention phase an on-line questionnaire was distributed to the participants, in order to collect participants' feedback on several aspects, including questions related to app usability, motivation and intention to save energy as well as measures to improve IAQ, among others.

The overall hypothesis of the PT pilot is that implementation of simple and readily deployable tools to provide real-time information on electricity consumption and IAQ will allow the users to identify periods of peak of electricity consumption and of exposures (in which levels of air contaminants are high) and encourage them to take actions to promote energy savings and health at home.

NUDGEs and research questions
The implementation of the PT pilot is expected to yield high dimension data sets including data from continuous monitoring of electricity consumption and of IAQ levels in 101 homes of Portuguese families and informative data on the respective building physics and indoor conditions. The home-specific information and the monitoring data were explored to provide answer the introductory research question defined for the study: *What are the factors influencing electricity consumption and air quality in the homes of Portuguese families?* In addition, the PT pilot intended to test very specific research questions:

- **NUDGE 1** – *How might access to detailed historical and real-time information on energy use through a smartphone app impact the user behaviours and electricity consumption in households?*

This nudge allows users to comprehensively monitor their electricity consumption at home during the intervention period. The delivery of this nudge includes the introduction of new features in the App:

i. dashboards showing electricity consumption evolution over different time scales (hourly, daily, weekly, monthly basis);
ii. a circular graph presenting the percentage of electricity usage of specific equipment within the overall consumption of the household, which is only relevant to the homes with single-phase electrical switchboard (89% of the participant households). Therein, one clamp has been used for measuring the total consumption of the house, and the two available clamps of shelly 3EM devices

have been used to monitor the energy consumption of two equipment (or groups of equipment), which is of reported interest to participants.

- **NUDGE 2** – *How effective is the access to real-time data on home IAQ through a smartphone app for encouraging families to conduct actions to improve air quality? How will it affect energy consumption?*

Other sub-research questions of the activities conducted at this stage are the following:

- *What is the potential of using an IoT architecture based on low-cost sensors for increasing the level of citizen's literacy on the factors that may influence exposure to air pollution at home?*
- *Will the integration of aspects related to air quality increase the engagement of the citizens to save energy?*

NUDGE 2 was implemented from November 16th, 2022, till January 24th, 2023. The nudging treatment was focused on recommending actions for improving indoor environmental quality (IEQ) through a screen in the app that presented the real-time levels of air parameters (CO_2 and particulate matter ($PM_{2.5}$ and PM_{10}), temperature and relative humidity). This included: i) qualitative indicator using a coloured grade allowing the participant to identify when the levels are within the recommended limit values (green), when the levels are reaching the limit values (yellow) and when the levels are out of the limit values (red); and ii) push notifications when average concentrations for the last hour exceed healthy thresholds. For CO_2 (If mean 1h [CO_2] > 1500 ppm), the message was "High CO_2 levels! Please open the window(s) to introduce fresh air in the room for at least 10 minutes." For PM (If mean 1h [$PM_{2.5}$] > 25 µg/m^3 OR if mean 1h [PM_{10}] > 50 µg/m^3) the notification shown to the participants stated: "High particle levels in the air! Please: • Avoid indoor sources such as air fresheners, incense, candles and tobacco smoke. • Close windows facing sources of pollution (e.g., roads with heavy car traffic) • Prefer cleaning procedures that promote the effective elimination of particles deposited on surfaces (dust) without promoting its resuspension into the room's ambient air. • Whenever you detect "burning" odours, smoke and/or aerosols, try to identify and mitigate the respective source (e.g., burnt food), and immediately ventilate the area. • Prefer to apply antiperspirants and other personal and cosmetic products in spaces with mechanical/forced ventilation (bathroom) and check the correct functioning and hygiene of these systems."

- **NUDGE 3** – *How do the energy conservation nudges focus on indoor environment heating affect electricity consumption?*

This nudge was implemented in the heating season 2022/2023. The features incorporated into the App intend to recommend actions for optimising the use of the heating systems in the participants' households:

i. bar charts showing the evolution of the daily energy consumption during the last 7 days with a comparison with the mean daily consumption in the last month.
ii. real-time data of temperature and relative humidity, with the presentation of a qualitative indicator using a coloured grade (green - levels within the comfort zone; yellow - levels in the limit of contort zone; red - levels out of comfort zone).

iii. notification to the users having a thermostat for regulating the target indoor environment: request to reduce the temperature set points in the thermostats (at least in 1 °C, if the target temperature is higher than 19 °C). If the users do not have a thermostat, the indication will be directed for requesting the reduction of the "intensity" mode of the devices used for indoor heating.

iv. push notifications sent when the outdoor temperature is > 2 °C than the indoor temperature for recommending turning off the heating systems and opening the windows in order to use outdoor air as a thermal carrier.

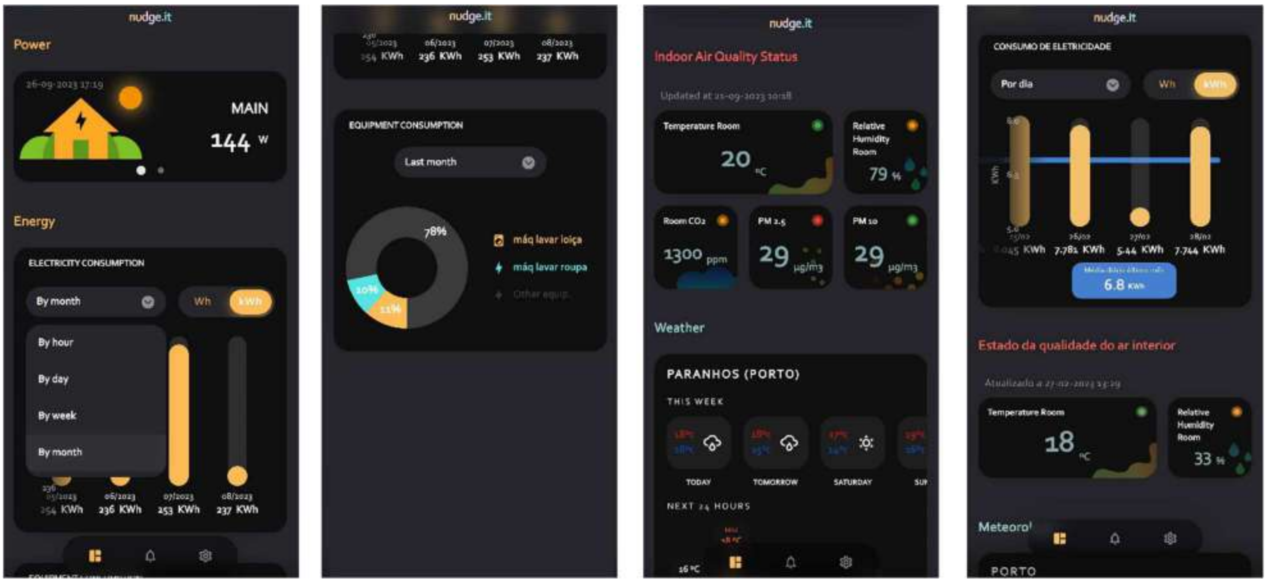


Figure 53. App screens of NUDGEs.

2.4.2. Participant Households

All participant **households are located within a 40 km radius from Porto** (the second-largest city in Portugal). The PT pilot includes participant households **distributed across 13 municipalities** Porto (n=36), Matosinhos (n=18), Maia (n=15), Vila Nova de Gaia (n=13), Gondomar (n=10), Valongo (n=2), Vila do Conde (n=1), Póvoa de Varzim (n=1), Paços de Ferreira (n=1), Santa Maria da Feira (n=1), Ovar (n=1), Vila Nova de Famalicão (n=1), and Penafiel (n=1).

The approximate location of the dwellings of the participant families is presented in Figure 54.

Figure 54. Location of households of families with children engaged for the PT pilot in the region of Porto (Northern Region, Portugal, Southern Europe).

A geographical study of the area in which the houses were located was conducted based on the Google Maps view in order to collect information on the characteristics of the surrounding outdoor environment. This is particularly relevant to collect data on putative outdoor sources of air pollution in the proximity of the participant's homes. A user-friendly electronic checklist was developed to assist in the standardised collection of data on the characteristics of the buildings, occupants, indoor spaces, energy use, pollution sources and surrounding outdoor environment. All participants (n=101) agreed to provide information for completing the checklist. Data were collected by a trained interviewer during the visits to the participant households for energy-meter installations.

Main data obtained from the checklist are presented in Table 14 (frequencies, percentages and/or, if applicable (for numeric data), mean and absolute minimum and maximum values).

Table 14. Summary of the results on the characteristics of the households participating in the PT pilot.

Household characteristics	***n* (%)**	**Mean (Min – Max)**
Period of construction		
Before 1950	8 (8)	
1950-1980	8 (8)	
1980-2010	67 (66)	
After 2010	18 (18)	

Recent (last 6 months) refurbishing works	39 (39)	
Dimensions of the dwelling (approximate)		
Floor area (m^2)	--	171.0 (62.0 – 680.0)
Mean ceiling height (m)	--	2.6 (2.4 – 3.4)
House Typology		
Apartment	64 (63)	
Single-family house	37 (37)	
Number of floors		
1	60 (59)	
2	22 (22)	
3	16 (16)	
4	3 (3)	
Location of the dwelling within the building (floor)*		
Ground floor	7 (11)	
1	10 (15)	
2	18 (28)	
3	14 (22)	
4 or upper floors	16 (25)	
Number of occupants of the house per age groups		
Babies (0-4 years old)	66 (65)	1.0 (0.0 – 2.0)
Children/adolescents (5-17 years old)	62 (61)	1.0 (1.0 – 3.0)
Adults (18-65 years old)	101 (100)	2.0 (1.0 – 5.0)
Seniors (> 65 years old)	3 (3)	1.0 (0.0 – 2.0)
Period living in this dwelling		
< 2 years	19 (19)	
2 - 5 years	46 (46)	
6 - 10 years	17 (17)	
> 10 years	19 (19)	
Planning to move to a new home within the next 2 years	4 (4)	
Energy supply systems		
For home environment and water heating		
Electricity	77 (76)	
Natural gas	68 (67)	
Bottle gas (propane/butane)	17 (17)	
Solar Photovoltaic energy	4 (4)	
Solar Thermal Energy	18 (18)	
Wood (logs or chips)	32 (32)	
Pellets	6 (6)	
District Heating	0 (0)	
Other	2 (2)	
None	0 (0)	
For cooling		
Electricity	36 (36)	
Solar photovoltaic energy	4 (4)	
Other	0 (0)	
None	65 (64)	
For cooking		

Electricity	100 (99)
Natural gas	17 (17)
Bottle gas (propane/butane)	6 (6)
Solar Photovoltaic energy	4 (4)
Wood (logs or chips)	1 (1)
Pellets	0 (0)
Other	1 (1)
None	0 (0)
Electricity switchboard	
Single-phase	90 (89)
Three-phase	11 (11)
Electricity tariff	
Simple	88 (87)
Bi-hourly	12 (12)
Tri-hourly	1 (1)
Equipment and other appliances	
Heating, ventilation/acclimatisation devices	
Electric heating appliances	
Air conditioner(s)	26 (26)
Portable electric heater	32 (32)
Space Radiators	13 (13)
Central heating	42 (42)
Radiant/heated floor	4 (4)
Humidifiers	2 (2)
Dehumidifiers	25 (25)
Combustion devices	
Open Fireplace	7 (7)
Modern Fireplace (closed)	28 (28)
Heating stove	4 (4)
Portable gas heater	15 (15)
Fan heater	32 (32)
Fan	10 (10)
Air purifier(s)	2 (2)
Other	1 (1)
None	4 (4)
Water heating appliances:	
Gas water heater (boilers)	73 (72)
Heat pump	8 (8)
Electrical heaters	20 (20)
Solar water heaters	18 (18)
Other	0 (0)
Cooking Devices	
Gas stove	22 (22)
Electric stove	100 (99)
Wood stove	1 (1)
Other	3 (3)
Home EV charging point	8 (8)

Set points for temperature		
For domestic hot water		
Cold season (ºC)	38 (38)	54 (39 - 70)
Warm season (ºC)	37 (37)	51 (37 - 65)
For indoor environment		
Cold season (ºC)	27 (27)	21 (18 -25)
Warm season (ºC)	8 (8)	21 (17 - 24)
Consumer Products - Indoor use		
Air freshener and other fragranced products	74 (73)	
Manual	37 (37)	
Continuous/Automatic	31 (31)	
Incense	22 (22)	
Scented candles	23 (23)	
None	27 (27)	
Pesticides/Insecticides	32 (32)	
Manual insecticides	15 (15)	
Automatic aerosol insecticides	20 (20)	
Cockroach pesticide	0 (0)	
Rats control products	0 (0)	
Other	3 (3)	
None	69 (68)	
Cleaning products and procedures		
Bleach or detergent with bleach	89 (88)	
Spray	25 (25)	
Liquid	80 (79)	
Frequency (times per week)	--	1.8 (0.3 – 7.0)
Detergent with ammonia	28 (28)	
Spray	4 (4)	
Liquid	26 (26)	
Frequency (times per week)	--	1.5 (0.3 – 7.0)
Other detergent/cleaning products	99 (98)	
Spray	77 (76)	
Liquid	90 (80)	
Frequency (times per week)	--	1.8 (0.3 – 7.0)
Wax/Furniture polish	4 (4)	
Spray	2 (2)	
Liquid	3 (3)	
Frequency (times per week)	--	0.7 (0.5 – 1.0)
Indoors pets	50 (50)	
Dog	33 (33)	
Cat	20 (20)	
Other	7 (7)	
Plants inside the house	61 (60)	
Current practice to smoke indoors	6 (6)	
Cigar/cigarettes	3 (3)	
Electronic cigarettes	4 (4)	
Fenestration/Windows		

Window orientation		
North	52 (51)	3.6 (1.0 – 8.0)
West	56 (55)	3.6 (1.0 – 11.0)
South	62 (61)	3.3 (1.0 – 9.0)
East	58 (57)	3.4 (1.0 – 9.0)
Solar shading		
Both Internal and external	51 (50)	
Only Internal	34 (34)	
Only external	15 (15)	
None	1 (1)	
Opening windows		
Before 7 a.m.	0 (0)	
7 - 10 a.m.	73 (72)	
10 - 12 a.m.	56 (55)	
12 - 17 p.m.	57 (56)	
17 - 20 p.m.	36 (36)	
after 20 p.m.	0 (0)	
Opening windows during the cleaning procedures		
Always	73 (72)	
Often	21 (21)	
Sometimes	6 (6)	
Never	1 (1)	
Signs of indoor pathologies		
Physical	24 (24)	
Moisture-related	39 (39)	
Surrounding outdoor sources at distance up to 100 meters		
Traffic-related	62 (61)	
Busy road	44 (44)	
Highway	4 (4)	
Car parking	8 (8)	
Gas stations	7 (7)	
Other	34 (34)	
Industrial-related	4 (4)	
Agricultural-related	42 (42)	
Animal husbandry	14 (14)	
Cultivated fields	40 (40)	
Commercial	75 (74)	
Laundry	12 (12)	
Coffee bar/ Restaurant	64 (63)	
Other commercial	45 (45)	
Other outdoor sources	81 (80)	
Landfill, waste disposal	0 (0)	
Bus stop	42 (42)	
Green/Forested area up to 100m	51 (50)	
Other	3 (3)	

EV, Electric vehicle; Max, maximum; Min, minimum
n (%) refers to the total number of respondent families and respective percentage in the valid cases
* Only applicable to apartments

Main information from the table:

- Most (n = 67; 66%) of the participant families live in buildings constructed between 1980 and 2010, with about 16% living in buildings older than 1980 and 18% in buildings completed after 2010. A great portion of the residences consisted of apartments (n = 64; 63%), and the average area and ceiling height of the dwelling was 171.0 m^2 and 2.6 m, respectively.
- 4 families were planning to move to a new home within 2 years. Thus, the PT pilot risks losing these participants during the execution of the project, but this is being closely monitored.
- 90 participants have a single-phase electric switchboard. For these participants, the 2 clamps available in the 3-phase electricity meter (shelly 3EM) were used to monitor the consumption of 2 specific equipment/devices for which the participants were most concerned about the consumption, in addition to the overall consumption of the home.
- 99% of the households use electrical devices for cooking and about 76% of the households surveyed use electricity as energy vector for indoor and/or water heating. In addition, 36% use electricity for cooling purposes in the warm season.
- For those participants controlling indoor environment temperature through thermostats (only 27%), the reported set points defined for the heating season varied from 18 to 25 ºC. Moreover, 7 participants reported to define in their thermostats target temperature values higher than 21ºC.
- In the households with a PV system (4%) an extra energy meter was installed for measuring produced PV energy.
- Regarding the existence of putative sources of pollution that can compromise the IAQ of the homes (relevant data for the 2nd intervention to implement in the PT pilot in September 2022):
    - About 6% of the families stated that they smoke indoors;
    - 73% of the households used air fresheners and/or other fragranced products;
    - 32% of the households utilised manual (n = 15; 15%) and/or automatic aerosol insecticides (n = 20; 20%);
    - 72% of the participants reported that they always open the windows during the cleaning practices;
    - Some of the dwellings present signals of physical (24%, noticeable cracks, fissures, altered staining or peeling) and moisture-related (39%, dampness and/or mould) damages in the dwelling's surfaces;
    - A variety of outdoor sources of air pollution were identified in the surrounding environment of the households (mainly traffic and commercial-related sources).

