ChArGED: Implementing a framework for improving energy efficiency in public buildings through IoT-enabled energy disaggregation and serious games

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***Abstract*— This paper reports on the approach for the design and development of the H2020 ChArGED project framework. ChArGED addresses energy wastage and proposes a framework that aims to facilitate achieving greater energy efficiency in public buildings. The framework leverages IoT-enabled low-cost devices, to improve energy disaggregation mechanisms that provide energy use and -consequently- wastage information at the device, area and end-user level. The identified wastages are concurrently targeted by a gamified application that feeds personalized real-time recommendations to each individual end-user. The ChArGED solution is being developed iteratively, with the end-users' engagement during the analysis, design and development phases in public buildings located in 3 different countries: Luxembourg (Musée National d'Histoire et d'Art), Spain (EcoUrbanBuilding, Institut Català d'Energia headquarters, Barcelona) and Greece (General Secretariat of the Municipality of Athens).**

Keywords*— *energy efficiency, gamification, public buildings

I. INTRODUCTION

ChArGED (CleAnweb Gamified Energy Disaggregation) develops a gamified framework that aims to change occupants' energy-consumption behaviors and reduce energy wastage in public buildings. By leveraging low-cost IoT devices (NFC/BLE), ChArGED will improve energy disaggregation mechanisms and identify energy wastages at the device, area and end-user level. At the same time, it will engage and motivate users with serious-game approach accessible through a mobile app. The gamified approach in ChArGED advances the state of the art, since it will be employed in public buildings, where multiple appliances are shared among multiple users. Energy disaggregation in this context is particularly challenging due to the vast area that needs to be monitored and the difficulty of associating particular actions to specific users. In addition, other related applications, e.g., Kill-Ur-Watts, Energy Tracker, Watts Plus, etc., mainly focus on increasing energy-consumption awareness, assuming that the users are already interested in their energy consumption and motivated to reduce it. In a public building, employees are primarily busy with their job activities and moreover they do not pay the energy bill. Therefore, their engagement to such a game app cannot be taken for granted and thus a carefully-designed gamified approach has to be followed. There have been some prior efforts to employ serious games for demand side management [1], [2] in public/office buildings. "Energy Chickens" [1] evaluated the effectiveness of a virtual pet game in reducing plug-loads in a mid-size commercial office. Changes in device-specific energy consumption were reflected in the relative "health" of chickens in a virtual farm. ChArGED app has far more ambitious goals than [1] in the sense that it aims to change a vast range of energy-wasting behaviors at work. Also, most efforts in [2] focus on boosting user awareness towards energy efficiency, as opposed to incentive building for that purpose in ChArGED. Additionally, there have been other research projects that target energy conservation through behavioral change with the use of serious games, such as those reported in [3-6], in homes and public buildings. In [3-6], the user in-game performance is linked to real-time energy consumption data collected from the respective building and user engagement is pursued mainly through user awareness and social media/networking tools. ChArGED employs a combination of direct incentives, peer pressure, life simulation (i.e., virtual tree) and game elements (e.g., badges, ranks, etc.) to maximize user engagement and achieve the desired behavior regarding energy-consumption reduction.

II. SYSTEM ARCHITECTURE

The ChArGED logical architecture (depicted on Fig. 1) consists of four main groups of functional blocks:

