IoT Architecture for Decentralised Heating Control in Households

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Abstract: Over the last two decades, electrical energy generation has become more sustainable (photovoltaic, wind energy, etc.), but also more distributed, less predictable, and less controllable. Besides storage and flexible production, Demand Response (DR) offers great opportunities to help stabilizing the electrical grid. This paper presents how the flexibility of space and domestic hot water heating in existing residential buildings can be controlled for grid services. It focuses on the Internet of Things (IoT) framework including both hardware and software to connect existing buildings to a central Virtual Power Plant (VPP) intelligence. It also presents field experiments that were performed during the European FP7 SEMIAH project.

1 INTRODUCTION

Clean energy is becoming one of the most important challenges of today's world – as witnessed by the ratification of the Paris Agreement within the United Nations Framework Convention on Climate Change (Rogelj et al., 2016). To address this challenge, intermittent and non-dispatchable renewable generation (photovoltaic, wind energy, etc.) has grown dramatically in Europe and elsewhere over the last few decades. The distribution of new renewables as well as their hard to predict intermittent behaviour pose a double challenge to electrical grid operators:

- keeping a global balance between production and generation,
- avoiding congestion at the local grid level.

Two categories of solutions can be envisaged: energy storage or management of flexible consuming processes. The latter solution is a priori interesting, as it requires only a control infrastructure and no new power infrastructure.

Demand Response (DR) "is the intentional modification of normal consumption patterns by end-use customers [...]. It is designed to lower electricity use at times of high wholesale market prices or when system reliability is threatened"[1]. Space and Domestic Hot Water (DHW) heating are appropriate processes for DR in households, as they both involve non-negligible energy amounts and as consumption shifting has minimal impact on inhabitants comfort (Maître et al., 2015).

Section 2 presents the context of the European FP7 SEMIAH project during which the proposed solution was developed, deployed and tested. The section 3 presents the most related works. The underlying ICT architecture is presented in Section 4. Finally, Section 5 describes the pilot of the project and its impact on the electrical grid.

2 CONTEXT

The European FP7 SEMIAH project aimed "to pursue a major technological, scientific and commercial breakthrough by developing a novel and open ICT infrastructure for the implementation of automated Demand Response (DR) in households so as to enable shifting energy consumption from high energy-consuming loads to off-peak periods with high generation of electricity from Renewable Energy Sources (RES)". The developed DR framework had to cope with existing appliances and electrical installations in households which are not designed for DR, as well as use the domestic internet connection for communication. The project aimed to provide real-time DR with a response time in the range of seconds. The SE-

[1] https://setis.ec.europa.eu/setis-reports/setis-magazine/smart-grids/demand-response-empowering-european-consumer

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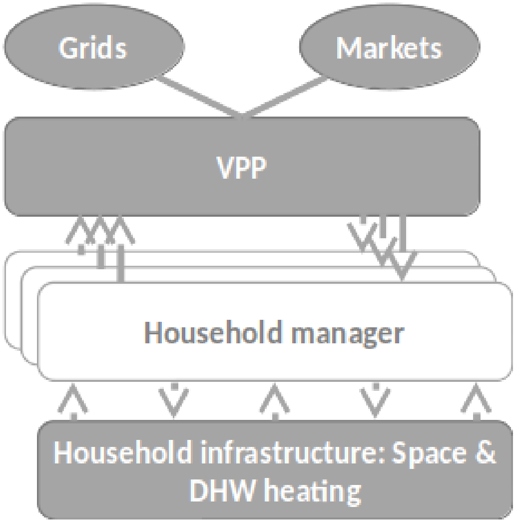

Figure 1: SEMIAH architecture for DR in households.

MIAH project addressed the full chain required for the deployment of DR services in households as illustrated in Figure 1:

1. a Virtual Power Plant (VPP) providing an aggregated view of the controlled households for grids and markets,
2. a Household Manager component turning an individual building into a dispatchable unit by processing monitoring signals and generating command signals,
3. appropriate sensors and actuators installed on the heating and electrical infrastructure of the building.

The VPP component used in the SEMIAH project was IWES.vpp developed by Fraunhofer IWES. The Household Manager was an ad-hoc component also developed by Fraunhofer IWES. The control loop performed by the Household Manager is illustrated in Figure 2. Since heating appliances have their own built-in controllers, the role of Household Managers is limited to enable or disable power supply (or act on the controller in the case of heat-pumps). Input parameters for the Household Manager were three temperatures (inside, outside and boiler) and the amount of electrical power consumed by the heating appliance.