2.4.3. Climate and Meteorological data

The climate in Porto is temperate oceanic, with mild, rainy winters and pleasantly warm, dry sunny summers. The PT pilot had a duration of 15 months (from January 1st, 2022, untill March 31st, 2023), with the time between January 1st and June 2nd, 2022, considered as the pre-intervention period. Although ambient air temperature data for December 2022 is not available in the Copernicus platform, the available temperature data for the whole PT pilot is presented in the figure below.

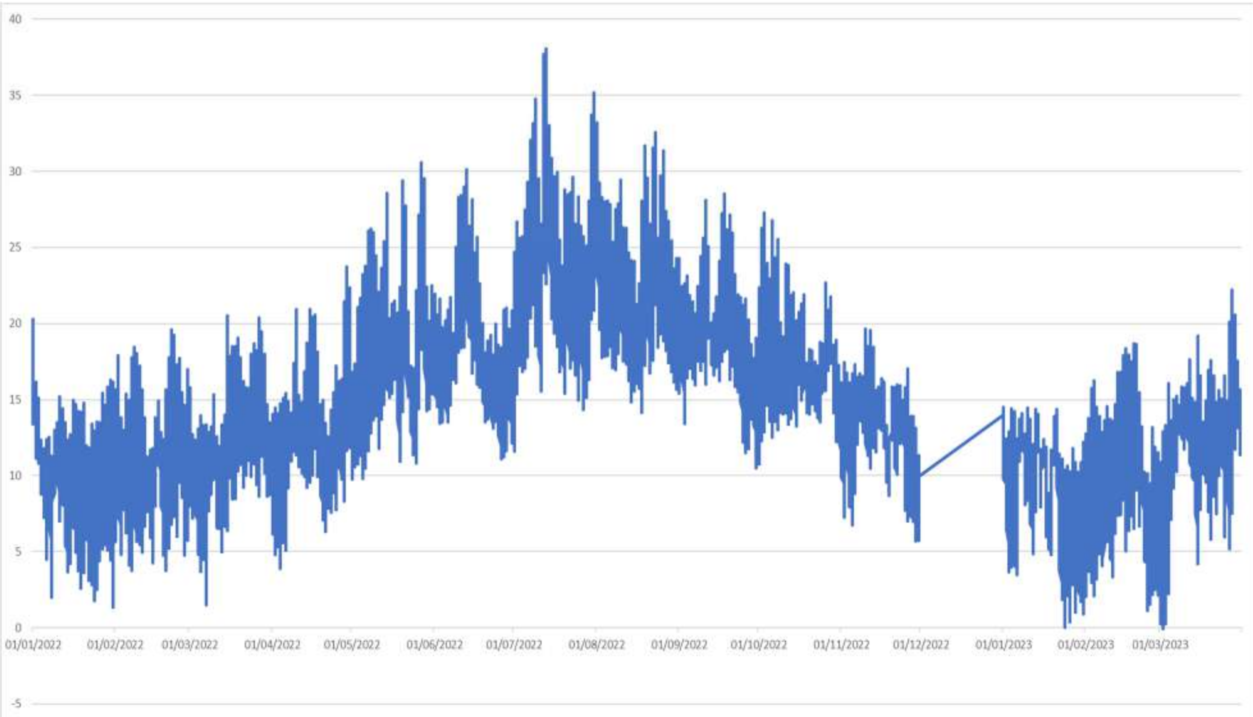


Figure 55. Ambient air Temperature in Porto from January '22 until March '23 (data from Copernicus project)

As observed in the Figure 55, during the baseline period (from January 1st until June 2nd,2022), the outdoor temperature has highly varied, ranging from 1.41 ºC (31/01/2022 6:00) to 30.57 ºC (27/05/2022 16:00). During the NUDGE 1 phase, which took place in the cooling season (from June 3rd, 2022, until the September 9th, 2022), the outside temperature ranged from 11.11 ºC (26/06/2022 04:00) to 38.06 ºC (13/07/2022 14:00). Moving on to the second phase, NUDGE 2, which occurred in the heating season (from November 16th, 2022, until January 24th, 2023), the temperature varied between 0.04 ºC (24/01/2023 08:00) and 17.04 ºC (26/11/2022 14:00). Finally, the third phase, NUDGE 3, which mostly overlapped with the heating season (from 24/01/23 until 31/03/2023), saw temperatures ranging from –0.07 ºC (02/03/2023 05:00) to 22.22 ºC (28/03/2023 14:00).

Table 15. Ambient temperature evolution for the cities considered in the PT pilot during the relevant study periods.

City	Ambient Temperature [Mean (Min – Max)] (°C)			
	Pre-intervention period (01/01/2022 - 02/06/2022)	NUDGE 1 period (03/06/2022 - 08/09/2022)	NUDGE 2 period (16/11/2022 - 23/01/2023)	NUDGE 3 period (24/01/2023 - 31/03/2023)
Porto	12.50 (1.41 – 30.57)	21.21 (11.11 – 38.06)	10.60 (0.04 – 17.04)	10.07 (-0.07 – 22.22)

2.4.4. Main Results from the Pilot Implementation

The home visits conducted in an early stage of the PT Pilot resulted in a comprehensive dataset on the characteristics of the participant households, mainly in terms of building features and on factors that could putatively impact energy use and/or indoor air quality (please see Table 14). The preliminary analysis of this information during the pre-intervention phase was of major importance to characterise the recruited participants and to identify opportunities for promoting energy-efficient and healthy behaviours among pilot participants as fully reported in the work entitled Opportunities for Promoting Healthy Homes and Long-Lasting Energy-Efficient Behaviour among Families with Children in Portugal published in the journal Energies (Gabriel et al., 2023) .

In addition, the continuous monitoring work carried out in the PT pilot resulted in the collection of important datasets on:

- *comprehensive electricity consumption data relative to more than 1 year-round (Pre-intervention/baseline, NUDGE 1, NUDGE 2, NUDGE 3 and post-intervention periods) for 98 households out of the 101 recruited participants (considering that 2 participants moved to a new home (and quit the project) and for one participant no baseline data was collected due to technical issues (group 0: 50 participants, group 1: 48 participants).*
- *levels of indoor environmental parameters for NUDGE 2 and NUDGE 3 periods for 84 out of 101 recruited families (the families that received a 2nd visit before NUDGE 2 for the installation of IAQ sensors).*

The main outcomes from the continuous data obtained from electricity and IAQ smart meters installed in the participants' homes are described in the following sections.

Electricity consumption in the participants homes throughout the study

Looking at Figure 56 showing the average daily consumption, the two similar-sized groups of participant households seem to follow the same energy pattern, and an apparent seasonal trend can be observed, with higher consumption in winter periods (as expected).

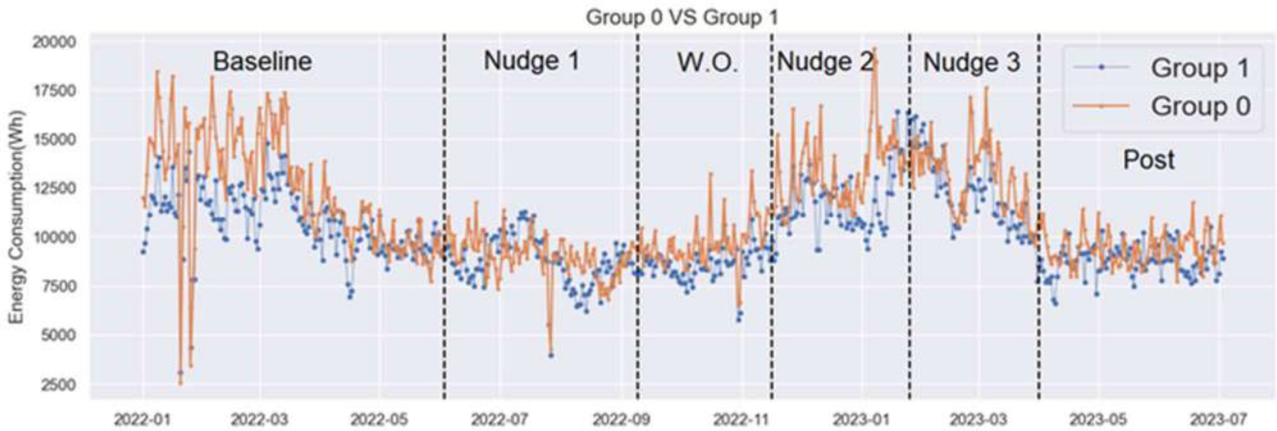
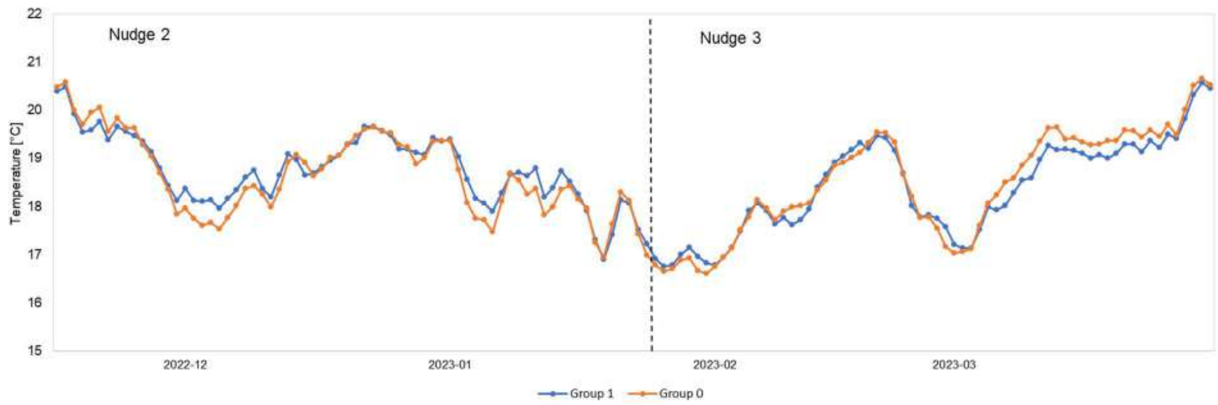


Figure 56. Evolution of average daily electricity consumption for PT pilot households assigned to group 1 and group 0 during the study period. W.O., represented a washout period of the intervention plan during which IAQ sensor installations were conducted.

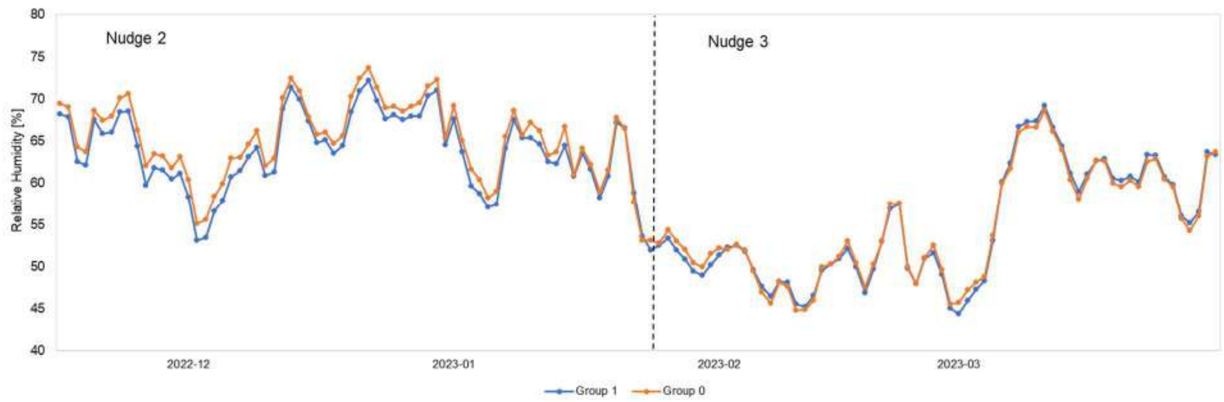
The average daily electricity consumption was 11 111 Wh for homes of the participants randomly assigned to Group 1 and 12 161 Wh for those of Group 0. The Portuguese daily mean electricity consumption per household, calculated from the available International Energy Agency data (2021), is 9 449 Wh, which is slightly lower than the average obtained for the PT pilot sample. This can be justified by the existence of a higher number of occupants in the households under study (mean: 4 occupants) compared to the reported national average occupancy per home (2 persons). This higher average occupancy is associated with the fact that the PT pilot targeted families with children as study population. In addition, although participants were randomly assigned to Group 1 and Group 0, it is noticed that households from Group 0 presented a slightly higher average daily electricity consumption than those homes from Group 1. This is likely to be justified by some characteristics of the case homes. Specifically, when compared to Group 1 households, Group 0 includes a higher number of single-family houses (Group 1: 16; Group 0:21), a higher number of houses using electricity for heating purposes (Group 1: 37 ; Group 0: 40), more homes that were built before 1980 (Group 1: 7; Group 0: 9) and more cases with glassed façades with openable windows oriented to north (Group 1: 21; Group 0: 30). The significant influence of these characteristics in electricity consumption is detailed in the subsection entitled "Household characteristics influencing energy consumption and IAQ" of this document.

Indoor environmental quality levels in the participants homes

The levels of the IAQ parameters assessed in this research showed a considerable fluctuation across the 84 households surveyed. However, in general, the pattern of evolution of the mean daily levels of indoor environmental parameters was similar for the homes of Group 1 and Group 0 (Figures 57 and 58).