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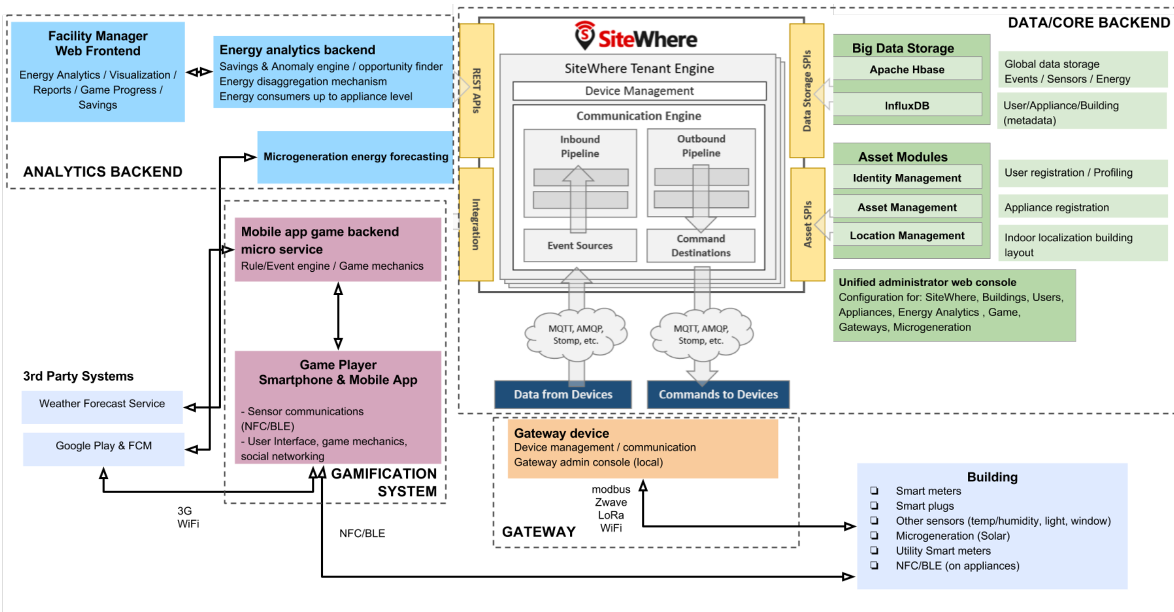

Fig. 1 The ChArGED Architecture

The Data/Core Back-end group is responsible for providing an environment in which data, assets and users are stored and managed. The Back-end components provide the software infrastructure on which the ChArGED app is developed. Even though that group of components is application agnostic, it is tuned towards the needs of the project. The Gateway group is responsible for integration of energy use and environmental data to the Back-end system, to determine variations over the energy context within the building. The Analytics Back-end component is responsible for delivering insights that will enable the ChArGED application to deliver custom and targeted feedback and incentives to the end-users. Finally, the Gamification group is responsible for processing field data and insights created from such data to make decisions as per the evolution of the game for each user, i.e., what the next step is towards more energy savings. That group also delivers the mobile app with the end-users that interact with the game and acts as the interface between the user and the ChArGED system, updating the user with the current game state and also providing information to the system about the users' behaviour towards pre-set energy saving goals. The architecture also includes an external system that is utilized to provide a solar-power microgeneration forecast based on weather predictions for the specific location of system deployment. It serves to maximize the energy savings of the building, to increase end-user awareness and to enable time shifting of electricity consumption towards periods of maximum solar-based electricity production, thus avoiding the need for batteries.

A. Data/Core Backend System

The Data/Core Back-end system components and infrastructure allow the overall platform to operate according to the requirements of the game challenges. SiteWhere [7] was chosen as the Data/Core Back-end system for our application, providing an open-source platform with a number of rules and mechanisms for data exchange and operations. SiteWhere's main functionality is to supply a server-based Java SPRING middleware between the sensing infrastructure and the different system components and to act as a controller for the processing of device data. It connects with NoSQL & Timeseries databases in order to provide persistence of the sensor data and scales effectively with a large number of devices so that the whole sensor data history is maintained and can be accessed at any point. It also provides the entity management mechanism in order to structure the devices and categorize them according to their type, location and ownership and offers full control on a device lifecycle (providing the functionalities of creating, deleting, updating, grouping, sending data). Moreover, it provides a web-based administrative console application that allows all of the system data to be viewed and manipulated in a structured way, which makes their overview and administration easier and more accessible.

SiteWhere provides an extensive list of third party frameworks and software tools with which it can be connected , so as to extend its capabilities. The options include different databases, identity management frameworks, event streamers, event processors, enterprise service buses and others. Moreover, being an open source software solution, new interfaces with other software tools and services can be created as needed. External communication with SiteWhere can be achieved via a built in extensive REST APIs. A communication interface utilizing the MQTT protocol is also implemented that can be used by devices and other embedded systems to send or get notified about new events and sensor data (e.g., NFC/BLE alerts and energy measurements).

