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ENCOURAGEing Results on ICT for Energy Efficient Buildings

Thibaut Le Guilly
Arne Skou
Petur Olsen
Per Printz Madsen
Michele Albano*
Luis Lino Ferreira*
Luis Miguel Pinho*
Miquel Casals
Marcel Macarulla
Marta Gangolells

*CISTER Research Center

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*CISTER Research Center

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail: mialb@isep.ipp.pt, llf@isep.ipp.pt, lmp@isep.ipp.pt

http://www.cister.isep.ipp.pt

Abstract

This paper presents how the ICT infrastructure developed in the European ENCOURAGE project, centered around a message oriented middleware, enabled energy savings in buildings and households. The components of the middleware,as well as the supervisory control strategy, are overviewed, to support the presentation of the results and how they could be achieved. The main results are presented on three of the pilots ofthe project, a first one consisting of a single household, a secondone of a residential neighborhood, and a third one in a university campus.

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Thibaut Le Guilly, Arne Skou, Petur Olsen, Per Printz Madsen
Aalborg University, Denmark
{thibaut,ask,petur}@cs.aau.dk
ppm@es.aau.dk

Michele Albano, Luis Lino Ferreira, Luis Miguel Pinho
CISTER/INESC-TEC, ISEP, Portugal
{mialb,llf,lmp}@isep.ipp.pt

Miquel Casals, Marcel Macarulla, Marta Gangolells
Universitat Politècnica de Catalunya, Spain
{miquel.casals,marcel.macarulla, marta.gangolells}@upc.edu

Keld Pedersen
Energy Nord, Denmark
kp@energynord.dk

***Abstract*—This paper presents how the ICT infrastructure developed in the European ENCOURAGE project, centered around a message oriented middleware, enabled energy savings in buildings and households. The components of the middleware, as well as the supervisory control strategy, are overviewed, to support the presentation of the results and how they could be achieved. The main results are presented on three of the pilots of the project, a first one consisting of a single household, a second one of a residential neighborhood, and a third one in a university campus.**

I. Introduction

An important step to move society towards sustainability is to optimize the energy consumption of households and buildings. At the same time, it is necessary to facilitate the integration of renewables into the energy mix, and thus to develop innovative infrastructures capable of handling the changes that they imply. For example, the European Union has set an objective of fulfilling at least 20% of its energy needs from renewables by 2020 [1], while Denmark has set it to 50% for the same year [2]. One of the tool to attain these objectives is the Smart Grid, an improved version of the electricity distribution network (the Grid). The Smart Grid aims at enabling a more flexible and distributed production and distribution of energy, where energy flows are not unidirectional anymore, but where actors can be at the same time producers and consumers (prosumers) of energy. For example, a house equipped with solar cells could distribute eventual surplus of energy production to its neighbors under sunny weather, or receive energy from another house equipped with a wind turbine when windy. The growing interest for the Smart Grid is illustrated by the outlook on European Projects on this subject by Covrig et al. [3], where they counted 42 projects started during the year 2013, with a total investment of around 415 millions euro.

The number and focuses of projects involved in Smart Grid also illustrate the variety of topics that need to be researched for its success. There is a large effort to be made to improve the integration of energy generated from renewable sources, on the Grid infrastructure to help it cope with increasing loads, and on policies and mechanisms. However, the Smart part essentially comes from the use of Information and Communication Technology (ICT) infrastructures that enable to gather and exchange of information, as well as remote control of consuming and producing devices. The information gathered from prosumer sites can help energy companies to forecast expected consumption and production in given areas, facilitating their planning tasks, and increasing Grid reliability. In addition, the control capabilities give more flexibility in their daily operations, enabling last minute adjustments to flatten out peak consumption, optimize the consumption, and avoid potential failures. The ENCOURAGE project[1], whose results are presented in this paper, was among the projects aiming at developing such ICT solutions for Smart Grids. Among its unique features are a state of the art, open source middleware, supervisory control of prosumer buildings, and demonstration of results in real environments.

The paper is organized as follows. Section II provides an overview of the project, as well as its initial objectives and research areas. Section III presents the architecture of the ICT solution developed to attain these objectives, with its different components. The supervisory control developed to optimize the energy efficiency is presented in Section IV. An overview of the different pilots of the project and their results is provided in Section V. The exploitation of the project results are presented in Section VI. Related Work is discussed in Section VII and a conclusion and planned future work are provided in Section VIII.