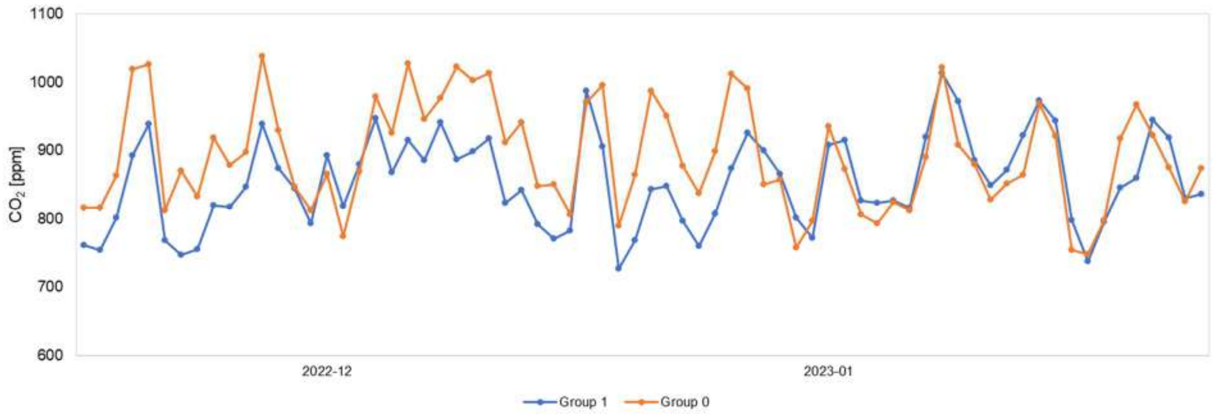
A



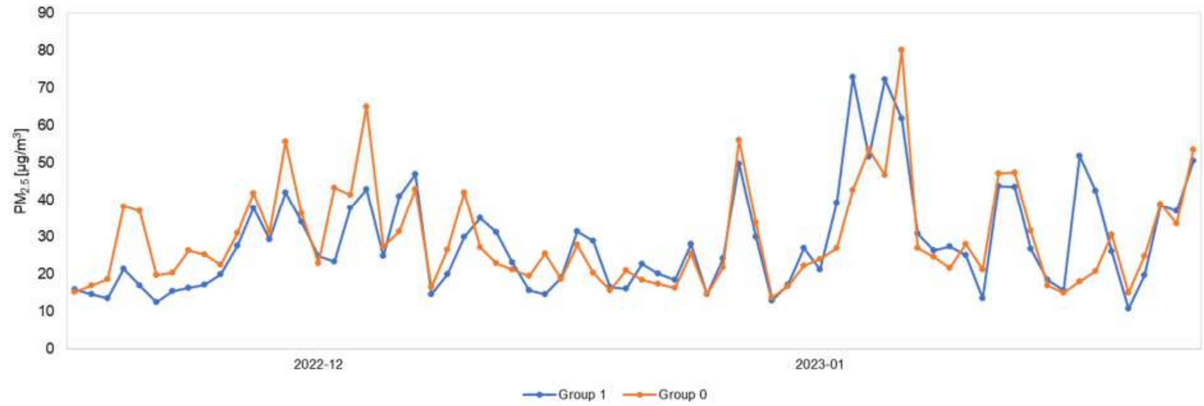
B

Figure 57. Evolution of average indoor temperature (A) and relative humidity (B) for PT pilot households assigned to group 1 and group 0 during the NUDGE 2 and NUDGE 3 phases.

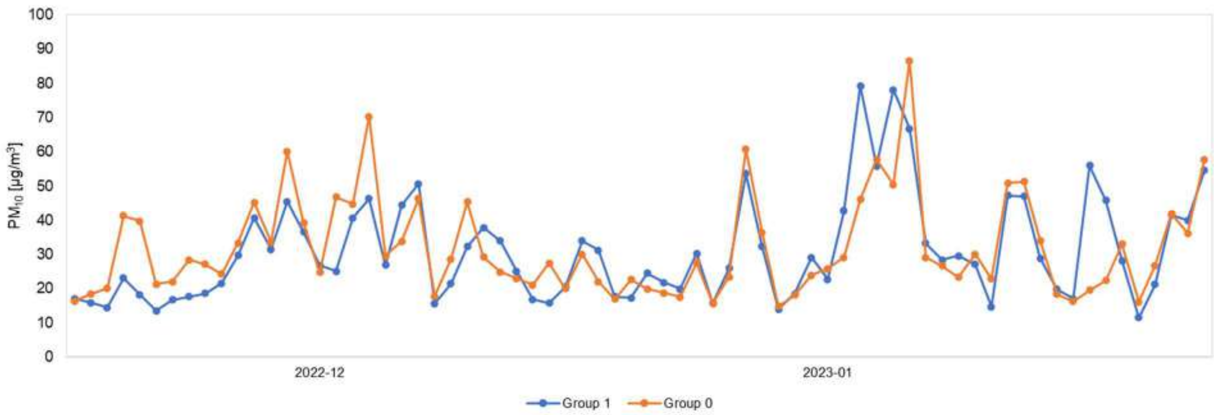
For indoor temperature levels, the average values recorded in the participant homes exhibited a range of 14.8 to 22.4 °C for NUDGE 2 and from 14.7 to 21.5 ºC for NUDGE 3. Regarding relative humidity, the mean levels obtained varied from 52.4 to 79.9% for NUDGE 2 and from 37.7 and 78.3% for NUDGE 3. The WHO recommends temperatures of 21 °C in the living rooms and 18 °C in other occupied rooms to achieve an adequate standard of warmth (WHO Regional Office for Europe, 2007). Since the preferential location for positioning the IAQ sensors was the living room, according to the data obtained it was found that 96% of the study homes presented mean indoor temperature lower than the 21 °C during NUDGE 2 and 94% during NUDGE 3. In fact, considering the maximum daily average values obtained per home, we found that 52% and 45% of the homes never reached a daily indoor temperature of 21 °C during NUDGE 2 and 3 periods, respectively.



A



B



C

Figure 58. Evolution of CO_2 (A), $PM_{2.5}$ (B) and PM_{10} (C) for PT pilot households assigned to group 1 and group 0 during the NUDGE 2 phase.

Noteworthy, the range of levels of both CO_2 and airborne particles assessed in this study were similar to those obtained from a previous study conducted in homes of 30 families with infants living in the same geographical region using reference methods (Gabriel et al., 2021), which covered a substantially shorter monitoring period (22-hr) than the one considered in the present work (about 2 months). For CO_2, the mean concentrations assessed in the 84 homes varied from 442 to 1690 ppm (previous study: 509-1603 ppm). Regarding airborne particles, assessed concentrations varied on average from 13 to 187 µg/m³ for $PM_{2.5}$, and

14 to 202 μg/m^3 for PM_{10} (range of 22-hr mean values in previous study: $PM_{2.5}$, 11.2 – 126.2 μg/m^3; PM_{10}, 13.2 – 135.1 μg/m^3).

Comparing the assessed CO_2 concentrations with the limit value that has been widely recognised as representative of good or excellent IAQ/ventilation conditions for several indoor environments of 1000 ppm (Lowther et al., 2021), it was found that 21 (25%) out of 84 homes presented mean CO_2 concentrations that exceeded this limit. Currently, in Portugal, there is no official legislation established for controlling IAQ in residential buildings, with the existing guidelines being directed to commerce and service buildings (Portaria n.o 138-G/2021 de 1 de julho, 2021). 7 homes (8%) presented mean CO_2 concentrations exceeding the limit imposed by the referred national recommendations (1250 ppm).

Comparing the $PM_{2.5}$ and PM_{10} average concentrations with the most recent WHO guidelines that define limit values of 15 and 45 μg/m^3, respectively (WHO, 2021), it was found that, on average, most of the homes (n=82, 98%) exceeded the $PM_{2.5}$ limit, while only 11 participant homes (13%) surpassed the PM_{10} limit. This achievement is also in line with the previous investigations employing short-term monitoring work using reference equipment, which reported that a great percentage of homes of Portuguese families with children present high concentrations of $PM_{2.5}$ (Gabriel et al., 2021; Madureira et al., 2016). These findings support the need for the establishment of corrective actions for decreasing exposure levels to particulate air pollution (in particular $PM_{2.5}$) and protecting health. For instance, according to WHO, air pollution in both outdoor and indoor environments has become recognised as the single biggest environmental threat to human health based on its notable contribution to disease burden. And this is particularly true for PM (both $PM_{2.5}$, i.e. particles with an aerodynamic diameter equal to or less than 2.5 μm, and PM_{10}, i.e. particles with an aerodynamic diameter of equal to or less than 10 μm) (WHO, 2021). It is well known that outdoor air can constitute an important source of airborne particles to indoor environments, particularly in urban areas. In fact, city and national level authorities have a major responsibility in prioritising actions to reduce ambient air pollution and actively ensure that the WHO guidelines are met. Nevertheless, although it is well-recognised that exposure to $PM_{2.5}$ can represent high health risks due to the fact that this particle fraction is likely to penetrate deeper into the respiratory tract to exert adverse effects, most of the existing national monitoring stations do not monitor $PM_{2.5}$ in the outdoor air. For the locations of the participant homes, reliable data is only available for PM_{10}. Thus, to ascertain the source of particulate matter in the household environment, indoor-to-outdoor (I/O) ratios were calculated for PM_{10} using air quality data from the nearest local monitoring station of each home (https://qualar.apambiente.pt/). The obtained I/O PM_{10} concentrations substantially varied across homes (average I/O per home for NUDGE 2 varied from 0.60 and 10.25; mean I/O value: 1.54), meaning that the indoor levels in the participant homes can have their putative nature attributed to both outdoor and indoor sources. This observation is in line with the existing literature and suggests that information on best-practices to avoid indoor and outdoor sources of particles can be useful to help families in being informed about actions to protect themselves from hazardous exposures at home.

Household characteristics influencing energy consumption and IAQ

The investigation of a statistical association between continuously monitored data (electricity and IAQ data collected through smart meters) for the period of study and the characteristics of the households (building survey checklist data) showed important significant associations, as listed in Table 16. In particular, it was found that electricity consumption was significantly linked to the dimension (area) of the houses, total number of occupants and children in the home and density of occupants as well. Similar results were obtained for single-family houses, i.e., families living in single-family houses registered significantly higher levels of electricity consumption than families living in flats. The existence of a home EV charging point, or a fireplace was also linked to higher electricity consumption rates. Also, houses with windows oriented to North (51 out of 101) presented significantly higher consumption of electricity. For instance, a higher number of windows in the North façade was also associated to an increased consumption of electricity. This is likely due to the fact that homes with glassed façade oriented to the North may have increased heating needs resulting from cold winter winds generally coming from the North and low solar gains. In addition, homes built before 1980 (16 out of 101) presented higher electricity consumption and relative humidity levels along with lower indoor temperature than those reported for more recent dwellings. According to the WHO guidelines for IAQ focusing on dampness and mould (WHO, 2009) persistent dampness in indoor environments is an indicator of health risk to occupants, namely potentiating the development of allergies, asthma and respiratory symptoms (such as cough and wheeze). In this work, signs of water damage or pathologies related to dampness and mould were observed in about 39% of the PT pilot participant homes (Table 14), and this characteristic was significantly linked to higher air relative humidity levels (Table 16). Noteworthy, the percentage of the existence of pathologies was about 1.6-fold greater that the percentage obtained in previous studies conducted in homes of families with newborns and infants (Gabriel et al., 2020, 2021).

In relation to the CO_2, considered an important indicator of the quality of ventilation (air renovation) of the indoor spaces, the mean concentrations obtained were significantly increased in homes with lower areas (m^2) and higher density of occupancy (persons/m^2). Interestingly, significantly higher CO_2 concentrations were found in homes using bottled gas (propane or butane) for indoor environment and/or water heating. In turn, concentrations of airborne particulate matter were significantly linked to both the use of bottled gas but also of wood or pellets for heating purposes. Further, according to the results obtained from the statistical analysis, the practice of smoking indoors and the existence of evident signs of physical pathologies (e.g., noticeable cracks, fissures, altered staining or peeling in the dwelling's surfaces) can constitute factors that may contribute to the risk of being exposed to higher $PM_{2.5}$ and PM_{10} concentrations at home.

Table 16. Main outcomes from statistical analyses conducted for exploring the existence of significant links between household characteristics and IAQ and electricity consumption monitored during PT pilot implementation.

Home characteristics	Environmental quality					Electricity consumption
	T	RH	CO_2	$PM_{2.5}$	PM_{10}	Whole period
Building characteristics						

Homes built before 1980	**$t(82)=-2.068$ [a]** * -	**$t(82)=2.999$ [a]** ** +	$U=330.5$, $z=-1.620$ [b]	$U=437.0$, $z=-0.303$ [b]	$U=438.0$, $z=-0.291$ [b]	**$U=411.0$, $z=-2.405$ [b]** * +
Area (m^2)	$r_s=0.055$ [c]	$r_s=0.006$ [c]	**$r_s=-0.268$ [c]** *	$r_s=-0.089$ [c]	$r_s=-0.090$ [c]	**$r_s=0.423$ [c]** ***
Single-family houses	$t(82)=-0.991$ [a]	$t(82)=1.497$ [a]	$U=823.0$, $z=-0.078$ [b]	$U=807.5$, $z=-0.226$ [b]	$U=808.0$, $z=-0.221$ [b]	**$U=609.0$, $z=-3.891$ [b]** *** +
Occupancy						
Number of children (5-17 years old)	$r_s=0.159$ [c]	$r_s=-0.108$ [c]	$r_s=-0.151$ [c]	$r_s=-0.191$ [c]	$r_s=-0.191$ [c]	**$r_s=0.258$ [c]** **
Number of occupants	**$r_s=0.229$ [c]** *	$r_s=-0.068$ [c]	$r_s=0.082$ [c]	$r_s=-0.110$ [c]	$r_s=-0.110$ [c]	**$r_s=0.336$ [c]** ***
Density of occupancy (person/m^2)	$r_s=0.035$ [c]	$r_s=-0.030$ [c]	**$r_s=0.311$ [c]** **	$r_s=0.041$ [c]	$r_s=0.042$ [c]	**$r_s=-0.294$ [c]** **
Energy supply systems and equipment						
Electricity for heating	$t(82)=-1.587$ [a]	$t(82)=0.250$ [a]	$U=491.0$, $z=-1.943$ [b]	$U=594.0$, $z=-0.895$ [b]	$U=593.5$, $z=-0.900$ [b]	**$U=552$, $z=-2.668$ [b]** ** +
Bottled gas	$t(82)=-1.272$ [a]	$t(82)=0.728$ [a]	**$U=310.0$, $z=-2.160$ [b]** + *	**$U=289.0$, $z=-2.413$ [b]** + *	**$U=288.0$, $z=-2.425$ [b]** + *	$U=676.0$, $z=-0.195$ [b]
Wood or pellets	$t(82)=-0.076$ [a]	$t(82)=0.131$ [a]	$U=709.5$, $z=-1.280$ [b]	**$U=538.5$, $z=-2.839$ [b]** + **	**$U=539.5$, $z=-2.830$ [b]** + **	**$U=778.0$, $z=-2.590$ [b]** ** +
Open or modern fireplace	$t(82)=0.523$ [a]	$t(82)=-0.531$ [a]	$U=670.5$, $z=-1.488$ [b]	**$U=548.5$, $z=-2.611$ [b]** + **	**$U=549.5$, $z=-2.602$ [b]** + **	**$U=672.0$, $z=-3.191$ [b]** *** +
Home EV charging point	$t(82)=1.265$ [a]	$t(82)=-0.839$ [a]	$U=247.0$, $z=-0.869$ [b]	$U=245.0$, $z=-0.899$ [b]	$U=244.5$, $z=-0.907$ [b]	**$U=199$, $z=-2.118$ [b]** * +
Factors with putative impact on air quality						
Smoke indoor	**$t(82)=-2.475$ [a]** *	$t(82)=1.613$ [a]	$U=162.0$, $z=-0.671$ [b]	**$U=64.0$, $z=-2.524$ [b]** ** +	**$U=64.0$, $z=-2.524$ [b]** ** +	$U=255.0$, $z=-0.352$ [b]

Moisture-related pathologies	$t(82)$=-1.644 [a]	**$t(82)$=2.077 [a] ***	U=742.0, z=-0.984 [b]	U=683.5, z=-1.517 [b]	U=683.0, z=-1.522 [b]	U=1102, z=-0.410 [b]
Physical pathologies	$t(82)$=0.543 [a]	$t(82)$=-0.229 [a]	U=637.0, z=-0.253 [b]	**U=462.5, z=-2.056 [b] * +**	**U=463.0, z=-2.051 [b] * +**	U=798, z=-0.833 [b]
Fenestration/Windows						
Openable windows oriented to the North (N, NW, NE)	$t(82)$=-0.193 [a]	$t(82)$=-0.165 [a]	U=848.0, z=-0.287 [b]	U=797.5, z=-0.739 [b]	U=796.5, z=-0.748 [b]	**U=715.0, z=-3.564 [b] *** +**
Number of windows oriented to the North (N, NW, NE)	r_s=-0.032 [c]	r_s=0.030 [c]	r_s=0.01 [c]	r_s=-0.075 [c]	r_s=-0.076 [c]	**r_s=0.422 [c] *****

a t-test, b Mann-Whitney U test, c Spearman method.
**** Significant at 0.05 level.***
***** Significant at 0.01 level.***
****** Significant at 0.001 level.***
+ positive associations, - negative associations

Interaction of the participants with the mobile app

The smartphone app, developed to serve as the interface tool to expose PT pilot participants to nudges, was made available in app stores and distributed in March 2022. Some indicators of the app usage, including the number of openings of the app and new data requests, were continuously monitored during the study (March 2022 to February 2023). Unfortunately, due to a technical problem related to a collapse in the subcontracted app developer's infrastructure (resulting in a loss of data and a huge downtime) data for the second half of the NUDGE 3 period was lost. However, since data was available for all other critical phases of the study, it is expected that this issue does not substantially impact the overall analysis of the interaction of the users with the app and subsequent investigations.
Figure 59 shows that the number of participants using the app was variable across the days of study. In addition, it was observed that in the first days of each nudge implementation there was typically a high number of participants using the app due to the notifications that were sent to the participants informing them that new functionalities were activated in the app.