B. Gateway

To achieve the data acquisition process the Sensor Gateway has two connection interfaces within the global architecture, one with the building sensors (e.g. Smart plugs and Smart Meters) and another with the SiteWhere Data/Core backend (Fig. 2). Various hardware and software requirements have to be fulfilled to support the needs of the platform. The Sensor Gateway software/middleware by Bosch Software Innovations is used as the basis of the Sensor Gateway. For the remote software management and provisioning of the product, the ProSyst Remote Manager (PRM) [8] is used.

The Raspberry Pi (version 3 Model B) was chosen as the hardware basis for the Sensor Gateway. The Raspberry Pi is installed with a standard Raspbian OS, including the Oracle Java SE Runtime Environment (Java8), the Communications Device Class Abstract Control Model (CDC_ACM) USB to serial driver and, as mentioned before, the ProSyst mBS SH Runtime for ChArGED.

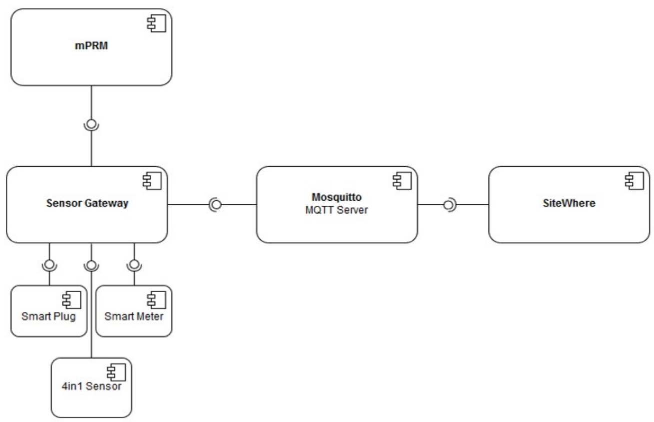

Fig. 2 Illustration of the Sensor Gateway Data Collection, Processing and Communication to Sitewhere

The data collection process required development of sensor drivers to retrieve data from third party sensors using industry leading communication protocols. For the connection of Z-Wave (Plus) devices, various controller options have been investigated, and two units have been selected: A "Razberry" GPIO Module for Raspberry Pi and a USB Z-Wave Controller.

Various Z-Wave devices were connected to the Sensor Gateway such as: (1) Fibaro Smart Plugs, (2) Fibaro 4in1 Sensor (Temperature, Humidity, Luminosity, Motion/Presence) and (3) Fibaro Contact sensors.

These devices are managed by the mBS SH Runtime and included into the product portfolio, which allows data to be immediately collected from the devices. The AcuRev 2000 multichannel Modbus meter by Accuenergy was also connected to the Sensor Gateway via the Modbus protocol, to collect detailed energy measurements at the three pilot sites. All connected devices communicate their data to the Sensor Gateway, which preprocesses and forwards it to the SiteWhere backend via MQTT.

C. Analytics Backend

The Wattics Analytics backend is interfaced with the Sitewhere backend via RESTful web services, which allow energy measurements, NFC swipe alerts and BLE location events to be received as input, and measurements of load demand reduction and energy savings as well as energy saving opportunities to be returned. Authenticated data streams are processed in real-time through parallel analytics engines to produce valuable insights for the application. The Wattics backend infrastructure is brought to the project as background IP, and has been adapted to the needs of the project with the following addtions:

- API endpoints to process NFC and BLE data packets.
- An analytics engine to validate that control actions have been taken by users (e.g. device switched off when going home or when away for more than N minutes), and to estimate the energy savings achieved by such actions. In addition, the new Analytics engine is able to diagnose inefficient operation of electrical devices based on concurrent power activity (e.g. A/C left on when window is open), and to estimate the energy wasted due to such actions.
- A notification mechanism to export insights generated to Sitewhere. In addition to these extentions to the Wattics backend, a micro service was developed to reside in between SiteWhere and the Wattics Analytics backend to enable seamless integration of both backend systems via Amazon SQS.

