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PROMOTING HEALTHY HOMES AND LONG-LASTING ENERGY EFFICIENT BEHAVIOUR AMONG FAMILIES WITH CHILDREN IN PORTUGAL: PRELIMINARY DATA FROM NUDGE PROJECT

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Abstract
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 5 trials in different countries, with a striking diversity in terms of energy usage scenarios. This work intends to present the preliminary data obtained from the pilot study that has been implemented in Portugal, which aims to promote long-term energy savings while providing healthy and comfortable homes for 101 families with children (<12 years old). In the pre-intervention phase, two tools – a building survey checklist and a questionnaire – were developed and implemented to collect harmonised data on building-specific characteristics and on participants' socioeconomic status and behaviour. Data from energy bills (January-June 2022) were also analysed for preliminarily assessing electricity and gas consumption and related costs. Briefly, findings allowed for deriving the following main hypotheses: i) strategies aiming at informing families about their overall and disaggregated (specific equipment) energy use motivate important energy-efficient behavioural changes; ii) the use of Internet of Things (IoT) systems for monitoring environmental parameters and triggering warnings to the occupants (e.g., when it is necessary to open windows due to high levels of CO_2) promote healthier behaviours; and iii) heating season, when significantly higher energy consumption and costs are observed, is a particularly opportune time for providing guidance to families to achieve energy-efficient and improved thermal comfort conditions. Based on these results, the homes were equipped with energy meters (overall and disaggregated consumption) and indoor air quality (IAQ) sensors (temperature, relative humidity, CO_2, and particles). Three sequential nudging interventions are being delivered to end users through a smartphone app by presenting informative data and/or recommending different actions to optimise energy use, also taking into consideration IAQ and comfort.

1. INTRODUCTION
Promoting energy efficiency and decarbonising the residential building sector – that accounts for 17% of total direct and indirect energy related carbon dioxide (CO_2) emissions – is a pressing issue due to its contribution in overall energy use [1], [2]. The multiple benefits approach to energy efficiency policy seeks to expand the perspective of energy efficiency beyond the traditional measures of reduced energy demand and lower greenhouse gas (GHG) emissions by identifying and measuring its impacts across many different spheres [3]. Helping homeowners improve energy efficiency in their homes can be an effective strategy to reduce energy demand, save money, improve comfort and reduce GHG emissions [4] but other benefits can be explored. In Portugal,

energy poverty constitutes a significant concern due to the negative impact it has on the living conditions and on the health of the most vulnerable population groups, especially considering prevailing inadequate levels of energy services in households [5]. For instance, 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% [6]. Moreover, if we focus on the homes of families with children, the results from the Healthy Homes Barometer 2019 showed that, based on four primary indicators for assessing living conditions – dampness, darkness, cold and excess noise – Portugal was the worst of the 28 EU countries with a rate of one in two children living in an unhealthy home [7], [8]. In the last decade, research conducted in Portugal provided evidence on the existence of inadequate environmental conditions in homes, with levels of air quality indicators that do not comply with national and/or World Health Organization (WHO) guidelines [9], [10]. In particular, the existence of insufficient ventilation rates, as estimated based on CO_2 levels, and levels of air pollutants exceeding the national and/or WHO limit values, namely for particulate matter ($PM_{2.5}$ and PM_{10}) have been reported consistently across studies.

Overall, existing evidence at national level suggests that it is of utmost importance to implement effective measures that target both energy efficiency and non-energy benefits, such as poverty alleviation, reduced thermal stress, improved air quality, health and wellbeing. This study aims to comprehensively characterise a sample of 101 Portuguese families with children to identify evidence-based opportunities for designing actions and interventions that promote both long-term energy efficiency and health-promoting behavioural change related to IAQ.