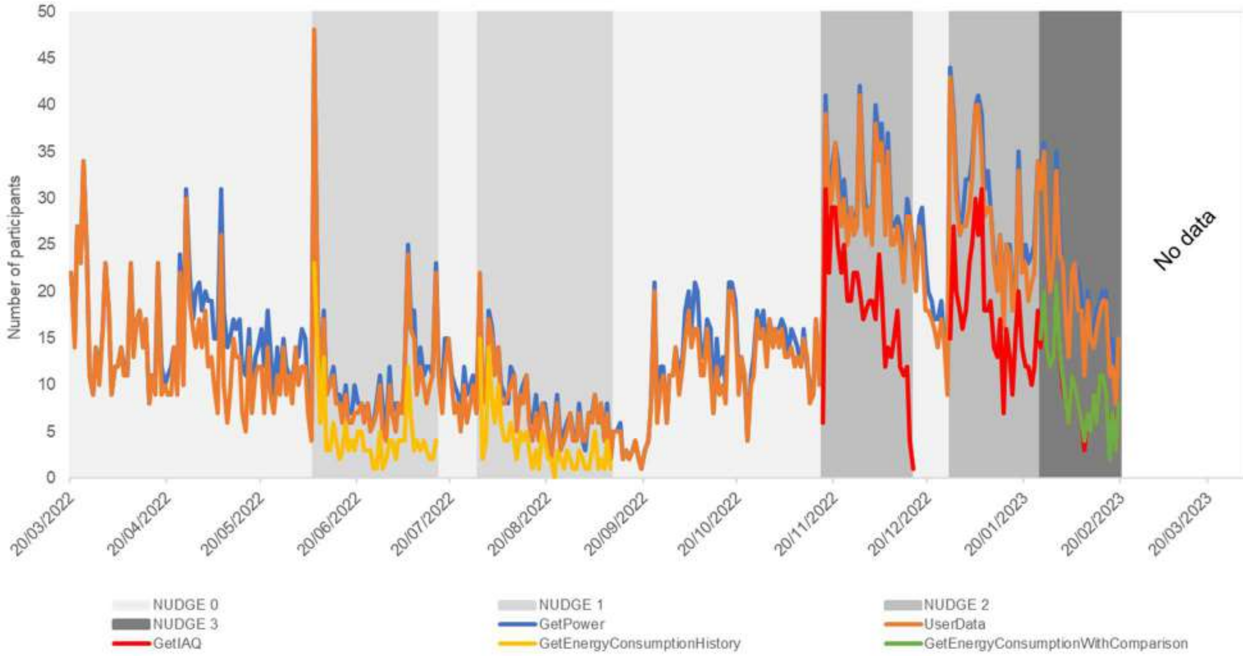


Figure 59. Number of participants interacting with the app during the PT pilot implementation.

In fact, although app features of NUDGE 2 were activated only for the 84 participants that had an IAQ sensor installed, it can be noted that NUDGE 2 was the intervention that promoted a more constant number of participants interacting with the app per day during the whole nudging period (Figure 59). Also, comparing the number of days in which participants interacted with the app (nudge exposure days) during the different NUDGEs, it was verified that a significantly higher average was obtained for the NUDGE 2 period (Table 17).

Table 17. Summary outcomes from t-test for PT pilot' s nudge exposure days across the tested NUDGEs.

	Nudge exposure days			
Intervention	**Mean**	**SD**	**p value**	**T-test**
NUDGE 1	9.41	10.28	0.0000	8.1623
NUDGE 2 (n=78)	19.64	11.29		
NUDGE 2	20.58	10.85	0.0000	12.4380
NUDGE 3 (n=74)	7.21	5.69		
NUDGE 1	9.67	10.57	0.0158	2.4723
NUDGE 3 (n=73)	7.02	5.69		

Also, by focusing on the average days of interaction with the app per week of the baseline and nudging periods, it was found that most of a great part of the users interacted with the app:

- 1-2 days per week during the pre-intervention and NUDGE 1 periods.
- 4-2 days per week during the NUDGE 2 period.
- 1-3 days for the NUDGE 3 period.

Overall, the results from the app usage analysis suggest that NUDGE 2, focusing on presenting IAQ data and informing participants on high CO_2 and/or airborne particle levels, was the intervention conducted in the PT pilot that has encouraged higher level of exposure to intervention app features.

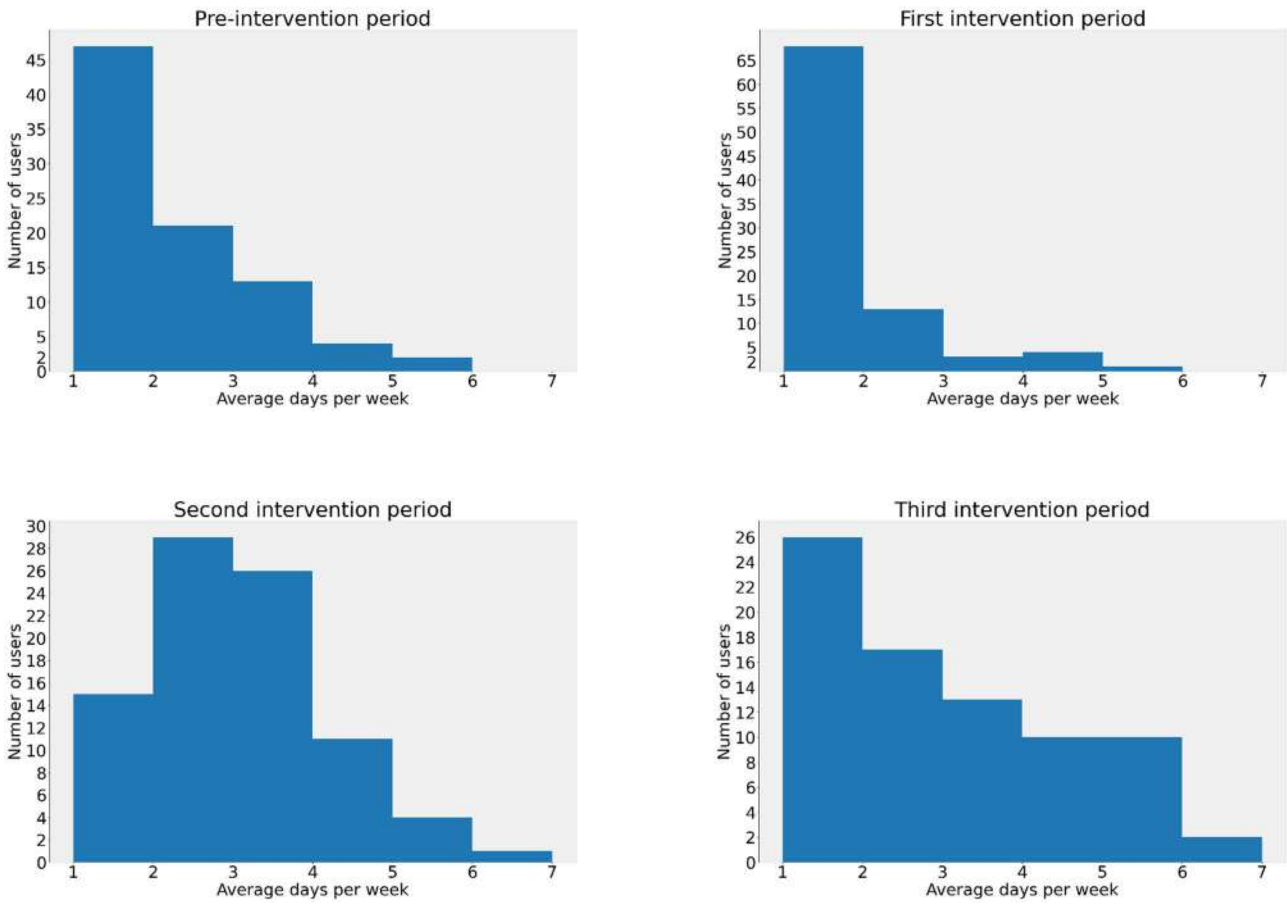


Figure 60. Distribution of average weekly days of interaction with the app across the pilot participants during the pre-intervention and the three intervention periods.

In the questionnaires distributed immediately after each intervention period (post-intervention surveys) participants were requested to provide feedback on their satisfaction with some usability features of the app. In general, results showed that the participants rated their app usage with positive scores (Figure 61).

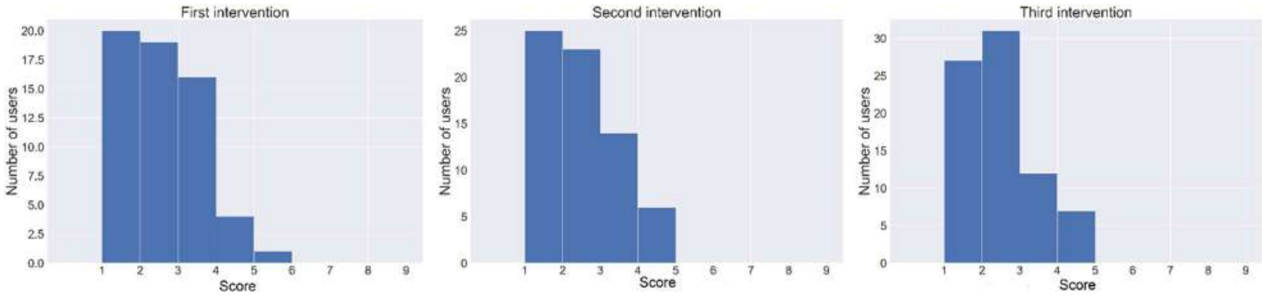


Figure 61. Distribution of app ratings at the 1-9 scale according to the responses of PT pilot participants in the three post-intervention surveys (1-4: positive scores; 5-neutral; 6-9: negative scores).

An apparent improvement in satisfaction with the app was obtained on the feedback representing NUDGE 2 and NUDGE 3 periods in comparison to the feedback collected in NUDGE 1. This observation can be justified by a learning effect across the study period and also due to the fact that some of the participants, at the time of NUDGE 1 implementation, seemed to be not completely informed that the app functionalities would be activated and deactivated throughout the study. In fact, some complaints were received from the participants after the NUDGE 1, requesting the activation of NUDGE 1 features, and the team carefully explained that due to the design of the study the new functionalities would be only active during about 1 month, and that we would ensure that at the end of the study the participants would be able to visualise all app functionalities (from September 2023 onwards). The increased satisfaction scores obtained for the subsequent periods showed that participants were very understanding. In particular, the participants appreciated the app time-saving features, its comprehensibility, and user-friendliness, and the characteristic of the app that received lower satisfaction scores was related to the question "unadaptable to my needs - adaptable to my needs".

Nudge impacts

Nudge effects on electricity consumption

For the investigation of the effects of nudges on electricity consumption a difference-in-differences (DiD) estimation model with two-way fixed effects (TWFE) was employed. The regression is set up to account for differences across groups ("first difference") by adding household fixed effects, i.e., allowing for a separate intercept term for each household. In practical terms, this cancels out factors that are common for a household over time, such as the type of existing electric equipment, their energy-consumption habits, and the energetic properties of the building. Then, a second set of fixed effects is added for each time period (day) to cancel out factors that are common to all households on a given day, the main such factors being the weather and the developments during the energy crisis. The assumption here is that the news and policy changes are common to all households, so the time-fixed effects can absorb their effect. This is the "second difference". The DiD then captures only what is left over: the treatment effect (nudgeEmpact). The outcomes of the statistical analyses conducted per participant Group of PT Pilot are summarised in Table 18.

Table 18. Main outcomes from DiD tests for electricity consumption during each nudge with no effect and fixed effects added to the model.

Model (log(Wh))	NUDGE 1		NUDGE 2		NUDGE 3	
	Group 1	**Group 0**	**Group 1**	**Group 0**	**Group 1**	**Group 0**
Basic (no effect)	0.0458 (p=0.141 R2=0.009)	-0.0328 (p=0.233 R2=0.031)	**-0.1510** **(p=-0.0000 R2=0.026)**	**0.1286** **(p=0.000 R2=0.040)**	**-0.1382** **(p=0.000 R2=0.036)**	**0.0682** **(p=0.025)**
Entity-fixed	0.0681 (p=0.1607 R2=0.0085)	-0.0195 (p=0.7015 R2=0.0545)	**-0.1281** **(p=0.0450 R2=0.0278)**	0.0905 (p=0.1802 R2=0.0689)	-0.1060 (p=0.2236 R2=0.0628)	0.0588 (p=0.3420 R2=0.0320)
Time-fixed	**0.0492** **(p=0.0288 R2=0.0067)**	-0.0357 (p=0.0507 R2=0.0065)	**-0.1488** **(p=0.0000 R2=0.0150)**	**0.1241** **(p=0.0000 R2=0.0142)**	**-0.1344** **(p=0.0000 R2=0.0133)**	**0.0627** **(p=0.0005 R2=0.0110)**
TWFE	0.0692 (p=0.1440 R2=0.0009)	-0.0222 (p=0.6655 R2=0.0001)	**-0.1258** **(p=0.0471 R2=0.0080)**	0.0851 (p=0.2044 R2=0.0019)	-0.1016 (p=0.1618 R2=0.002)	0.0525 (p=0.3970 R2=0.0008)

TWFE, two-way fixed effects
Bold values denote statistical significance at the $p < 0.05$ level.

As shown in the table above, most of the obtained results from the DiD models employed were statistically insignificant – as p-values over 0.05 were achieved – suggesting that the interventions implemented in the PT Pilot of NUDGE had an apparent low or no impact on the electricity consumption of the participant homes. In particular, from the TWFE models employed, a significant reduction in electricity consumption was only noticed for the homes of participants of Group 1 during the intervention period of NUDGE 2. For the remaining NUDGEs no significant impacts on electricity consumption data were obtained. Other attempts were conducted to adjust models (e.g., based on a different baseline period, excluding participants with low degree of interactions with the app) as reported in Deliverable D2.3.) but no consistent significant impacts were noticed.

NUDGE 2 impact on indoor air quality of participants' homes

The NUDGE 2 allowed the users to visualise IAQ levels monitored in their homes for a defined period of the study (intervention period) in the app. In addition, real-time notifications were sent to participants, informing them when CO_2 and/or PM concentrations were too high. It was expected that participants might exploit this information to identify periods or situations in which the home air quality can be compromised and assist them in conducting actions to enhance IAQ. For the investigation of NUDGE 2 impacts on IAQ data DiD models cannot be employed as done for electricity consumption, since we do not have a robust baseline data for IAQ (due to the time needed for development and validation of the IoT System designed for IAQ monitoring). In turn, Wilcoxon tests were employed for investigating the existence of statistically significant differences in the CO_2 and airborne particles concentrations obtained in the periods in which the same participants worked as control and intervention groups.

In particular, significantly lower CO_2 concentrations ($z=-2.644$, $p=0.008$) were detected in the homes for nudging periods (when NUDGE 2 app functionalities for presenting IAQ data were active). If we analyse homes individually, considering the indoor CO_2 concentrations assessed with IAQ low-cost sensors (LCS) modules during NUDGE 2 (Figure 62), it was observed that 52 (out of 84) homes presented lower average CO_2 concentrations in the period in which they were able to visualise IAQ data in the app than those found in control period (in which no IAQ data was available). Considering these 52 households, the achieved reduction of indoor CO_2 concentration from control to intervention period was on average 10.3% (varying from 0.2% to 45.3%).

For airborne particles ($PM_{2.5}$ and PM_{10}, Figure 62), no significant differences were obtained between levels assessed in control and intervention periods. However, compared to the control period, a reduction of the average of both $PM_{2.5}$ and PM_{10} levels in the intervention period was observed in 46 homes, with the respective mean % of reduction of 19.2 (ranging from 0.6 to 93.2%).