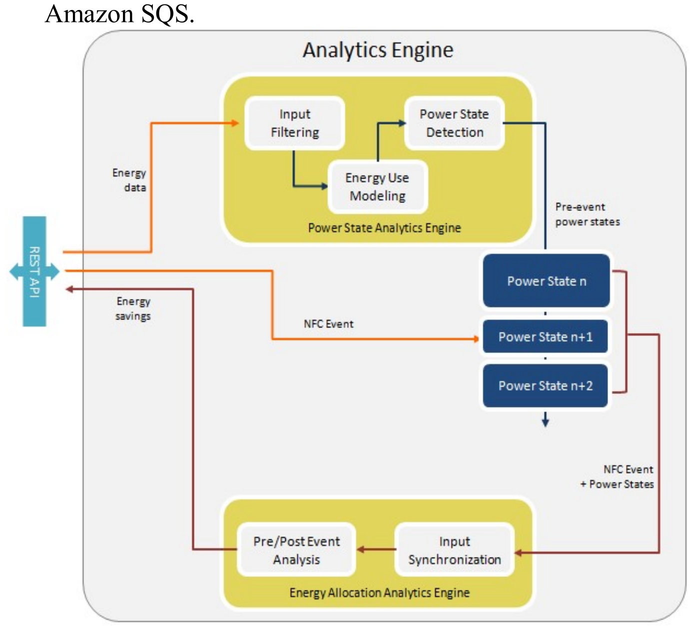

Fig. 3 Architecture of the analytics engine in charge of validating user control actions and estimating energy saving generated

The analytics component in charge of validating the control actions and estimating the savings generated has been implemented based on the architecture shown in Fig. 3.

The only commercially viable option, adopted within the project, is to submeter medium-level electrical circuits feeding groups of appliances and run analytics on the data collected to monitor power variations of specific electrical equipment fed from such circuits. The validation of a control action claimed by a user is achieved with circuit-level measurements taken by multi-channel meters, combined with metadata provided by the user NFC-swipe events and BLE beacon location sensors. The principle of such analytics is energy-use allocation, where energy savings are disaggregated from the power signal thanks to user-triggered notifications and allocated to users associated to the equipment being operated. The default interval for the measurement polling of the abovementioned IoT devices is 20 sec, but it can be reconfigured to reduce or increase the recorded data samples for the processing conducted in the Analytics Backend.

The Pre/Post Event Analysis is where the algorithms for control validation and estimation of energy savings happen. The disaggregation and energy allocation engine works as follows: (1) The core/backend platform informs the analytics engine that an appliance has been operated by the user as soon as it receives an NFC swipe alert from the user's mobile app, (2) the analytics software runs the NFC swipe alert against the power measurements of the circuit feeding the appliance operated by the user to detect significant power variations, (3) the analytics software analyses the power variations and informs the core/backend platform of the drop in energy use measured in relation to the user's operation of the appliance, as well as a quantification of the savings achieved by doing so and (4) the game backend calculates the points to be given to the user and the savings are stored within the platform database.

D. *Gamification Group*

The Game Backend implements the logic of the game rules that are employed, in order to decide the progress of a user in the game, update the user scores and leaderboard, and keep track of the currently accepted/available challenges of a user. It has been implemented in Java and communicates with SiteWhere via MQTT and REST. All the communication between the software components happens through SiteWhere. Whenever an event is sent to SiteWhere from a device (i.e., a measurement or an alert), the event is stored and forwarded to a predefined MQTT topic, which other interested software components are subscribed to. The Game Backend listens to events sent to SiteWhere that describe the users' behavior and actions (such as NFC swipes, user location updates and energy updates), processes the data and determines the user progress with respect to the challenges that have been accepted or schedules delayed or recurrent processing. The processing performed by the game backend is not necessarily tied with the specific arrival time of an alert. Separate logic can also be triggered or executed at a different time to check/update the game progress and provide updates to the other system components. Internally, the Game Backend consists of three different subcomponents (Fig. 4). The first one is responsible for interfacing with the rest of the system through MQTT and REST. This interface is used to receive/request and update data according to the results of the rules. The second sub component is the core engine that implements the game logic. It consists of a preprocessing component, which handles the incoming messages and accordingly selects the relevant rule out of a list of rules. These are the main parts of the game logic and game challenges or actions that should be performed. One such rule determines that at the end of the week the challenges, which have not been accomplished, should be identified and released if they have been assigned to any user. The third subcomponent is the scheduler. Its main use is to schedule rules that should be scheduled for the future or executed at specific time intervals (i.e., every day, every week, etc). New rules can be added as needed to incorporate new challenges. A separate submodule allows to easily add rules, ensuring the scalability and continuous enrichment of the game challenges. It organises rules in a specific structure by inheriting from an abstract class rule, which defines a common interface as well as implements common functionality. Additionally, the ChArGED Mobile App front-end visualizes data and game challenges in a user friendly, appealing, modern and motivating interface to ensure continuous engagement. The app is designed for Android smartphones supporting API Layer 21 (Lollipop) and above, equipped with NFC and BLE capabilities.