2. THE NUDGE PROJECT

The project NUDGE – NUDging consumers towards enerGy Efficiency through behavioral science – includes a comprehensive applied methodology focusing on testing the potential of behavioural-science inspired energy efficiency interventions with real users and quantify the respective energy-efficient behaviour change by the implementation of 5 pilot trials in different European countries:

- Efficient control of heating and DHW preparation for Natural Gas consuming boilers in Greece;
- Interdisciplinary project-based education on home energy consumption for children in Belgium;
- Optimization of EV charging with self-produced PV power in Germany;
- Promoting distributed self-production for local Energy communities in Croatia;
- Healthy homes for long-lasting energy efficiency behaviour in Portugal (PT).

The five pilots offer high heterogeneity and differentiate with each other with respect to contextual factors of the pilot participants (country, age groups, income), energy use scenario (household heating, EV charging, PV production), technology/platform used as mediator for operationalizing the interventions (e.g., mobile app, web portal) and to the means of measuring and communicating (e.g., human interaction, short notifications by a feedback system). At the same time the pilots share the use of energy monitoring and management tools (energy consumption and production where applicable) and of digital user interfaces (enabling the interaction with end consumers and the operationalization of the planned interventions), suited to the pilot-specific needs. In addition, the execution of all five pilots in NUDGE follows 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 consists of the implementation of 3 sequential interventions ($1^{st}/2^{nd}/3^{rd}$ intervention phases, called also of NUDGE 1, NUDGE 2 and NUDGE 3) that are delivered to the users through the pilot-specific interface tools (apps, webportal). This work will be focused on presenting preliminary data for the PT pilot.

3. THE PORTUGUESE PILOT – AIM AND METHODS

The pilot study organised in Portugal aims to promote long-term energy savings in building energy use while providing healthy and comfortable homes for families with young children.

The works for recruitment started on July 2021 targeting participants who meet all 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; and iv) do not plan to move to a new home in the next 12 months. The recruitment activities resulted in 101 eligible participants that provided consent to participate in the study, who have been contacted for scheduling the visits for interview and building survey and smart electricity meters' installation works. Participants were also invited to send in a regular basis energy bills (electricity and natural gas, if applicable). For continuously measuring electricity consumption during the project execution, Shelly 3EM devices were installed in the domestic electrical switchboard. Because most of the participant homes have a single-phase electrical switchboard, the device was configured to measure three separate points of a mono-phase electrical system: the total consumption and two specific pieces of equipment or groups of equipment (the ones that are of more concern for the participants). For the homes with 3-phase electrical switchboard (n=11; 11%), the device was used to measure each of the 3 phases of the installation in order to allow the calculation of the total electricity used. In households with PV (n=6; 6%), an additional device (Shelly EM) was selected to be used for measuring the produced electricity. The home visits for shelly devices installation and collection of relevant data on the households' characteristics were conducted from July 2021 to April 2022. Because the aim of the PT pilot is to optimize the energy efficiency and, at the same time, ensure healthy environmental conditions in participating households, sensors for measuring indicators of indoor environmental quality (IEQ) in the homes should also be installed in the participating households. Because the solutions currently commercially available are expensive and are not yet well established, an innovative low-cost Internet of Things (IoT) IEQ multi-sensor architecture was developed and

validated by comparison with reference methodologies. The basic requirements established for the multi-sensor module were the following: i) allow for obtaining continuous (per min) and concurrent monitoring of thermal comfort indicators (temperature, relative humidity), ventilation rates (CO_2), and air pollution indicators (particulate matter (differentiated measurement of $PM_{2.5}$ and PM_{10})); ii) be composed of highly accurate IAQ sensors able to monitor multiple points in real-time over long periods (at least 12 months); iii) be as compact as possible, silent, easy to install and with low power demands; and iv) transmit data through the participant home Wi-Fi network to a secure server at INEGI connected to the NUDGE central platform. From the 101 participants, 84 agreed to receive a second visit for installing IEQ sensors (works conducted from September to December 2022).

Nudging interventions are being delivered to end users through an application for smartphone that was specifically developed for the pilot, by presenting informative data and/or recommending different actions to optimise energy use, also taking into consideration IEQ.