This article's focus is on the distributed part of the ICT architecture, ranging from existing appliances in buildings to Household Managers.

Household Managers can be deployed either on a local gateway in each building or in the cloud. A cloud based solution is described in this article, as well as its implementation in the trial phase of the SEMIAH project.

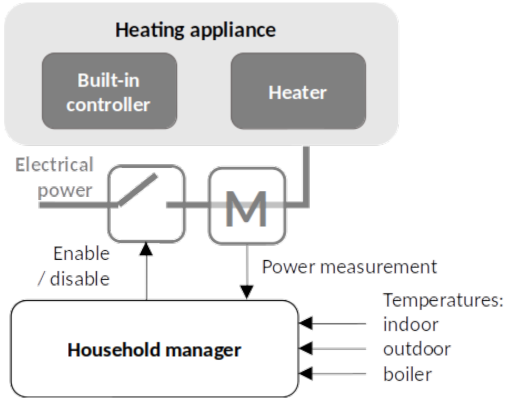

Figure 2: Control loop for DR service.

3 RELATED WORKS

The combination of cloud computing and Internet of Things offers a new paradigm with promising topics for both research and industry (Botta et al., 2014), especially in the domain of energy management. Numerous papers present a state of the art of IoT technologies. For example, (Al-Fuqaha et al., 2015) describes how low-level architectures are used to implement IoT frameworks. (Mazhelis et al., 2013) offers another overview of the potential of IoT in business. Similarly, cloud computing is detailed in several papers such as (Srinivasan et al., 2012; Zhang et al., 2010). The combination of IoT and cloud computing is also detailed in a few papers. For example, (Daz et al., 2016) presents lists of components that can be used to combine IoT and cloud for each level in a global architecture. Regarding energy one can mention that, at the end of their paper, they describe three case studies with two of those concerning energy management. (Zhou et al., 2013) presents a novel architecture combining IoT and cloud computing, including a review of several existing architectures. This article describes also an IoT smart-home scenario, highlighting how the combination of IoT and cloud computing offers great opportunities for energy management.

Multiple open-source IoT-Cloud framework exist already with TRL 7 or above. A first example is the modular platform Eclipse Kapua[2] and its companion the Eclipse Kura open-source framework to build IoT gateways. This framework, of strong industrial relevance, is a platform for IoT-Cloud integration, based on Java OSGi and efficient message brokering. Eclipse Kapua possesses a modular approach and provides a comprehensive management of

[2]https://www.eclipse.org/kapua/

IoT edge nodes, such as their connectivity, configuration, and application life cycle. Finally, Eclipse Kapua offers a web-based administration console and is accessible through RESTful API for easy application integration. cloud.iO and Eclipse Kura/Kapua implement broadly the same set of services and also share the same messaging system for devices-cloud interconnection (MQTTs). Whereas Eclipse Kura/Kapua is a standalone mature environment, with a lot of features for configuration, deployment, and supervision, cloud.iO is made up of more scalable, field-proven legacy open-source frameworks, linked by a set of independent lightweight dedicated components.

The second example is FIWARE[3]. It is an open-source platform promoting "open sustainable ecosystem around public, royalty-free and implementation-driven software platform standards that will ease the development of new Smart Applications in multiple sectors". The FIWARE platform provides a simple set of APIs that ease the development of Smart Applications in multiple vertical sectors. Moreover, an open-source reference implementation of all FIWARE components is publicly available so that multiple FIWARE providers can emerge faster on the market with a low-cost proposition. FIWARE focuses on big data analysis and application dashboards. Such applications are not part of the cloud.iO framework. However, cloud.iO could act as a front-end platform for FIWARE, handling device connectivity and providing an abstract and homogeneous access to field data.

4 DISTRIBUTED ICT ARCHITECTURE

4.1 Overview

The control strategy requires the deployment of the following sensors (generating monitoring signals) and actuators (consuming command signals) in participating buildings:

- temperature sensors for space (living room, outdoor) and for hot water (boiler),
- sub-meters to measure the power consumption of heating appliances,
- a meter to measure the household total consumption,
- power relays to enable/disable power supply to heating appliances (electric heaters and heat pumps).