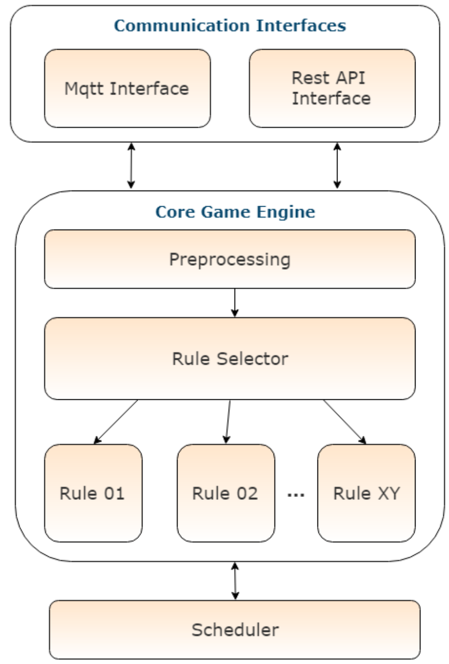

Fig. 4 Game Backend Internal Architecture

The gamified app visualizes information about energy behaviour both at user level and team level. Users are informed about their progress while their actions -directly contributing to the building energy consumption- can be traced.

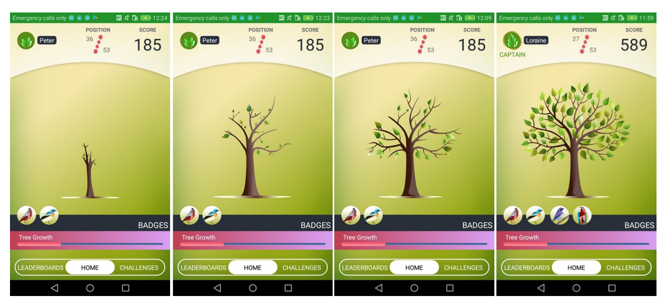

Fig. 5 Screenshots of the Mobile App

Achieving energy savings and accomplishing challenges results in accumulating scores. A visual emotional inceptive in the form of a living tree, as shown in Fig. 5, grows and prospers according to the user score, thus rendering the game also visually attractive and engaging. When a challenge is completed, the scores and the game progress for each user and their team are updated in real time between the backend and the mobile app. The game backend has been installed on the project server and connected with the MQTT broker, and through it, with the other software components. The design goal of the backend is to work on the background and send notifications via MQTT whenever there is a new update.

E. Component for microgeneration Energy Forecasting

This component utilizes a solar inverter (Kaco) with rich data communication capabilities (over Modbus TCP protocol), in order to monitor the generated electricity and assist the energy production forecasting mechanism which is based on daily weather forecasts. This forecasting is used for directing the game challenges towards optimizing energy use. The solar inverter is connected to the Sensor Gateway with the middleware / IoT integration software mBS SH. Through the device abstraction of the mBS SH the data are sent via MQTT to the ChArGED core platform and from there they are made accessible to all other system components. The Component for Microgeneration Energy Forecasting gets periodically (every day for five days ahead) updated on the specific location weather forecast and provides the hourly forecast of the expected energy. The solar forecast software is connected to 3rd-party weather forecast provider APIs for obtaining the weather forecast data (such as yr.no, wunderground.com, weatherxm.com, etc.).