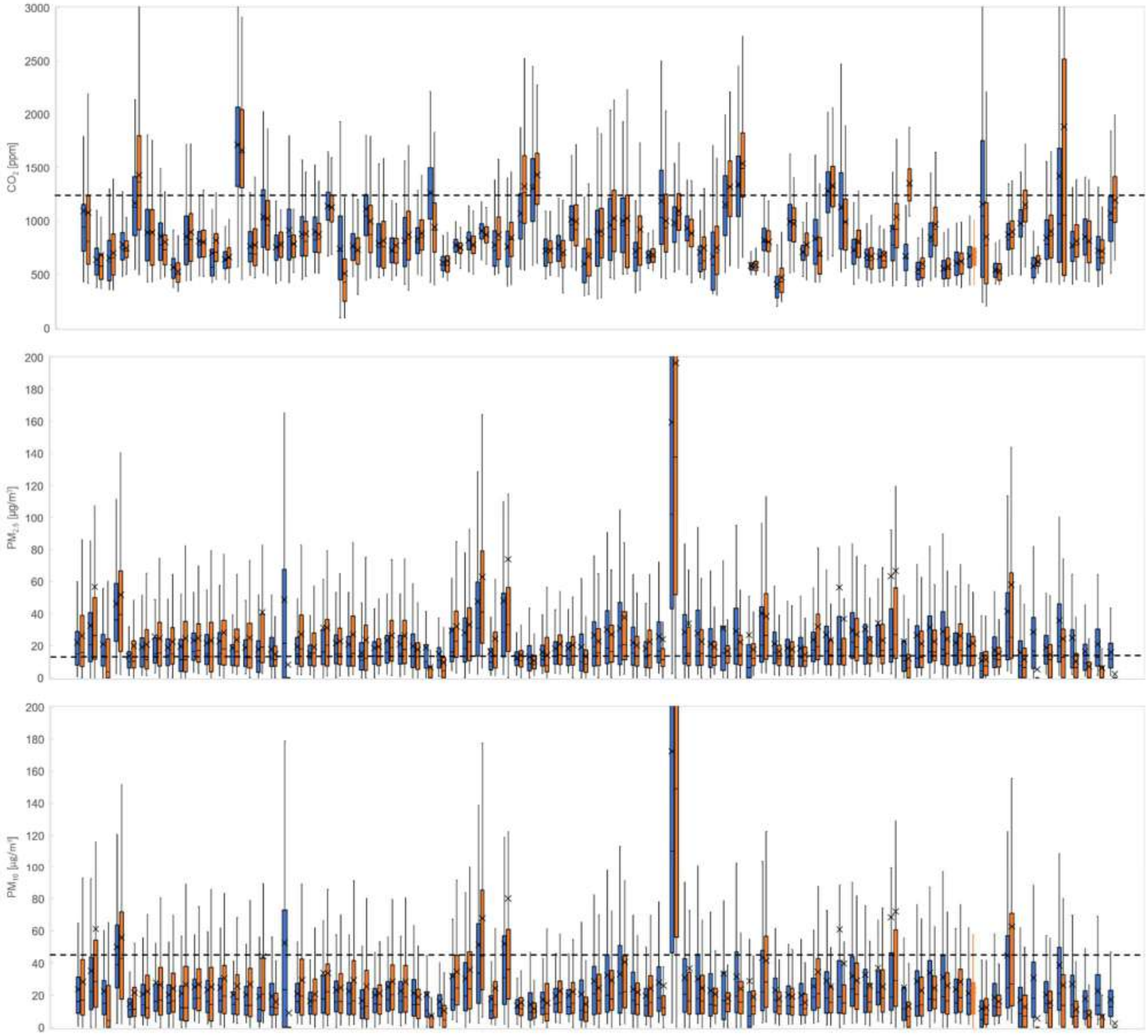


Figure 62. Boxplot representing the concentrations of A. CO_2, B. $PM_{2.5}$ and C. PM_{10} levels obtained in the 84 participant homes during the respective control and intervention periods. The bottom and the top of the boxes represent the 25th and 75th percentiles. The band near the middle of the box and the X represent the median and the mean values, respectively. The ends of the whiskers indicate the 10th and 90th percentiles. Dotted lines represent exposure limits defined for each parameter: CO_2: 1250 ppm (national recommendations); $PM_{2.5}$: 15 µg/m³ and PM_{10}: 45 µg/m³ (WHO guidelines).

Nudge impact on participants' motivation and intention to change behaviours

The on-line questionnaires that were distributed at the final stage of the pre-intervention phase and immediately after each nudge (4 waves of questionnaire administration) included common items aiming at asking the participants for their intention and motivation to save energy in their homes and also at monitoring relevant changes throughout the study. Mean values obtained for scoring participants' intention and motivation to save energy across survey waves are represented in Figure 63.

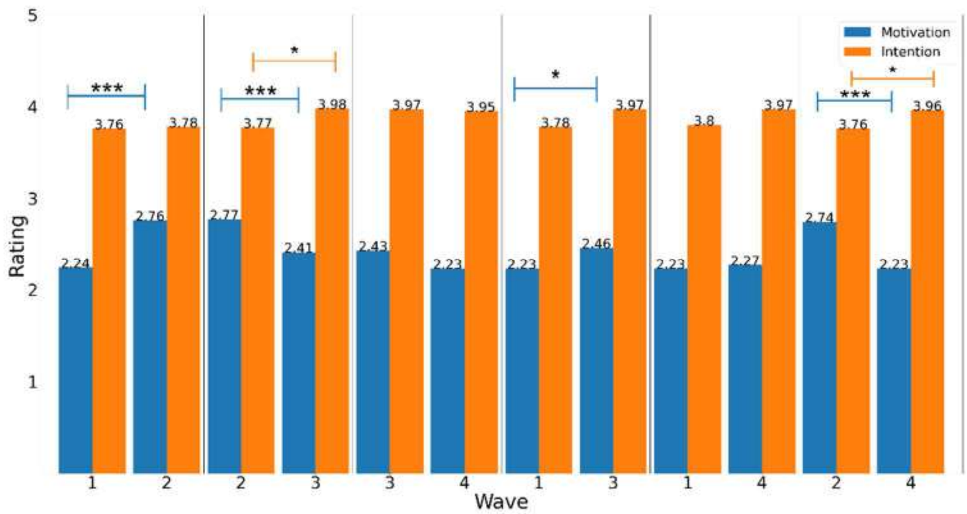


Figure 63. *Portuguese pilot's survey responses mean values compared between waves for intention and motivation to save energy. Waves 1 – pre-intervention; 2– NUDGE 1; 3 – NUDGE 2; 4– NUDGE 3. Asterisks represent significant levels from statistical outcomes * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.*

According to outcomes from the t-test, NUDGE 1 (Wave 2) and NUDGE 2 (Wave 3) resulted in a significant increase in the motivation to save energy in comparison with the pre-intervention phase (Wave 1). Interestingly, comparing participant feedback obtained from NUDGE 1 and those obtained in the subsequent interventions, a significant decrease in motivation to save energy was noticed from NUDGE 1 to both NUDGE 2 and 3. However, in both cases this effect went along with a significant increase in the intention to save energy. In fact, NUDGE 1 was the intervention that resulted in the highest mean scores of participants' motivation to save energy, but NUDGE 2 and NUDGE 3 produced the highest scores for the intention to save energy.

The participants were also requested to position themselves in a 9-steps ladder that has on the 1st step people who live not at all energy conscious and on the highest step, the 9th, people who live very energy conscious. The obtained average scores per relevant study phases were the following: pre-intervention – 6.27; NUDGE 1 – 6.5; NUDGE 2 – 6.8 and NUDGE 3 – 6.84. Compared to the score obtained in the pre-intervention phase a statistically significant increase in the scores was observed during NUDGE 2 and NUDGE 3.

Some questions were included in the questionnaire post-NUDGE 2 in order to ascertain if the participants found that the information in the app was useful for improving IAQ. Briefly, the majority of participants (85.7%) agreed or strongly agreed with the statement 'I tried to improve the indoor air quality at home in the last two months'. Also, a great share of participants (72.9%), reported that the information provided by the application had shifted their perception of home air quality, with responses falling into the categories of 'somewhat true,' 'mostly true,' or 'very true'. Accordingly, participants overwhelmingly felt that the data presented in the app motivated them to take useful actions to enhance indoor environmental quality, with a substantial 77.1% indicating responses such as 'somewhat true,' 'mostly true,' or 'very true'. true'. We also asked participants about energy consumption, and a significant 74.3% of respondents expressed their agreement with the statement: 'I would be more motivated to save energy if considerations related to indoor environmental quality, encompassing thermal comfort and air quality, were integrated into the process'. The great majority of the respondents also recognised that they would like to have more detailed information (e.g., historical data) for IAQ in their homes.

2.4.5. Concluding Remarks on Pilot Outcomes

The comprehensive approach developed in the Portuguese pilot study allowed to provide robust datasets on electricity consumption and IAQ in homes of families with children living in Portugal. The data was particularly explored for evidence on the potential effects of nudging treatments specifically designed for the pilot in promoting improvements in energy savings, air quality and on the participant level of literacy on energy and air quality topics. The following concluding remarks on the pilot outcomes can be derived, providing answers to the research questions.

What are the factors influencing electricity consumption and air quality in the homes of Portuguese families?

The results obtained suggest that electricity consumption in family housing can be significantly impacted by multiple factors including the area, occupancy, typology and construction period of the dwelling, and orientation of window glazed façades. Regarding air quality, levels of particulate matter appear to be significantly associated with the use of bottled gas and wood or pellets for heating, the existence of physical pathologies inside the dwelling (e.g. cracks in the walls) and indoor smoking. CO_2 levels were significantly higher in houses with a smaller area, higher occupancy density and which use bottled gas for heating. It is important to note that these were the factors from a panel of household features that were studied showing a significant association with the monitored data. However, the possibility that there may be other important determining factors that were not covered in the study (efficiency of electrical appliances used in the participant homes) should not be excluded.

How might access to detailed historical and real-time information on energy use through a smartphone app impact the user behaviours and electricity consumption data in households? (NUDGE 1)

According to the results of the data analysis carried out in the NUDGE project, there was no noticeable effect on electricity consumption during the period of NUDGE 1 (the period in which the functionality for providing historical electricity consumption data was active). Nevertheless, there was a significant increase in participants' motivation to save energy (but not in their intention to do so). It is important to note that due to delays in the installation works caused by external factors (mainly associated with the COVID-19 pandemic), NUDGE 1 needed to be implemented during the summer season, a period in which people tend to spend less time at home (more frequent outdoor activities and/or vacation periods) and consequently had lower energy consumption/bills (less opportunities for improvement). The possibility that the summertime is not the most suitable period for testing nudging treatments in this pilot should be considered as an important source of uncertainty to the reported results on the impacts of NUDGE 1 in the Portuguese case.

In fact, because an increase in motivation to save energy was obtained, we cannot exclude the possibility that this nudge contributes to a learning effect that can result in more efficient behaviours later on. For instance, some participants could have used NUDGE 1 to identify a corrective action to implement (e.g., identify appliances that are not the most energy efficient options) but the effective behaviour change (e.g., replacement of the devices) can happen only in a later stage (not able to be assessed by the conducted study design).

How effective is the access to real time data on home IAQ through a smartphone app at encouraging families to conduct actions for improving air quality? (NUDGE 2)

The results obtained were suggestive of the existence of behavioural effects in the participants, who seem to have learned to identify periods in which ventilation may be compromised and to implement improvement actions (opening windows to reduce CO_2 concentrations). Also, a large percentage of participants recognised that the data provided helped them to better understand the factors that influence IAQ and reported being very motivated to contribute to improving IAQ in the future.

How will it affect energy consumption? (NUDGE 2)

Interestingly, a significant reduction in electricity consumption was observed for participants of Group 1 during the NUDGE 2 period, however, we cannot robustly establish whether this reduction is truly attributed to NUDGE 2, to a long-term learning effect from NUDGE 1, or to other unassessed cause(s). However, the results suggested that even if the participants open windows during a short period as a strategy to reduce indoor CO_2 levels in winter months, it will not negatively affect electricity consumption.

What is the potential of using an IoT architecture based on low-cost sensors for increasing the level of citizen's literacy on the factors that may influence exposure to air pollution at home?

The works conducted in the PT pilot included the development and validation of an IoT system incorporating LCS to collect real-time data on CO_2, temperature, relative humidity and particulate matter ($PM_{2.5}$ and PM_{10}) in participants within the implementation of NUDGE 2. In fact, a growing body of evidence has recognised IoT systems with LCS as an extraordinary opportunity to manage and control buildings, empowering citizens to control their environments (Ródenas García et al., 2022). Nevertheless, currently there is still a lack of evidence on the potential of these IoT sensing technologies in citizen-science studies.

PT pilot of NUDGE constitutes a step forward in providing innovative evidence of the usability of the IoT systems using LCS for citizen-oriented science aiming to promote healthy environments. The system was very effective in allowing participants to identify CO_2, $PM_{2.5}$ and PM_{10} concentration peaks.

Will the integration of aspects related to air quality increase the engagement of the citizens to save energy?

A substantial proportion of participants recognized that they would feel more motivated to save energy if aspects related to ensuring IAQ were taken into account in the process. In addition, there was a significant increase in the intention to save energy and in the perception of participants' self-positioning in relation to energy issues.

Overall, results from NUDGE 2 are suggestive of some beneficial effects of the introduction of air quality in the study. Nevertheless, as already referred above, since the implementation of nudges was consecutive, it is important to disclose that we cannot robustly establish if the effects are due to NUDGE 2 or due to a combination of NUDGE 2 with long-lasting learning effects resulting from NUDGE 1 (or to other reason(s)).

How do the energy conservation nudges focusing on indoor environment heating affect electricity consumption? (NUDGE 3)

Overall, the results obtained were not entirely clear about the effect of NUDGE 3 on electricity consumption (and behavioural changes). The results of NUDGE 3 as a whole suggest a low potential for implementing nudges focused on optimising the use of heating systems, possibly associated with the national context (most of the homes do not have a central heating system, with the devices used for heating purposes being used according to the individual comfort-related needs). In fact, indoor temperature data showed that a low % of Portuguese families heat their homes to reach a good standard of thermal comfort (21 ºC for living rooms according to WHO). This observation should be interpreted along with the national status of energy poverty and the % of Portuguese families that are unable to keep their homes adequately warm. In fact, recently, a governmental proposal for a long-term national strategy to combat energy poverty was subjected to public consultation, presenting a national strategy that aims to diagnose and describe the energy poverty problem, develop follow-up indicators and monitoring strategies, establish medium and long-term energy poverty reduction goals at national, regional and local levels, and propose specific measures to achieve these goals, as well as forms of financing to mitigate this problem in the coming years (DGEG, n.d.). Some governmental actions have been implemented, including the distribution of some financial incentives to improve the thermal isolation of the buildings and replace devices with more efficient solutions. Although the nudging intervention tested in this work seems to have a low potential when implemented alone to induce energy savings, it could be valuable to consider for further works the implementation of a more integrative approach aiming at combining the current planned financial incentives along with actions for promoting literacy on energy efficient behaviours and on how to plan the energy-efficient refurbishment.

2.5. The Croatian (HR) pilot

2.5.1. Overview on Pilot implementation

Context and Aim

Increasing use of residential photovoltaic (PV) power systems and the development of energy regulations have occurred in tandem in Croatia. The number of residential PV systems linked to the grid saw a significant growth, rising from 1 478 in February 2022 to 2 851 in September 2022. In September 2023, the total count reached 8 779 household PV systems connected to the grid (information requested by email to HEP-Distribution System Operator). Current billing structures are classified as "self-consumption" and "final customer with own production." It was essential to have a thorough understanding of these models, as households could switch between them based on their energy balance, affecting investment returns. This model will remain in effect until the end of 2023, with households maintaining their status of self-consumption beginning in 2024 (Zakon.hr, 2023). In addition, households had limited knowledge of their energy consumption, relying solely on monthly bills that contained insufficient data. This lack of knowledge prevented intelligent energy decisions. In this context, the Croatian pilot project aims to enhance PV system usage in households. It addresses the need to educate users on billing regulations and improve their knowledge of energy consumption patterns. Traditional monthly bills do not provide sufficient insight, requiring a more informed strategy, which can be enabled through smart metering. The objective of the project was to equip users with the knowledge and resources needed to navigate evolving regulations, optimise energy consumption, increase energy-efficiency in homes, and understand which nudges are relevant to achieve higher self-consumption and less grid dependence.