[3]https://www.fiware.org

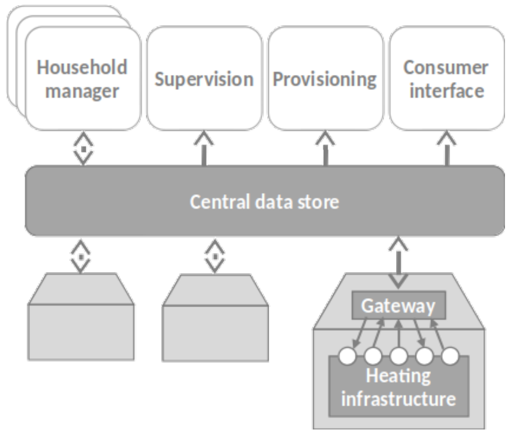

Figure 3: Distributed part of the SEMIAH ICT architecture.

These devices, together with an internet connected gateway, form a wireless Home Area Network (HAN). Wireless networking is required to limit installation costs in existing buildings (Gill et al., 2009). The Process Image is an image, mirrored in a central data storage solution by the gateway, of the current status of monitoring and command signals. Four Applications interact with the Process Image, as illustrated in Figure 3):

- Household Managers (considered as a single Application),
- a supervision system, independent of the DR intelligence, detecting faulty conditions and generating alarms accordingly,
- a provisioning system supporting the deployment of the DR service in new participating buildings,
- a web based interface for consumers.

4.2 The Home Area Network

The HAN is based on Zigbee, with the gateway acting as coordinator and the sensors/actuators as devices. Zigbee devices are compliant with the Home Automation or the Smart Energy profiles defined by the Zigbee Alliance.

4.3 The cloud.iO IoT Framework

4.3.1 Vision and Architecture

The cloud.iO IoT framework aims to simplify the development of embedded and distributed "Things" (called Endpoints in cloud.iO) and of cloud-hosted Applications interacting with them.

The heart of cloud.iO is the Process Image, which contains an up-to-date centralised mirror of the status of distributed Endpoints. An Endpoint updates the

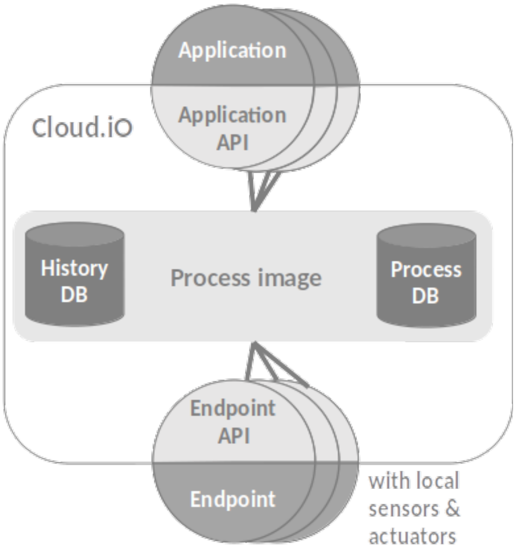

Figure 4: cloud.iO architecture.

Process Image when the value of a monitoring signal has changed. Applications can subscribe to monitoring signal updates and are notified on new values. Applications can modify set points of command signals in Endpoints (see Figure 4). cloud.iO provides dedicated APIs for the development of Applications and Endpoints. The Process Image contains two databases:

- the Process Database, with the current status of the Endpoints (connection state, list of signals with their current values) is a searchable database containing the full information models of all Endpoints.
- the History Database, storing time series for monitoring and command signals, uses the Attribute names from the Process Database as identifiers to access the time series.

4.3.2 cloud.iO Class Model and Endpoint Information Model

The cloud.iO class model is derived from the IEC 61850 class model (Mackiewicz, 2006). IEC 61850 is the ICT standard for power utility automation.

The cloud.iO class model allows a tree-shaped structure definition and is composed of Endpoints, Nodes and Objects. A cloud.iO Endpoint is evidently the equivalent of an Endpoint instance. An Endpoint is composed of a set of Nodes themselves composed of Objects. The tree-shaped structure appears in Objects as an Object can be composed of other Objects. Attributes, in Objects, represent the roots of the tree.

cloud.iO allows the use of either a free information model, without a predefined structure, or a constrained information model (i.e. an information model compliant with some schema). Schemas are defined by Interfaces (similar to Logical Nodes in IEC 61850) and Classes (similar to Common Data Class in IEC 61850). The resulting class model is presented in Figure 5. The instances of Nodes, Objects and Attributes in an Endpoint form its information model.