III. Process View

This section deals with the dynamic aspects of the ChArGED platform. The system operation revolves around three main process flows, depicted in the following with UML Sequence Diagrams.

A. Collection of data from the building via meters and environmental sensors connected to the ChArGED Sensor Gateway

Metered data are communicated to the Data/Core Back-end system via MQTT and then assigned to Devices for use by other system components. Sites, devices and assets are created beforehand via the Administrative User Interface.

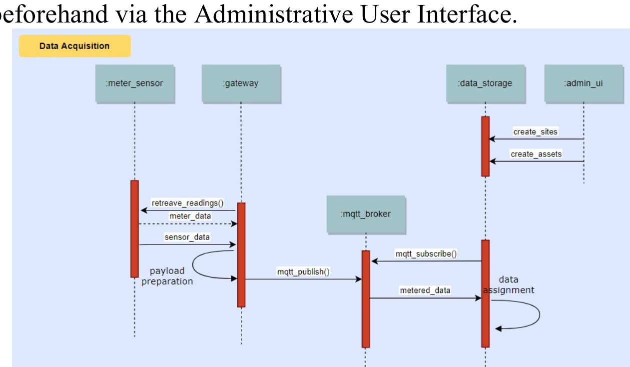

Fig. 6 Sequence Diagram Showing the process of collecting data from building via meters and environmental sensors connected to the ChArGED Sensor Gateway

B. Claim of energy saving achievements from the end-users via the mobile app

Energy measurements collected by the Sensor Gateway are sent to the Data/Core Back-end system and from there forwarded to the Analytics backend for modelling of the energy use. When the mobile app reports user-triggered NFC and BLE events via MQTT or REST, such events are sent to the Data/Core Back-end system and from there are also forwarded to the Analytics backend for modelling of the energy use as well as to the Game backend for accessing their effects on the game state.

C. Discovery of energy saving opportunities to assist the end users in saving energy.

Energy measurements collected by the Sensor Gateway are processed to create models of energy use. When new data are received, the Analytics backend compares them with the expected energy use at that time of the day and diagnoses deviations, which are in turn communicated to the Game backend. The Game backend will use that information to notify the end users if savings opportunities exist.

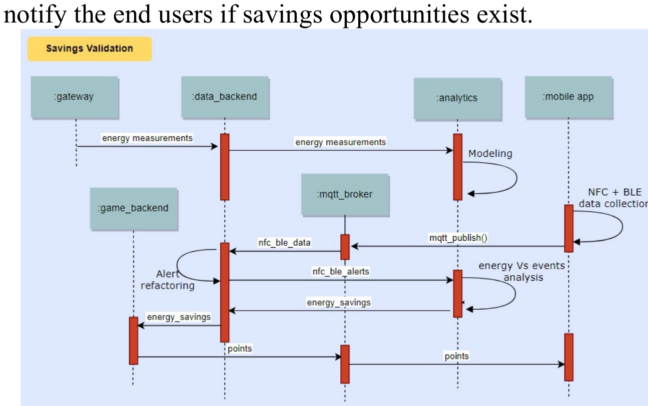

Fig.7 Sequence Diagram showing the process of claiming energy saving achievements from the end-users via the Mobile App

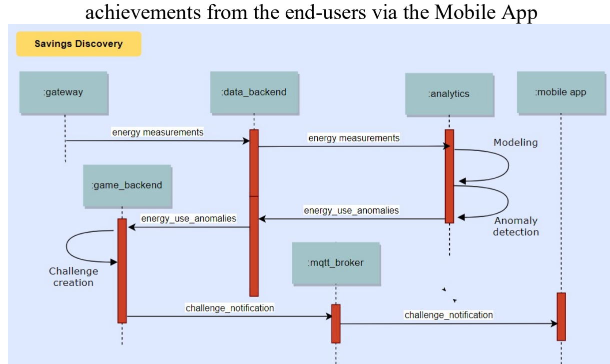

Fig. 8 Sequence Diagram showing the process of discovering energy saving opportunities and feeding such insights to the Game Engine

IV. Identifying User Requirements For Effective Game Design

The ChArGED solution has been designed in an iterative process involving end-users for analysis, design and development in public buildings located in 3 different countries: Luxembourg (Musée National d'Histoire et d'Art), Barcelona, Spain (EcoUrbanBuilding, Institut Català d'Energia headquarters, Barcelona) and Greece (General Secretariat of the Municipality of Athens).