3.1. PRELIMINARY RESULTS FROM THE PRE-INTERVENTION PHASE

Since the intervention plan and the analysis of data from the PT study is currently ongoing, this section will present some preliminary data obtained for the pre-intervention phase for characterizing participant families and their homes [11], and briefly describe the interventions (nudges) that are being considered in the intervention plan.

More than half of the participant families lived in buildings constructed between 1980 and 2010 (66%), with about 16% living in buildings older than 1980, and 18% in buildings completed after 2010. The average area of the dwellings was 171.0 m^2, and the density of occupancy (person/m^2) varied from 0.01 to 0.06. The number of children (< 17 years old) per family ranged from 1 to 4 (mean: 2). Forty-two percent of the surveyed homes were equipped with a central heating system. Among the participants in this study who use thermostats to control indoor temperature, the reported temperature set points varied from 18 to 25°C during the heating season, with seven participants reporting their thermostats set at target temperatures above 21°C. The electric space heating appliances used by participants included portable electric heaters (32%), air conditioners (26%), space radiators (13%) and radiant/heated floors (4%). Some of the houses uses combustion devices such as modern closed fireplace (28%), portable gas heater (15%), open fireplace (7%) and heating stove (4%).

The data collected from the energy bills of the study participants showed that there is a significant seasonal influence on both electricity and gas consumption (electricity: U=1235.0, z=-2.589, p=0.009; gas: U=298.0, z=-3.474, p<0.001), suggesting that the heating season may be a particularly opportune time to promote energy-efficient practices. In agreement with existing findings from other European studies [12], [13], families living in single-family houses presented significantly higher levels of electricity consumption than those living in apartments. Nevertheless, in turn, no significant association was found between electricity or gas consumption and the number of occupants. Interestingly, the number of windows facing north was significantly linked to greater electricity and gas consumptions (r_s=0.296, p =0.012; r_s=0.349, p =0.024). This is likely due to increased heating needs resulting from cold winter winds generally coming from the north alongside with typical low solar gains. Additionally, homes with openable windows facing north had also a higher prevalence of signs of dampness. In fact, 39% of the surveyed homes showed signs of damage caused by moisture, such as dampness and mould, on their internal surfaces. This prevalence is higher compared to other studies [14].

This study found that 73% of families reported to using air fresheners and/or other fragranced products, such as incense and aromatic candles, and 88% reported using cleaning products such as bleach or detergent with bleach about 1.8 times per week. This percentage is higher than the observed in similar recent studies [9], [15]. There is evidence showing that the exposure to fragranced products, is linked to risk of development of a wide range of health problems, including respiratory constraints, mucosal symptoms, headaches, dermatological effects, asthma attacks and neurological problems [16]. It is important though to recommend ventilating during and after the pollutant emitting procedures, such as cleaning and activities that use declared pollution sources (e.g., painting, other events using varnishes/paints/fragranced products), to remove chemicals and promote healthy indoor air in homes. In this study, the morning period from 7 to 10 a.m. was the preferred time of day to open windows, which coincides with the typical morning periods of high traffic, during which the outdoor levels of pollutants such as particulate matter and nitrogen dioxide (NO_2) can be particularly high. In fact, ventilation practices can be optimized on a case-by-case basis. These practices may include recommendation to open windows that are sheltered from external pollution sources, taking into account the local wind patterns, and to open windows during periods when the pollution sources are less active (e.g., avoiding rush hour traffic). In addition, for regions with temperate climates, such as Porto, the use of natural ventilation can meet most thermal comfort requirements for a significant portion of the year. Thus, promoting practices of opening windows in the periods of higher or lower ambient temperatures are expected in cold and warm seasons, respectively, might have a three-fold beneficial effect: promoting air quality, thermal comfort, and energy savings (by reducing heating/cooling needs).

3.2. INTERVENTION PLAN AND NUDGES

The Portuguese participants were randomly assigned to 2 different groups (A and B) to implement the crossover study considering the implementation of 3 sequential nudges. The nudges considered in the PT pilot were the following:

- NUDGE 1 – The energy conservation nudges decrease electricity consumption in households.