Study design and methodology

During the project's engagement phase, 415 individuals expressed interest in the study. They filled out a Google form online to determine their eligibility based on the status of their PV system. 39.3% had PV systems already installed, while 15.2% were in the installation process. The eligible participants were then subjected to a technical evaluation, which included considerations such as metre type, fuse board space, Wi-Fi quality, and electrical wire length. Those who met these requirements were accepted into the project and granted access to the Sunči monitoring app. Smart meters have been installed to monitor household energy usage. The final set of 82 consumers engaged in the pilot were able to access real-time data from their PV systems and receive guidance through push notifications, educational content, and app features. This user-friendly smartphone app encourages energy optimization and tracks its impact. Additionally, a data collection platform stores smart meter data, enabling seamless integration with the NUDGE central platform and ZEZ's Sunči app.

KPI & data

Regressions were used to examine the impact of the nudges on self-consumption and autarky. Due to Croatian regulations offering further incentives to modify total consumption, this was included as an additional outcome variable. Results from this extra analysis are shared when they provide further understanding.

A more detailed examination of individual household behaviours was conducted by merging survey data with sensor data. Given the limitations due to the small sample size, this investigation is presented as a descriptive evaluation.

NUDGEs and research questions

In the Croatian pilot project focusing on PV power system optimization, nudges play a vital role. The nudges designed aimed to cultivate empathy, enhance awareness of energy usage, and encourage energy efficiency goal setting. The project utilises empathetic nudges to link energy consumption with societal and environmental impacts. Participants receive messages highlighting how their energy choices affect vulnerable groups, fostering compassion and promoting energy conservation, as well as a visual representation of CO2 impact and savings (Figure 65).

Besides the push notifications, users were able to engage with a donation feature within the Sunči app accessible through energy use and efficiency nudges. With a donation, energy efficiency packages were bought and delivered to the energy vulnerable households. However, it is important to note that this feature (donation) was introduced in Nov '22, as an additional feature to the designed instigating empathy as shown in Figure 64.

		Nudge 1: Instigating empathy		Nudge 2: Feedback		Nudge 3: Target setting	
Group 1	Baseline	Treated	Control	Treated	Control	Treated	Control
Group 2		Control	Treated	Control	Treated	Control	Treated
Timeline	Jan - Jul '22	Aug - Sep '22	Sep - Oct '22	Nov - Dec '22	Dec'22 - Jan '23	Feb - Mar '23	Mar - Apr '23

Figure 64. Experiment outline for the Croatian pilot.

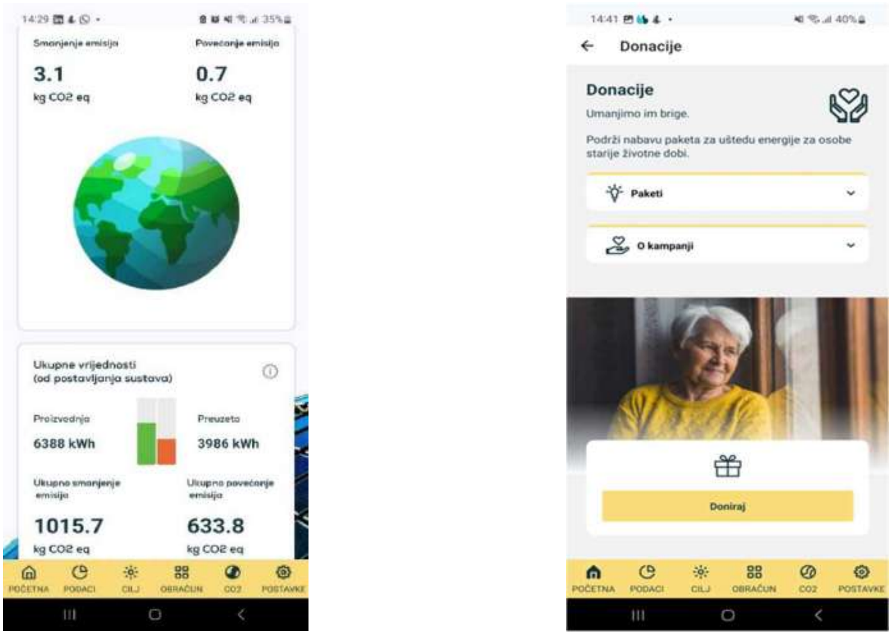


Figure 65. Instigating empathy nudge (left) and donation button app feature (right).

In addition to empathy-based nudges, the project incorporates feedback and awareness nudges delivered via push notifications. These nudges provide real-time information and suggestions based on weather conditions and the participants' energy production and consumption. They prompt users to consider whether to use household appliances during sunny days to maximise self-generated energy or to conserve energy during cloudy periods. Moreover, goal-setting nudges encourage participants to set personal energy efficiency targets and track their progress over time.

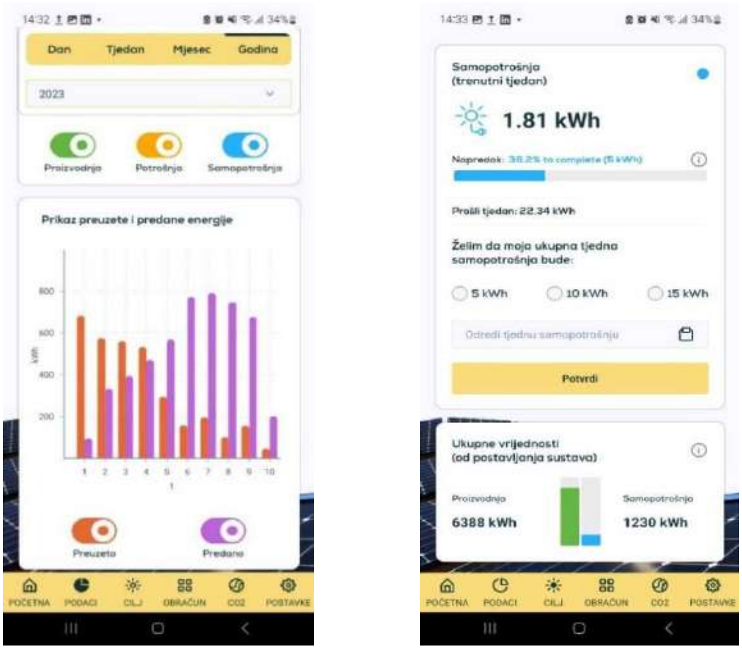


Figure 66. Feedback and aware nudge (left) and goal setting nudge (right).

In the investigation of the nudge design and implementation, we explored the following research questions:

- *How do empathetic nudges influence participants' awareness and attitudes towards their energy consumption, particularly considering the impacts of climate change on vulnerable populations?*
- *To what extent are feedback and awareness nudges effective in prompting participants to adjust their energy consumption behaviours, taking into account real-time data and weather conditions?*
- *Can goal-setting nudges lead to sustained improvements in energy efficiency? How do participants' goal-setting behaviours align with actual energy savings?*
- *In what ways do these diverse nudge strategies collectively contribute to fostering more energy-conscious and environmentally responsible behaviour among participants?*

Moreover, recognising the strong interplay between behaviour and regulatory frameworks, we have posed additional questions specific to the Croatian pilot:

- *How are changes in energy regulations, particularly transitions between billing models like "self-consumption" and "final customer with own production," impacting participants' decisions regarding energy consumption and the utilisation of PV systems?*

- *What significant challenges and barriers do participants encounter when adapting to evolving energy regulations, and how can we harness the power of nudges to effectively address these challenges, promoting compliance and optimising energy utilisation?*
- *To what degree does participants' understanding of billing models and their implications influence their energy-saving behaviours, and how can educational nudges enhance their comprehension and decision-making within this context?*
- *In what manner do participants' experiences with billing models influence their willingness to invest in PV systems, and how can we tailor goal-setting nudges to align with their financial goals within the existing regulatory framework?*

The incorporation of the nudges and the examination of their impacts through rigorous research questions aim to shed light on the efficacy of behaviour-based interventions in promoting sustainable energy practices within households. The findings from this study have the potential to inform not only the Croatian context but also contribute valuable insights to the broader global efforts in mitigating climate change through individual behaviour change and regulations.

2.5.2. Participant Households

The Croatian pilot mainly focused the recruitment on two key areas: Varaždin and Zagreb County, along with their respective environs in the Continental region of Croatia. In addition to this, due to the support and active collaboration extended to our study by local installers, the eastern part of Croatia, commonly referred to as the Slavonia region, was also incorporated. This expansion specifically includes cities such as Osijek, Vukovar, Slavonski Brod, and Vinkovci.
The geographical distribution of the 82 participating households in our Croatian pilot is visually represented in Figure 67, with the Continental region displayed on the left and the Slavonia region on the right side of the accompanying map. Our rationale for including this second region lies in its analogous demographic and geographical characteristics when compared to the primary location of our Croatian pilot.

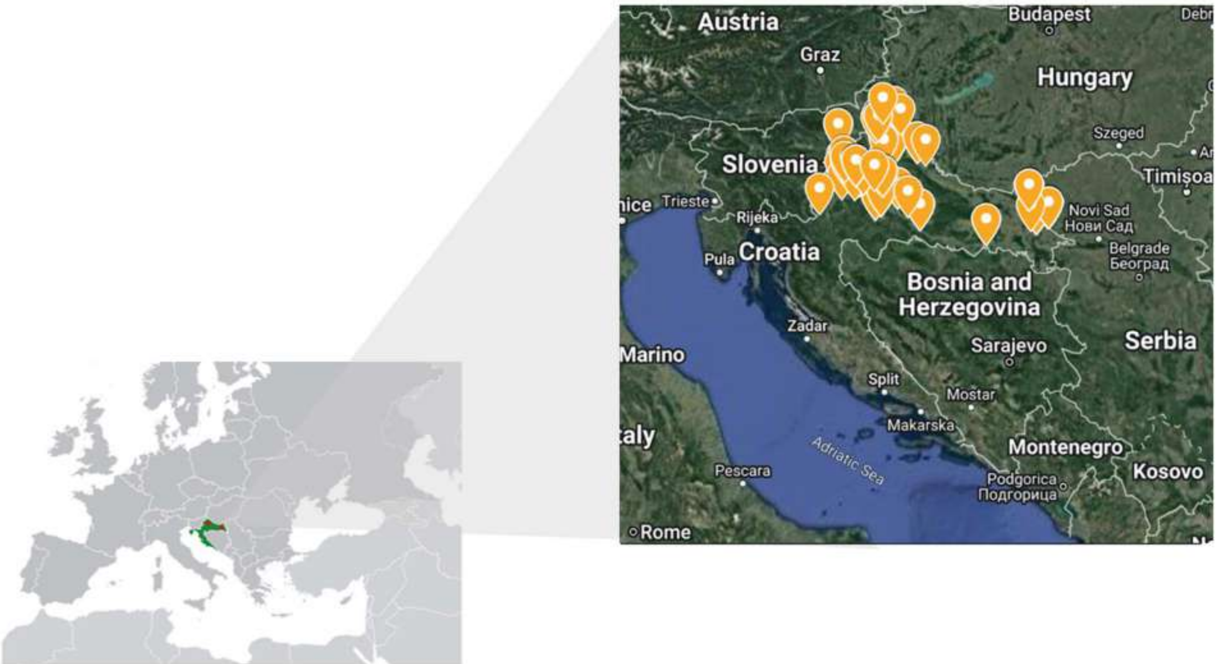


Figure 67*. Location of households for the HR pilot in the north and north-east region of Croatia.*

As of December 2022 (referred to as M28), the Croatian pilot study included a total of 82 households (HH) equipped with Shelly smart meter devices. Among these 82 engaged households, 61 were equipped with Shelly 3 EM devices, indicating their classification as 3-phase households. The remaining 21 households were equipped with 1-phase meters and were consequently installed with Shelly EM devices. This distinction in the number of phases is significant, as it aligns with the general pattern observed in the pilot where houses predominantly received 3-phase connections, while apartments were typically provided with 1-phase connections.

The insights gained from both the data analysis and Figure 68 provide valuable information about the preferences and choices of households participating in the Croatian pilot study regarding the size of their photovoltaic (PV) installations.

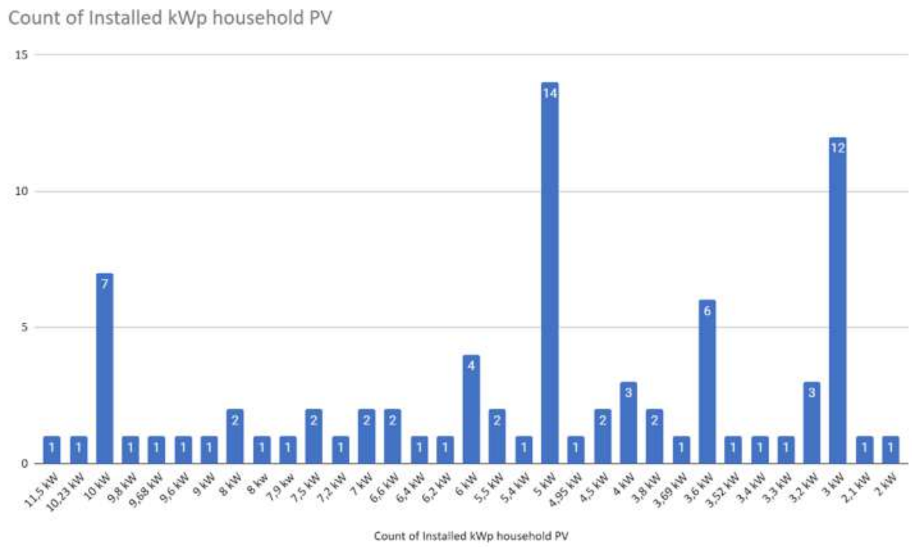


Figure 68. *Overview of the average PV plant size with the installed smart meter devices for Croatian pilot*

Firstly, the data presented in Figure 68 clearly shows that the majority of households opt for either 5 kW or 3 kW PV plants. This choice appears to align with the average household size of 3 to 5 residents. Smaller households, with 2 to 4 occupants, tend to have smaller PV installations, which is a logical and expected pattern.

What adds an intriguing dimension to this trend is the discovery that some households with fewer occupants are choosing to install larger PV systems. This decision is driven by the presence of energy-intensive electrical appliances, such as electric vehicles (EVs), in these households. This finding suggests that households are considering their energy needs and consumption habits when deciding on PV plant sizes, demonstrating a proactive approach to meeting their energy requirements sustainably.

Additionally, households with more than four residents typically opt for PV plant sizes between 3 kW and 5 kW, mirroring the average PV plant size presented in Figure 68. Notably, only a minority of households have PV plants larger than 5 kW, and this choice is typically associated with larger households (more than five residents) that also possess multiple high-energy-consuming appliances.

2.5.3. Climate and Meteorological data

All of the pilot participants are located in the north/north-east part of Croatia. The climate in those regions is similar - mild, and generally warm and temperate. The annual temperature profile for Varaždin and Zagreb are similar. For a measured period, the average in Varaždin (N) is 11.9 °C, Zagreb (N) is 11.5 °C and for Osijek (NE) is 12.4 °C. Households' energy demand varies with temperature. During colder months, there might be increased energy use for heating, while warmer months might see higher use of air conditioning. Knowing the temperature profile helps in predicting these variations in energy demand and planning accordingly. Even though this factor has not been directly analysed, it is reasonable to infer that the similar climate and temperature profiles across these regions would lead to comparable patterns in household energy consumption, both in terms of heating in the colder months and cooling during the warmer periods.

This similarity in climate conditions could provide a consistent basis for evaluating the performance and energy savings potential of PV systems across these areas, as well as predictions towards the surplus energy and its availability for sharing within the community. In the following Figure 69 and 70, the solid lines are presenting the beginning of the nudge phases, and the dashed lines the treatment switch from Group 1 to Group 2.