To identify an Attribute (e.g. to access to its value in the database), the whole hierarchy is used, its name is formed according to the following pattern:

```
<Endpoint-UUID>/ <nodeLabel>/ <objectLabel_1>/
    .../ <objectLabel_N>/ <attributeLabel>
```

4.3.3 Messaging System

Applications, Endpoints and Databases inside the Process Image are clients of a messaging system. Messages are composed of a routing topic and of a message content. Once a client has subscribed to a topic, it receives all messages featuring that topic. Table 1 presents the message routing concept used in cloud.iO for an Endpoint.

Hence, an Application is notified of any change on its subscribed monitoring Attributes. An Endpoint can freely decide when to update its monitoring Attributes in the Process Image. It is foreseen that Applications access Databases through the messaging service, but this function is not yet implemented in cloud.iO.

4.3.4 Security and Privacy

Endpoints, Applications and Databases connect to the message broker using SSL/TLS with X.509 certificate based client and server authentication. SSL/TLS provides state-of-the-art confidentiality, authentication and access control. cloud.iO allows managing access rights to Attributes. An Endpoint belongs to a User (either a person or an organisation). Users may grant read/write access permissions on their Endpoints to Applications.

4.3.5 Implementation

cloud.iO design philosophy is to take advantage of the power and reliability of open source components, with minimal specific code development. The central component is the message broker RabbitMQ. It connects Endpoints and Applications using respectively the MQTTS and AMQPS protocols. The databases can be deployed using any database management system. In the reference implantation of cloud.iO, InfluxDB and MongoDB are used for respectively the

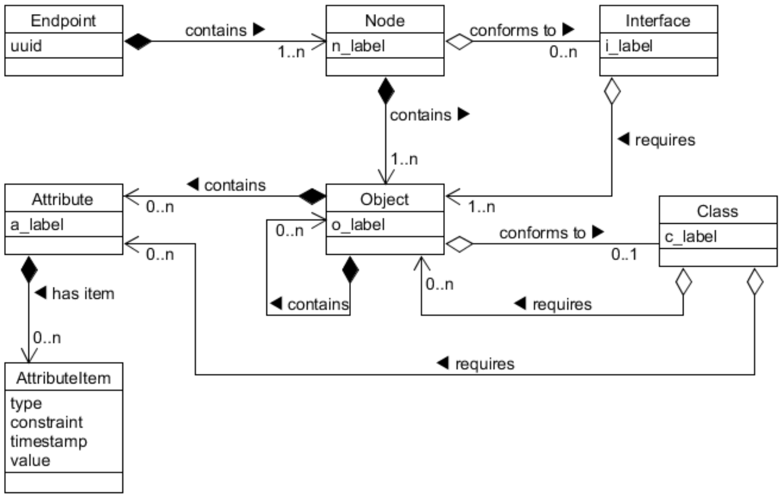

Figure 5: The cloud.iO class model.

Table 1: Message routing for an EndPoint.

Messaging client	Subscribes to topics:	Generates message with topic
EndPoints	/@set/<Endpoint_UUID>/*	/@update/<monitoring_attr_name>
Applications	/@update/<monitoring_attr_name>	/@set/<command_attr_name>
Database	/*	-

history database and the real-time database. If performance is required all components can be deployed as clusters.

4.4 The cloud.iO Framework Applied for SEMIAH

Gateways play the role of cloud.iO Endpoints. The Endpoint UUIDs are simply the Ethernet addresses of the gateways. Zigbee devices correspond to cloud.iO nodes. Zigbee devices feature their own information model, defined by the profile they implement. During deployment, the Provisioning Application elaborates a configuration file for the gateway. The file has a section per device, and each section contains a set of mappings between a cloud.iO Attribute and a Zigbee information model element. The configuration file itself is a cloud.iO Attribute that can be updated remotely. Hence, a Household Manager Application disposes of a logical view of a building, which is independent of Zigbee.

5 SYSTEM DEPLOYMENT

In the framework of the European FP7 SEMIAH project, a pilot with 200 households was in operation between October 2016 and May 2017. The deployment was performed under the responsibility of local Distribution System Operators (DSOs). One hundred households were located in Norway in the Adger region (DSO: Adger Eneri Net) and another hundred in Switzerland, canton of Valais (DSO: SEIC Teledis and EnAlpin). Most of the participating households were single-family houses. As the domestic internet connection was used for communication, gateways were typically located close to the home router.