This nudge allows users to comprehensively monitor their electricity consumption at home. This will include the introduction of new features in the App for presenting:

i) dashboards showing electricity consumption evolution at different timeframes (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; these specific equipment are defined only for the homes with single-phase electrical switchboard (about 90% of the participant households), in where, one clamp has been used for measuring total consumption of the house, and the two available clamps of shelly 3 EM devices have been used to monitor consumption of 2 equipment (or groups of equipment) for which the participants reported to be interested to have information on the respective energy consumption.

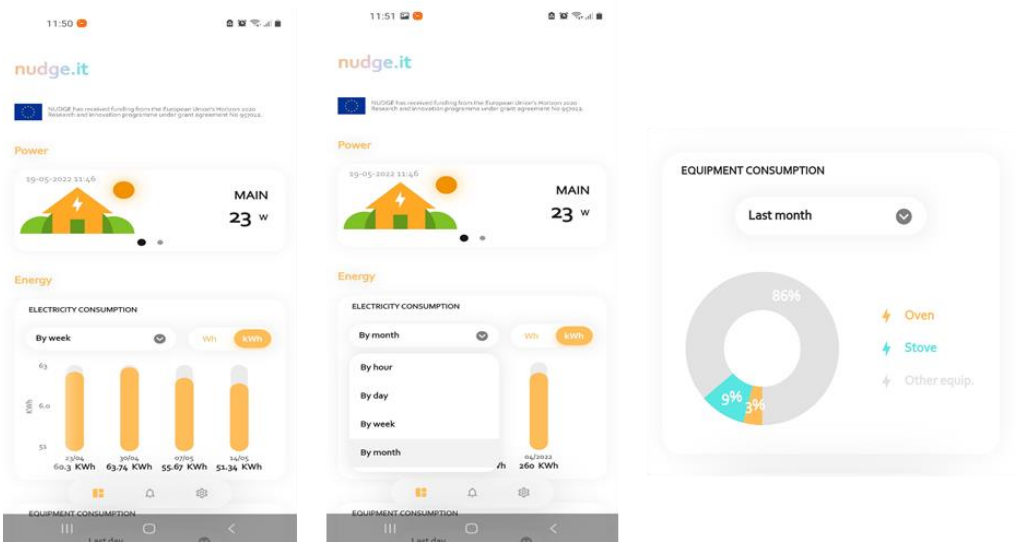

Figure 1. Example of App screens introduced in NUDGE 1 for the PT pilot.

- NUDGE 2 – The energy conservation nudges can positively impact indoor environmental quality (IEQ).

The nudging treatment will be focused on recommending ventilation for promoting IEQ taking into consideration energy efficiency, namely through:

i) introduction of a new screen that visualizes the levels of IEQ parameters (CO_2 and particulate matter ($PM_{2.5}$ and PM_{10}), temperature and relative humidity) over different intervals (day, week, month, year), with the indication of the exposure limit for each pollutant assessed. A qualitative indicator using a coloured grade allow to the participant 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);

ii) push notifications when concentrations exceed healthy thresholds continuously during 1hour (e.g., if levels of CO_2 are higher than the recommended limit, the app will produce a prompt requesting the user for opening the windows in the period when the indoor thermal comfort is more prone to benefit of the effect of outdoor environment);

iii) notifications for instigating empathy and providing information on impact of unhealthy IEQ, especially on children's health.