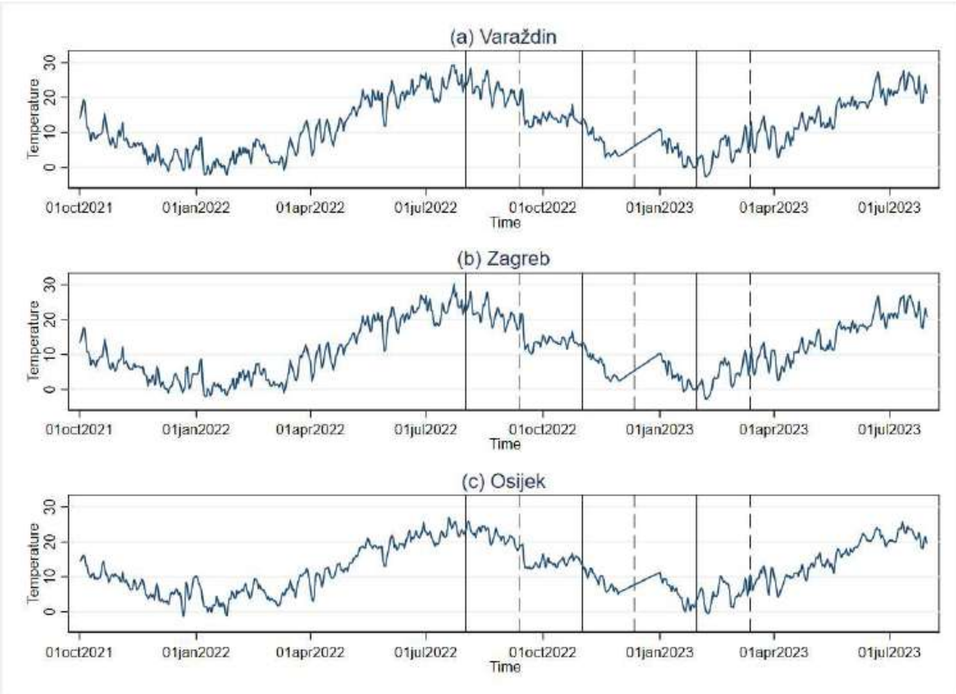


Figure 69. Ambient air Temperature in Varaždin (a), Zagreb (b) and Osijek (c) from October '21 until July '23 (data from Copernicus project).

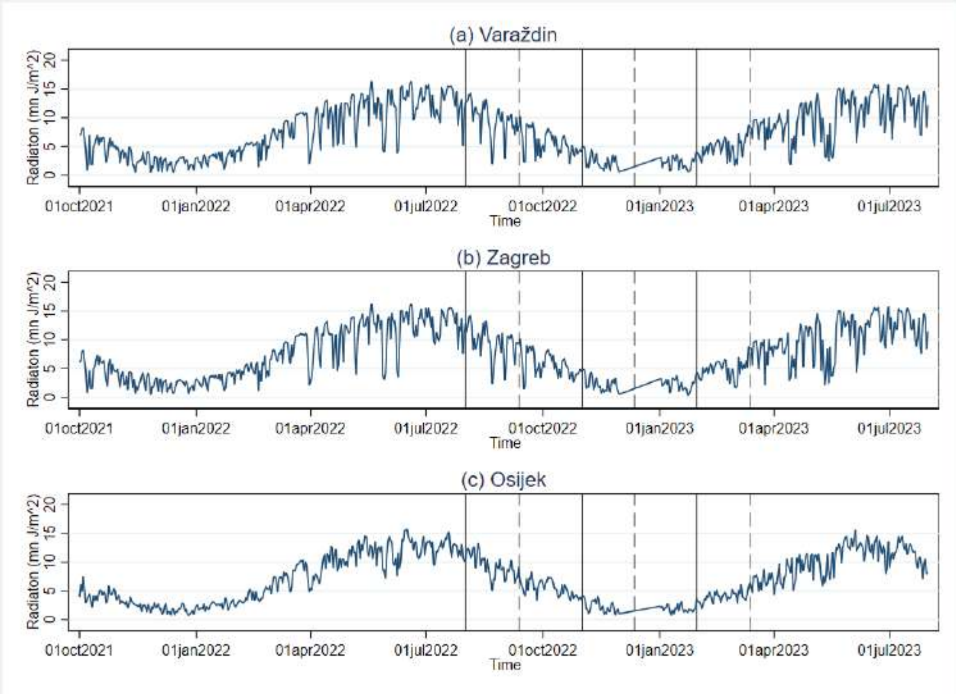


Figure 70. Radiation in Varaždin (a), Zagreb (b) and Osijek (c) from October '21 until July '23 (data from Copernicus project).

2.5.4. Main Results from the Pilot Implementation

This study examined the fundamental factors that influence individuals' motivation and intention with regards to energy consumption. Based on the available survey data presented in Table 19, it is evident that while the overall tendency to conserve energy exhibited relative stability, there were fluctuations in the inclination to engage in energy-saving behaviours, ultimately leading to an upward trend from survey 1 to survey 4. The data suggests that while participants' self-assessed energy consciousness saw a minor increase from survey 2 to survey 4, their intention for electricity saving and PV energy use remained relatively consistent. Interestingly, despite a stable intention to save electricity, there was an observable behaviour of participants turning on additional electrical appliances in both waves – apparently to increase /maintain the level of self-consumption. This is due to the fact that households that generate an excess of electricity beyond their own consumption may face specific repercussions most notably the potential loss of their self-consumption status. Therefore, we assume that this is potentially linked to the regulations around PV or overly dimensioned PV systems, as the data also reveals a slight decrease in the inclination to shut down the PV plant from wave 2 to wave 4. The NUDGE 2 was implemented in order to enhance participants' awareness of their consumption and production balance. The hypothesis argues that this particular intervention played a role in the observed decline in intention during wave 3.

Table 19. Analysis of Intention and Behaviour in Response to PV Regulation (Wave 2 vs. Wave 4).

Aspect	Wave 2 (n = 54)	Wave 4 (n = 80)
Self-assessed energy consciousness	7.24 (1.32) Min, Max: 5, 9	7.34 (1.25) Min, Max: 4, 9
Intention for electricity saving	3.56 (1.08) Min, Max: 1, 5	3.60 (0.99) Min, Max: 1, 5
Intention for PV energy use (self-consumption)	3.83 (1.10) Min, Max: 1, 5	3.85 (0.98) Min, Max: 1, 5
Increased self-consumption due to PV regulation	M (SD): 0.53 (0.94) "I am not sure": 6%	M (SD): 0.38 (0.97) "I am not sure": 2%
Turning on additional electrical appliances	Yes: 61% No: 26% Other: 13%	Yes: 63% No: 23% Other: 15%
Shutting down the PV plant	Yes: 44% No: 41% Other: 15%	Yes: 43% No: 50% Other: 8%

Delving further into the study, the sensor data offers a more detailed perspective on the dynamics of energy consumption.

1. *Non participating households*

Figure 71 illustrates the number of participating households and their data contributions over time became increasingly evident. Although initial delays in hardware installation hindered the anticipated commencement of the Croatian pilot, it became obvious that even when the program was fully operational, some pilot households did not provide data, due to the technical challenges or lack of internet connection. Specifically, the second group showcased noticeable growth only during the summer months.

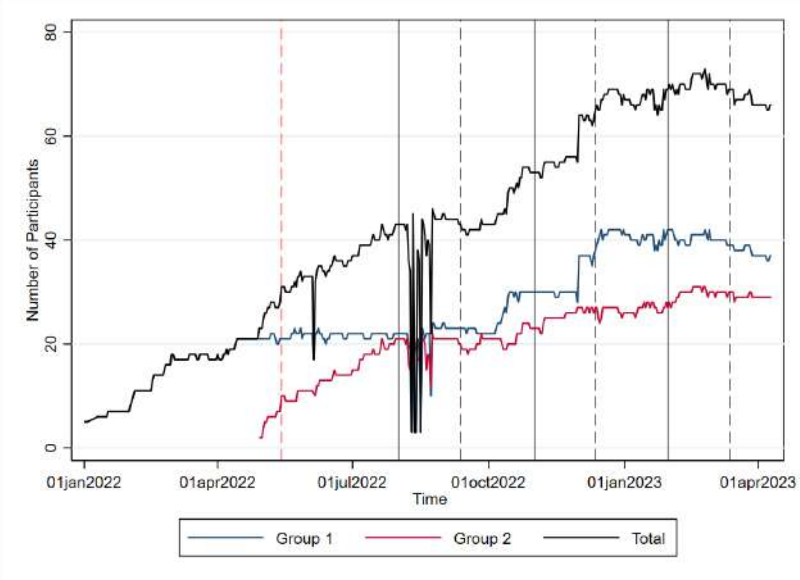


Figure 71. Number of participants based on transmitted data by group over time.

2. *Energy consumption behaviour, especially towards autarky and self-consumption*

Figure 72 brings to the forefront the energy consumption behaviours in terms of autarky rate and mean hourly self-consumption. Initial observations from this graph suggest that during the incipient phase, the two groups showcased a semblance in consumption trends. However, external factors, such as weather changes, induced short-term volatilities in consumption patterns.

Moreover, Figure 72 paints a detailed picture of households' energy utilisation strategies throughout different periods of the year. It is noticed that there is a broad spectrum in energy behaviour. Some households in the Croatian pilot exhibited near-complete energy autonomy for substantial periods, while others showcased a propensity to under-utilise their energy potential.

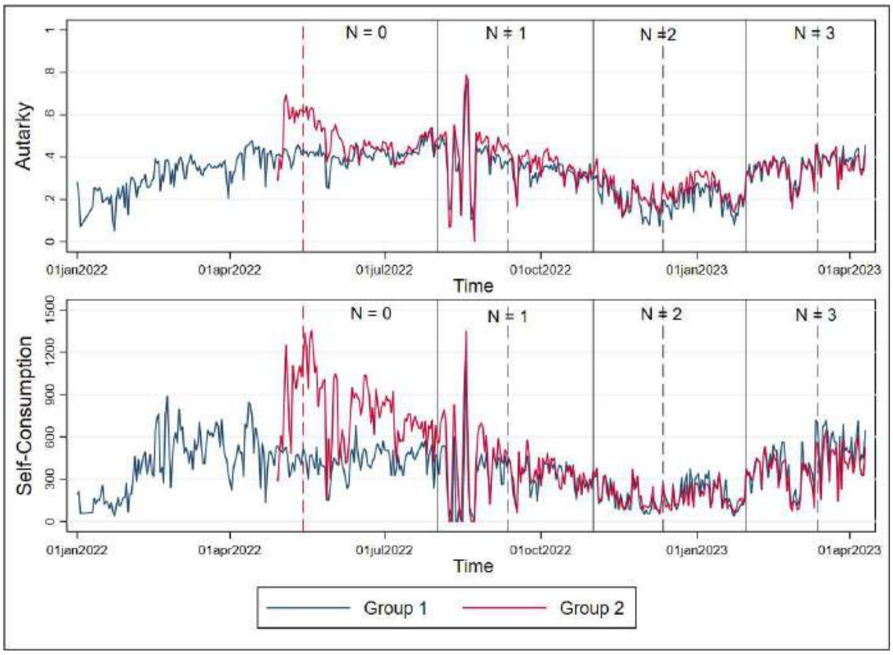


Figure 72. Indicators of self-consumption by group over time.

Additionally, it is important to examine the excess energy feed-in back into the grid (Figure 73). This surplus represents potential energy that can be shared, potentially providing an extra incentive for end users, especially once regulatory frameworks permit such sharing.

There is also a need to focus more on how households efficiently use energy, considering both its efficiency, economic and social aspects. This approach could lead to a more comprehensive understanding of energy dynamics in households with photovoltaic systems.

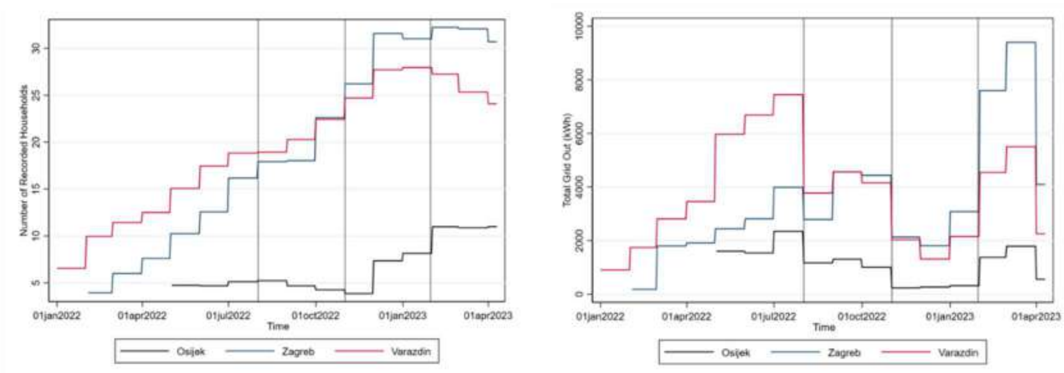


Figure 73. (Left) Number of Households Sending Data; (Right) Total Energy Returned to Grid.

In conclusion, the combination of sensor data from the Figure 72 and 73 and survey data from Table 20 provides a good understanding of the dynamics of energy consumption in the Croatian pilot study. A complex picture of different energy behaviour can be seen in the sensor data, as a result both individual intentions and larger trends. It emphasises that household energy use is heavily influenced by outside interventions, legislative frameworks, and even technical factors.

A more thorough analysis of participant actions was conducted in order to clarify the dynamics of energy consumption patterns. Although overall trends are insightful, smaller-scale behaviours at the household level frequently reveal the specifics of energy consumption choices. This analysis at the household level provides a window into how general policies and interventions affect decisions made on a daily basis.

Table 20. Users profiles.

User	Installed power	No. persons living in the household	Additional consumption appliances	Status
2	7,5 kW	2	EV	Temporary Shutdown of the PV
14	4 kW	5	N/A	Temporary Shutdown of the PV
19	3,6 kW	4	Solar collectors	Increase Consumption until Year-end
38	3,8 kW	2	Heat pump	Decrease in Consumption
40	7,5 kW	7	Solar collectors	Decrease in Consumption
43	7 kW	5	Electric heaters	Increase Consumption until Year-end
46	5 kW	2	EV	Reverted to their original consumption patterns
48	9,6 kW	4	Electrical hot water boiler, swimming pool heating system	Reverted to their original consumption patterns

Temporary Shutdown of the PV Plant until Year-end

One notable action that was observed in the operation of the PV plant was the temporary cessation of its activities, as evidenced by the behaviour of participants 2 and 14. Although production was halted by both parties, the sensor data from participant 2 indicates a noticeable rise in energy consumption, potentially indicating an attempt to offset the effects of the production stoppage. The change in behaviour may be linked to their choice to switch from a gas boiler to its electric equivalent. On the other hand, it can be observed that participant 14 predominantly employed the strategy of decreased production, exhibiting minimal modifications in consumption behaviours. Significantly, participant 14 experienced a change in status in the year 2023, which may provide additional insight, resp. explanation into this particular strategy.

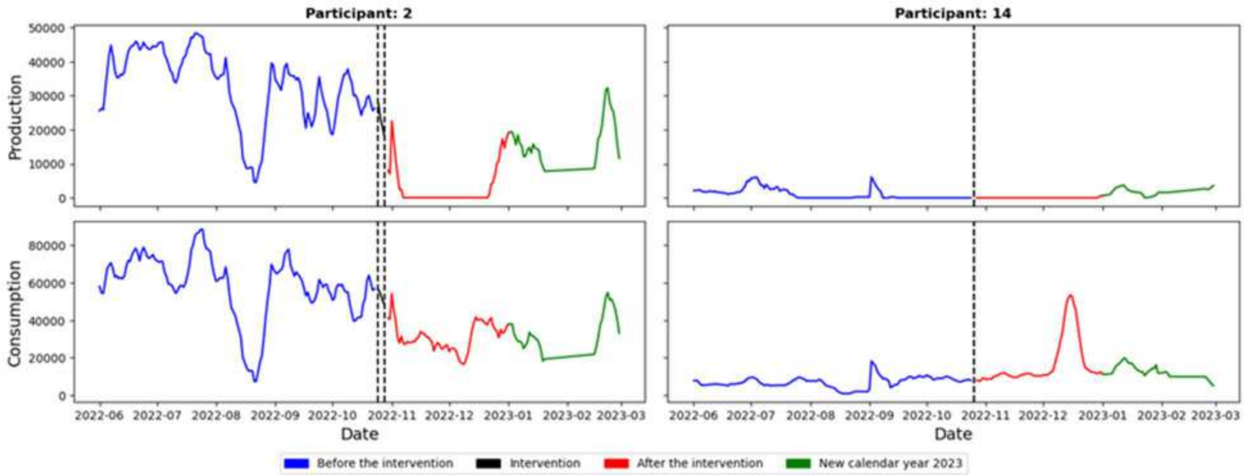


Figure 74. Production and consumption patterns for the user IDs 2 and 14.