The Zigbee devices and gateways were products of the Develco Products company[4]. The heating systems in the different households had a great influence on the installed sensors and actuators. Indoor and outdoor air temperature were measured using battery powered Zigbee sensors. Boiler temperature sensors were especially developed for the project: a digital temperature probe was fixed on the boiler outer wall and linked to a battery powered Zigbee device.

In Norway, single-phase electrical panel heaters and water boilers are connected to standard electrical sockets. Zigbee smart plugs were installed to monitor electrical consumption and enable/disable power supply. For decades, a DR system called Ripple Control (RC, shown in Figure 6) has been in operation in Swiss residential buildings as a tool for peak shaving on the distribution grid.

Every house is equipped with a RC receiver, which is configured with a multicast address. A RC manager generates telegrams (broadcasted using

[4]https://www.develcoproducts.com

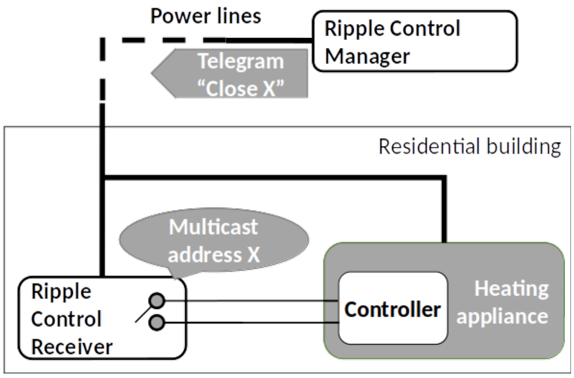

Figure 6: Principle of Ripple Control (RC).

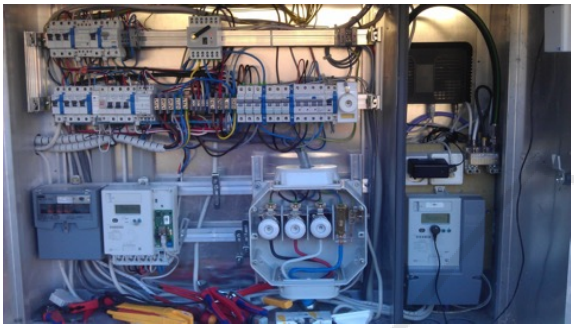

Figure 7: Real installation. The prosumer meter (top center) has been installed and wired in the existing electrical cabinet.

Power Line Communication) containing orders to switch on or off relays configured with a certain multicast address. RC implements a "blind" open loop control strategy. The SEMIAH Household Manager drives the control input on heating appliances, hence replacing the RC receiver. The SEMIAH control differs from RC control in two ways: The SEMIAH control is unicast (each appliance can be controlled individually) and closed loop (temperatures and electrical measurement are input parameters for the Household Manager). Since the heating appliances have their own controllers, the SEMIAH Household Managers cannot turn them off or on but only disable or enable power consumption. A Zigbee DIN-rail mounted relay with or without power measurement replaced the RC receiver. A further Zigbee device reads the overall power consumption on the official meter (through the "S0 impulse interface"). In some configurations, a Zigbee 3-way sub-meter (called prosumer meter) was used to measure the photovoltaic production, the heating consumption, the overall household consumption, or the net power exchange with the grid.

Figure 7 shows an example of how the hardware was deployed in a specific household. The wiring work can be observed with a prosumer meter installed in the electrical cabinet. Even if this picture shows that the solution had to be installed by a professional, there was always sufficient space in the electric cabinets to fit the SEMIAH hardware.

5.1 System Deployment Costs

During the Swiss pilot deployment, two technicians went to the different households to perform the installation. The first one was an electrician, working for the DSO in charge of the area, who did the electrical wiring work. The second one was an IT specialist who installed the gateway and checked the ZigBee and internet connectivity. The whole cloud.iO infrastructure was deployed and tested before the installation, to reduce the duration of the installation. Installations were performed in about 1 hour. With training and more experience, installations could be done by only one technician who would do the wiring and the IT checks. Taking into account travel costs ($\sim$1h), hardware costs ($\sim$300 CHF), and labour costs ($\sim$200 CHF), the total cost per installation was about 500 CHF. However, in the scope of this pilot phase, development, debugging, updates, and problem solving amounted to a much bigger amount. In a larger scale deployment, the relative importance of these costs would proportionally decrease.