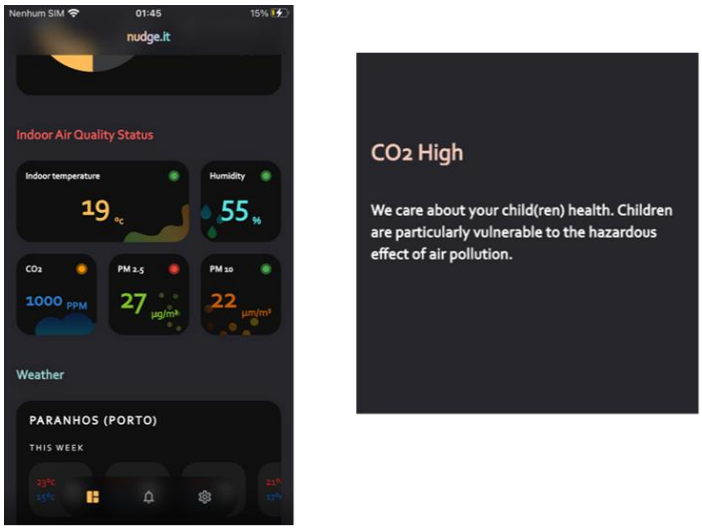

Figure 2. Example of App screens showing some features of the NUDGE 2.

- NUDGE 3 – The energy conservation nudges based on adjustments to heating appliances can reduce electricity consumption.

This nudge was implemented in the heating season 2022/2023. The features incorporated into the App intend to recommend actions for optimizing 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 presentation of 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, and they will be requested 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 spaces heating. A push notification will be also sent when outdoor temperature is >2°C than indoor temperature for recommending to turn off the heating systems and opening the windows in order to use outdoor air as a thermal carrier.

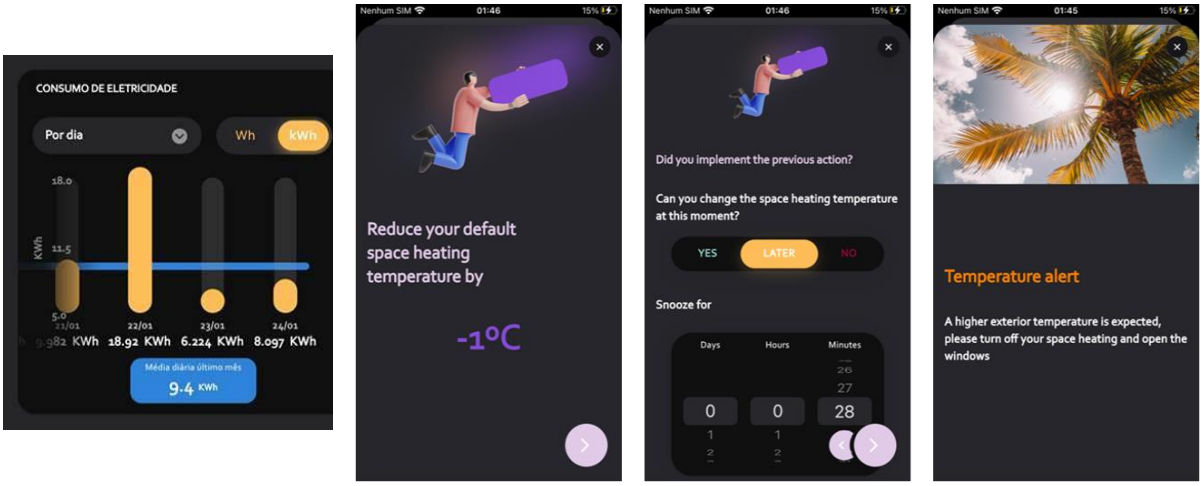

Figure 3. Example of App screens showing some features of the NUDGE 3.

4. CONCLUSIONS/FURTHER WORK

This study is part of a joint research project that combines the fields of health, energy and behavioural science to improve the quality of existing data on the Portuguese housing characteristics. Preliminary data allowed to characterize the participants of the NUDGE PT pilot and to derive the App features for the three nudging treatments that are being implemented in a randomized

crossover study. The information provided intends to empower participants while promoting awareness and increasing their level of literacy on the factors that may influence energy consumption and exposure to air pollution at home.

Energy consumption and IEQ sensor data, along with data gathered through the smartphone app (e.g., user interactions/visualisations, feedback, acceptance of recommendations) and questionnaire constitute the datasets that are being employed for evaluating the efficiency of the implemented nudges in promoting behaviour change of participating consumers focused on reducing energy consumption and improve IEQ.

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