Increase Consumption until Year-end

Participants 19 and 43's data show an increase in energy consumption, which is clearly different from the previous group. Intriguingly, the timeline implies that the NUDGE 2 may have had an impact on their actions. This steep increase in consumption started as soon as people were exposed to the nudge and then fell back to pre-intervention levels as the year progressed. Both participants confirmed the use of additional appliances, which was consistent with their behaviour, and were adamantly opposed to the idea of conserving electricity, as shown by the survey. The conflicting interests between the project's goals and the incentives created by regulations can be seen as the cause of this response.

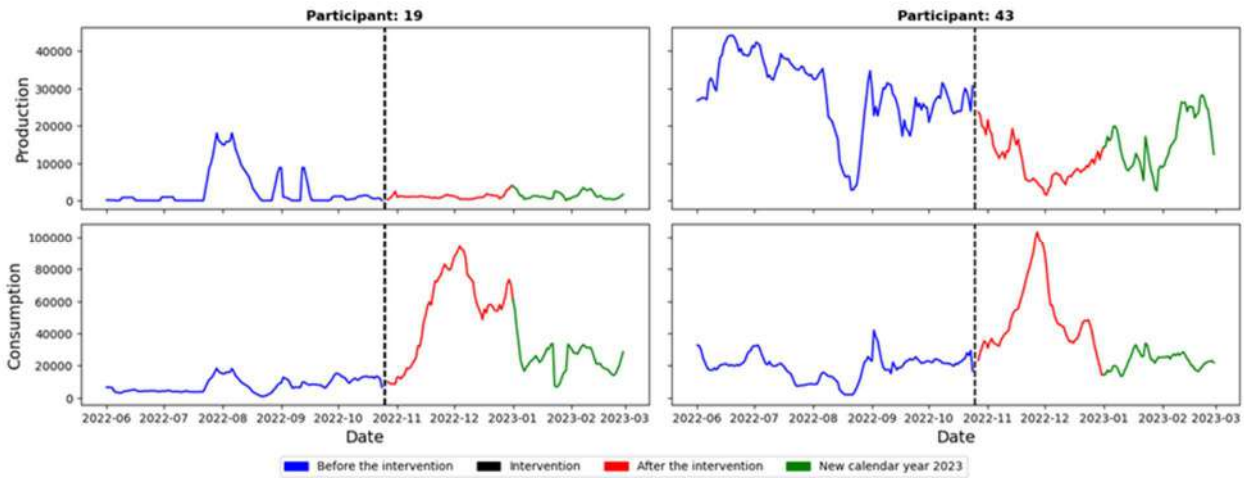


Figure 75. Production and consumption patterns for the users 19 and 43.

Decrease in Consumption Patterns

Another fascinating insight is the decision of some households to scale back on consumption. While participants 40 and 38 continued with their reduced energy use past the year-end, participants 46 and 48 reverted to their original consumption patterns.

The consistency showcased by the first group (participants 40 and 38) seems to be grounded in their high energy-awareness and intrinsic satisfaction derived from energy saving. Their behaviours resonated with their survey responses, underscoring the intent to conserve electricity and amplify self-production. The latter group (participants 46 and 48), which briefly showed signs of conservation, was more motivated by a desire to save money than by an awareness of the environment.

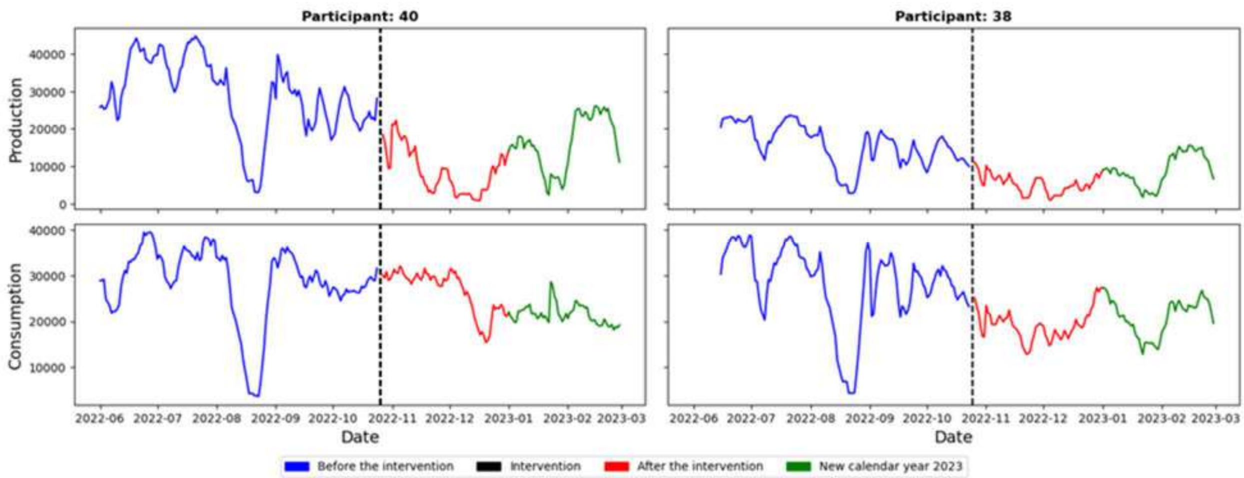


Figure 76. Production and consumption patterns for the users 40 and 38.

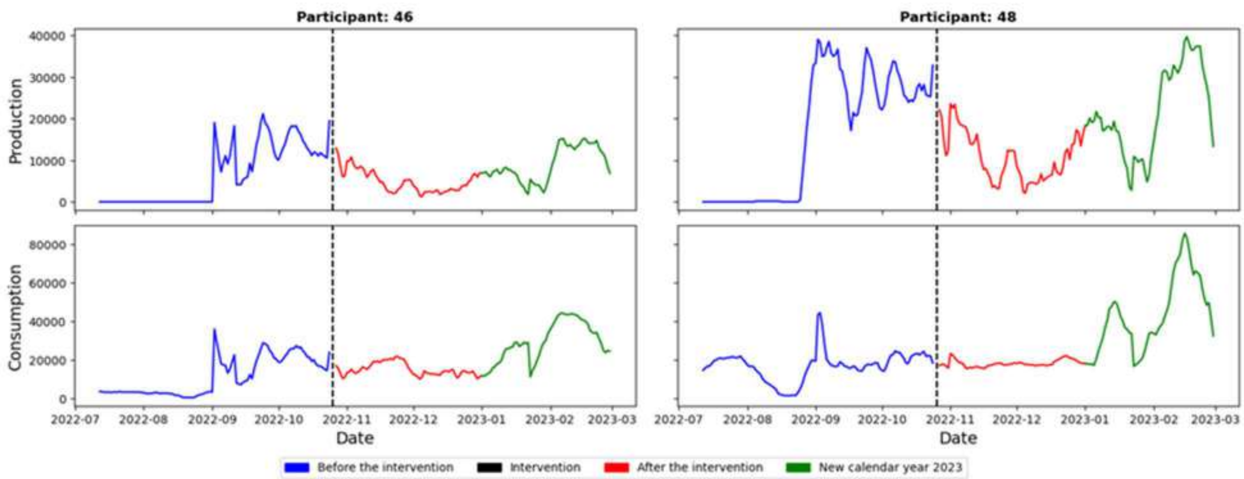


Figure 77. Production and consumption patterns for the users 46 and 48.

Absence of Reaction

It was difficult to determine the motivations and the success of the nudge for other participants' because their consumption patterns showed barely detectable changes. Their middle-of-the-road response in the survey supports their neutrality towards the policy or nudge. This group did not agree or disagree with feelings of guilt over energy waste or viewpoints on energy conservation. Even when asked about their carbon footprints, they were ambivalent. These observations are important for comprehending the

different levels of nudge efficacy in different consumer groups even though they do not directly support any particular hypothesis.
Additionally, it is noteworthy that 46% of people in survey wave 4 reported that they avoided the status switch because their PV plants were correctly dimensioned, which is a relevant figure in this context.

Nevertheless, it is important to note a disclaimer: discerning clear patterns is often challenging because it is difficult to determine with certainty where issues with data or highly volatile curves exist. This uncertainty led to the presentation of specific case studies.

2.5.5. Concluding Remarks on Pilot Outcomes

The Croatian pilot study on household energy consumption with photovoltaic (PV) systems provides an insightful analysis into the intricate dynamics of energy use. It uncovers a complex relationship between households' intentions to conserve energy and their actual consumption patterns. Despite aspirations to utilise PV energy efficiently, actual behaviours varied significantly, highlighting the difficulty in consistently translating intentions into actions.
A critical finding is that regulatory frameworks and the sizing of PV systems shape household energy behaviours. Households are seen adapting their energy use in response to these external factors, leading to unexpected behaviours like increased electricity usage during high production periods or even shutting down PV systems. This adaptation underscores the intricate interplay between regulations, system capabilities, and user behaviour.
The study also emphasises the varied effectiveness of behavioural interventions, such as nudges, in promoting energy-efficient behaviours across different households. This variation points to the need for more personalised energy management strategies that can adapt to changing circumstances, like the integration of more efficient appliances, increasing PV capacity or new services on the market.
Providing high-resolution energy data has notably increased users' awareness and understanding of their consumption patterns. However, being active in the electricity market, these users face a continuously evolving landscape of regulations and billing models. This situation necessitates adaptable behaviour, often driven by economic or other benefits. The lack of smart meters providing real-time data highlights a gap that energy companies, together with national support and strategies, could fill by offering all users access to their real time energy data. Such metering devices and data access would not only enhance energy efficiency tracking but also promote the use and sharing of locally produced energy, contributing to a more sustainable community.
The following table encapsulates the results of our study, directly addressing the research questions posed in sub-chapter 2.5.1.

Table 21. Summary of key findings and insights in response to research questions.

Research question	Key findings and insights
1. Influence of empathetic nudges on awareness and attitudes towards energy consumption	The study found that empathetic nudges moderately increased awareness about energy consumption and its impact on climate change.

	However, the influence on attitudes varied, indicating the need for more personalised approaches.
2. Effectiveness of feedback and awareness nudges in adjusting energy consumption	Feedback and awareness nudges were effective in some cases, especially when combined with real-time data and weather conditions. However, the effectiveness was inconsistent across different households.
3. Impact of goal-setting nudges on sustained energy efficiency improvements	Goal-setting nudges led to some improvements in energy efficiency. However, there was a disparity between participants' goal-setting and actual energy savings, suggesting a gap between intentions and actions.
4. Collective contribution of diverse nudge strategies	The diverse nudge strategies collectively contributed to fostering energy-conscious behaviour to some extent. Yet, the study highlighted the need for more adaptive and personalised strategies.
5. Impact of changing energy regulations in Croatia	Changes in energy regulations significantly influenced participants' decisions, particularly the transitions between billing models. Participants showed adaptability but also faced challenges in understanding and complying with these changes.
6. Challenges in adapting to evolving energy regulations	Participants encountered significant challenges in adapting to new regulations. The study suggests that nudges could be effectively used to address these challenges, promoting compliance and optimising energy utilization.
7. Influence of understanding billing models on energy-saving behaviours	A deeper understanding of billing models was crucial in influencing participants' energy-saving behaviours. Educational nudges could enhance comprehension and decision-making in this context.
8. Influence of billing models on investment in PV systems	Participants' experiences with billing models affected their willingness to invest in PV systems. Tailoring goal-setting nudges to align with their financial goals within the regulatory framework was seen as beneficial.

The outcomes of this study highlight the paradox created by the two models that were operational from 2021-2023, which led to inefficient consumer behaviour affecting both grid management and energy efficiency. Now that these models have been revised, one of the critical issues identified by the study has been addressed.

The study's results are instrumental in showing how access to data enhances awareness. This supports a strong case for granting all citizens access to their real-time energy data, enabling them to become more conscious of their consumption habits. It's also important to recognise that as regulations continue to evolve, there is still a need to either nudge or monitor user behaviour in order to boost energy efficiency and prevent increased consumption due to local energy availability. Additionally, with the rise in PV installations and greater capacities, households can use their surplus energy to supply renewable power to neighbours without PV systems or even engage in financial models that could benefit economically vulnerable households.

Overall Conclusion

The NUDGE project, through the implementation of five concurrent pilots conducted in Greece, Belgium, Germany, Portugal and Croatia, provides insights into the potential of nudging interventions to promote energy efficient behaviours in residential buildings. During the project execution a total of 472 households were engaged through direct contact as part of the pilot trial's implementation plans. This report outlines the specific aims and circumstances of the five pilots of the NUDGE project, while summarising the main results drawing on all available data set from the NUDGE project (including sensor, survey, app data and nudge impact data).

Some of the main objectives of the pilots were successfully achieved, i.e., to collect high resolution information (i) on energy use at residential buildings using smart meters, (ii) on behaviours of consumers through online questionnaires and (iii) on the use of interface tools (platforms and smartphone applications) for delivering relevant information and interventions (i.e., nudges) to users. Importantly, the implementation of the trials allowed to generate real-life datasets on energy use (and PV production, where applicable) for more than one year for the engaged households. In addition, some of the datasets collected included complementary contextual data (e.g., weather data, household characteristics) that broaden their usefulness (to better characterise and understand residential energy demand). In line with the main goal of the NUDGE project, most of the nudging interventions that were tested focused on using the real-time energy data collected with the aim of empowering the households with relevant information that they can use to comprehensively understand their consumption patterns and to identify opportunities for improvement.

The investigation of the effectiveness of the nudging interventions resulted in some evidence of effectiveness of nudges in improving energy efficient behaviours in specific settings (and in some situations for specific subgroups (results more comprehensively reported in deliverable D2.3. We cannot exclude the possibility that the presented outcomes showing notorious inconsistent evidence across the different settings can be associated with an important degree of uncertainty caused by experienced challenges related to important external events and real-world specificities of the study designs. Notably, the COVID-19 pandemic affected the ability of frontline workers of all pilots to engage participants and to schedule visits for energy meter installations with some pilot participants joining in a later stage of the pre-intervention phase. Also, the pre-intervention phase took place in a period that covered times in which obligatory isolations and great incentives to working remotely were practised in some countries (with potential impact on the quality/representativeness of baseline data). Further, participant behaviour during nudging periods could also be exacerbated by the impacts of Russia's invasion of Ukraine on global energy prices. Regarding the study design, the sample size employed, and the limited duration of the nudging intervention implementation (1 to 3 months) and the limited duration of the respective monitoring period are very likely to affect the robustness of the reported results.

The results also suggest that nudging cannot be used as a one-size-fits-all measure and probably should not stand alone. For instance, moving forward, there are still interesting questions that remain to be explored, namely:

(i) on the representativeness of findings for a larger sample size covering high number of clusters (and associated representative buildings/households) to ensure an advanced accuracy and representation of the residential building stock as a whole;

(ii) on the potential of employing nudging strategies hand in hand with financial support programmes and policies to enable and encourage energy efficiency improvements;

(iii) on effectiveness of an optimised nudge design considering the implementation of more automated nudging solutions involving less manual interaction (since low shares of app usage/nudge exposure was noticed in the NUDGE project) and/or the derivation of more personalised nudges (that could improve engagement based on feedback collected from participants in the surveys).

Also, the multiple and comprehensive datasets produced from the pilot studies conducted in the NUDGE project are suitable for several applications beyond their original project objectives and will be further explored and disseminated.

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