5.2 Analysis

Manual power cuts were performed through the provisioning application to test the behaviour of the whole infrastructure. They aimed at validating multiple objectives:

- verify the effective real relation between the cloud.iO abstraction and the installed hardware (actuators are really operated),
- evaluate the reactivity of the system (delay),
- evaluate the impact of power cuts of various durations on both household temperatures and load curves.

A series of cuts were conducted during one week, with enough time between two consecutive cuts to ensure that previous cuts had no effect on the current one. The power cuts were performed during week 8 in 2017 (February 20th to 24th).

Figures 8 and 9 respectively present the consumption and the temperatures measured for one household. Two observations can be made based on these Figures: It is clear that, during the cuts, the amount of energy consumption is drastically reduced. A 4-hour cut does not influence the temperature inside the

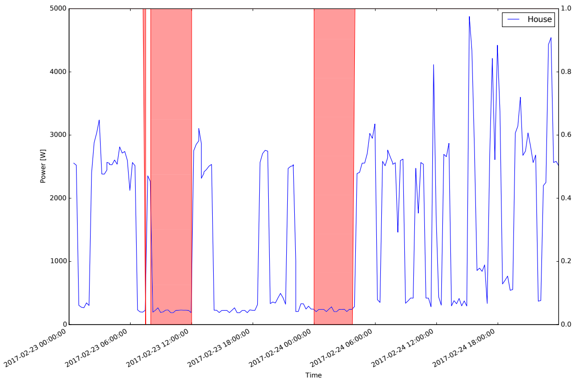

Figure 8: Consumption of one household during 48 hours, with two 4-hour cuts (in red). A really short cut (test) before the first 4-hour cut can also be observed.

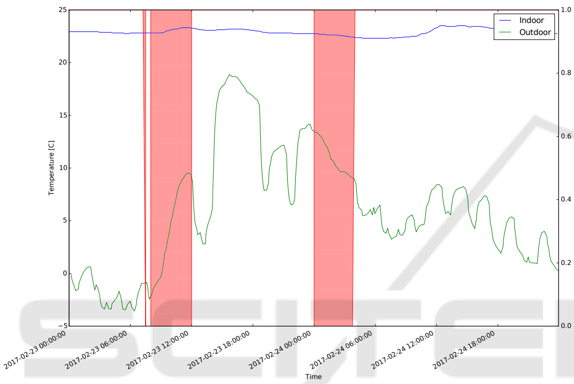

Figure 9: Temperature of household during 48 hours, with two 4-hour cuts (in red).

household. We can observe that the indoor temperature (blue curve in Figure 9) slightly increase during the first cut. This is due to the large increase of the outdoor temperature (green curve in Figure 9).

Further analyses with a larger number of households will be realised to better prove the value of such technology. However, it seems clear that a smart control of heating systems could have a high influence on the energy consumption.

5.3 Installation Drawbacks

Several problems occurred during the pilot phase of the SEMIAH project but most of them were quickly detected and resolved soon after. However, one of the most important remaining problem was range issues of the ZigBee hardware. Swiss building are especially strongly built with thick walls that were damping too much the communication signal. Being close to the limit had two main effects. It first increased the communication losses and thus induced many interruption of data collection. Moreover, lost packets lead to repeated communication at increased transmission power, taking an heavy toll on consumption and thus on battery life expectancy that dropped sometime to just a few months. This problem could not be easily solved by increasing the meshing with smart plugs, as sometime signal dampening was already too consequent through a single wall.

The installation of an innovative technology in households did also sometimes show unpredictable behaviours of the household inhabitants. For example, some participants were turning off their gateway during part of the day. Some placebo effects were also observed, with pilot participants complaining about a lower than usual room or hot water temperature, when no control was yet performed on their heating appliances.

6 CONCLUSION

This article presents cloud.iO, a IoT infrastructure allowing an abstraction in the cloud of diverse sensors and actuators installed in households on heating appliances. It also presents how data is stored and how the system was deployed in real households to manage those appliances. It presents the hardware used and how it was installed inside the households, and demonstrates the feasibility of deploying such a solution in a large scale at a relatively low cost. Finally, it presents effective results of power cuts performed with this infrastructure.

The described infrastructure was thus deployed and tested, showing that such a solution can be used to enable controllers (such as IWES.VPP) to easily access a big number of heating appliances located in households.

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