To design an effective, appealing gamified application that the users will be willing to adopt, ethnographic-style studies (i.e., semi-structured interviews) and online surveys were conducted. The aim was to better understand the situation regarding the individual factors that influence energy consumption by the employees in the pilot sites, their current energy-consumption habits as well as in-game preferences, work engagement and burnout levels. In terms of individual behavioral factors, the following results summarize the majority of the users' characteristics. The studies' participants (potential pilot users):

- exhibit positive environmental awareness and environmental worldviews.
- exhibit activated environmental personal norms, acknowledging that conserving energy and resources is important to them and their own problem.
- show sensitivity to social norms, claiming that saving energy is a collective effort.
- are willing to help their organization and to change their daily routine to conserve energy.
- consider their personal comfort at work of crucial importance.

Thus, in general, employees from the pilot sites are positively positioned towards pro-energy conserving behavioral changes, as long as their personal comfort is not significantly affected. A more detailed account of the findings from the interviews we performed can be found in [9], [10]. In terms of in-game preferences, most of the employees considered that only team efforts would be effective towards energy conservation at work. Also, a social competition would be of interest for the majority of employees, as long as individual performance was not exposed. Finally, employees find some sort of reward (monetary or not) motivating for energy conservation. These results have been considered for the implementation of the game mechanics and app. In addition to the insight gathered from the semi-structured interviews and on-line survey, baseline data have also been collected and analyzed, to record the situation before the game is provided. The energy consumption data collection was implemented for all pilot sites with the targeted use of IoT smartplugs and Accuenergy smartmeters before the game was adopted. This resulted in the identification of interesting general energy wastage patterns which have been targeted by specific game challenges in the ChArGED game:

- Monitors are mostly left on stand-by when employees leave office, even after switching-off their PCs.
- A/Cs are left on when no employees are present at their respective spaces.
- Printers are mostly left on after working hours.
- Employees open windows whilst the A/C is on.
- Lights are left on when not needed.

Although some of the energy-saving opportunities described above do not look impactful at first glance (e.g. monitors on stand-by mode do not usually consume large amounts of energy), targeting these energy wastage behaviors is none the less important. Behavioral consistency between similarly oriented actions (i.e. the various energy-saving opportunities at the workplace) is expected to have an impact on the successfulness of energy conservation behavioral interventions, due to their normative effect (i.e. saving energy in every possible way is important), while combining small amounts of energy wastage may amount to considerable energy savings over the long run (every little counts). In addition, based on the data collected through on-site visits, as well as insight from the employee interview process, specific energy wastages have been identified for each individual site. This insight has enabled us to explore the exact usage patterns and electrical installation characteristics, in order to more accurately specify the game play conditions and the monitoring and game setup requirements at each site. Furthermore, the topology of each pilot site has been studied, to identify locations of teams and all electrical appliances, electrical circuits and controllers. Moreover, the various building spaces' usage patterns have been studied, to specify what aspects should be monitored during the game execution such as, for example, to identify which devices are shared.

Finally, for the pilot execution, the pilot site in Athens has installed a PV microgeneration system with a peak power of 4.88 kWp, on the roof of the building.

V. CONCLUSIONS

This paper presents the ChArGED framework that aims to facilitate achieving greater energy efficiency and reductions of wasted energy in public buildings. This framework exploits IoT enabled, low-cost devices to improve energy disaggregation mechanisms that provide energy use and - consequently- wastages at the device, area and end-user level. A gamified application has been developed to target these wastages and provide personalized real time recommendations to each individual end user. The ChArGED solution is being developed with iterative end-users' engagement during analysis, design and development in public buildings located in 3 different countries.

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