II. Project Overview

The acronym of the project, ENCOURAGE, stands for Embedded iNtelligent COntrols for bUildings with Renewable generAtion and storaGE. It involved 11 partners from 5 countries: Spain, Portugal, Italy, Ireland and Denmark. Its aim was to develop embedded intelligence technologies to optimize energy usage in buildings, and enable their integration into the Smart Grid. The main application domains were non-residential buildings and campuses, but the solution was expected to also be applicable to private houses and neighborhoods, and included pilots in this domain as well. An overview of the domains covered by the project is represented

[1] http://cordis.europa.eu/project/rcn/102780_en.html

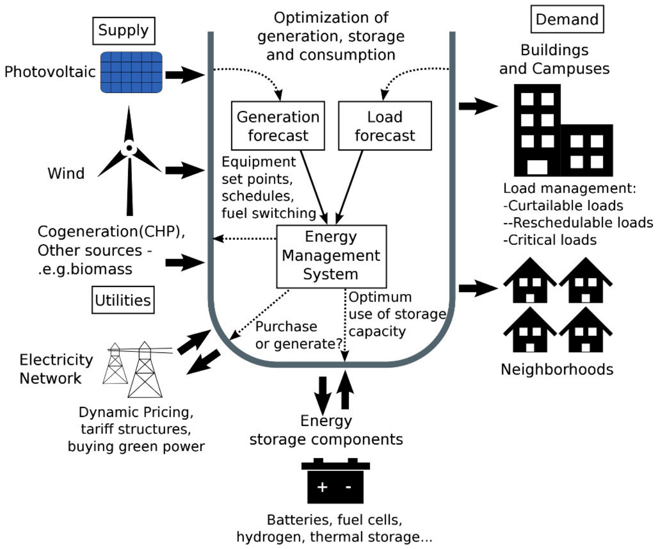

Fig. 1. Application domains of the project.

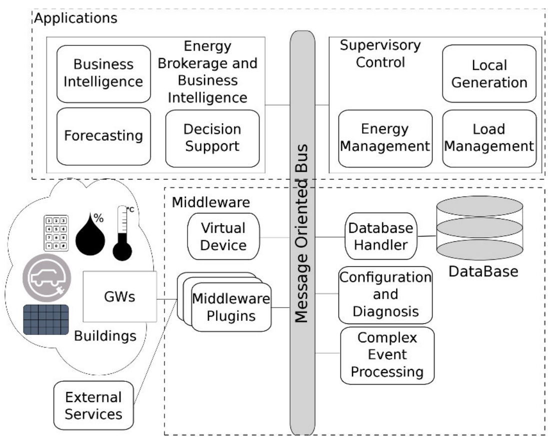

Fig. 2. Overview of the ENCOURAGE ICT architecture.

in Figure 1. The optimization objectives were expected to take place at different levels:

Device level: optimizing the energy consumption of individual devices through continuous monitoring to detect deterioration of the service performance;

Building level: performing optimization through control and orchestration of local consumption, generation and storage;

District (or neighborhood) level: enabling inter-building exchange of energy to optimize the consumption of energy at neighborhood scale.

III. Architecture

This section presents the architecture of the ICT infrastructure developed in the project. Note that this is an updated version of the architecture described in [4]. An overview of the architecture and its components is shown in Figure 2.

A. Message Oriented Bus

The messaging infrastructure is implemented on top of the Advanced Message Queue Protocol (AMQP)[2], specifically the RabbitMQ[3] implementation. RabbitMQ offers highly scalable communication, decoupling between systems, and well-tested, robust protocol. RabbitMQ focuses on communication using publish-subscribe through message queues, but supports also request-response communication. Both are used in the ENCOURAGE middleware, which distributes measurement readings to interested parties using publish-subscribe, and sends control signals to specific actuators via request-response communication.

The middleware uses the AMQP routing capabilities to optimize message delivery. A AMQP routing key is a path locator, which in ENCOURAGE is used to organize devices hierarchically. Routing keys are of the form /<macrocell-id>/<cell-id>/<device-id>, where a macrocell id identifies a geographical area, a cell id a building or room, and a device id a sensor or actuator in a specific building. This way a module of the middleware can listen for messages from an entire area, a building, or from specific devices. For example, the Supervisory Control (SC) module uses this feature to listen for specific measuring devices.

RabbitMQ is agnostic regarding the content of the messages sent, and therefore does not dictate a specific format for their encoding. ENCOURAGE chose to use the Common Information Model (CIM) standard IEC 61968-9 [5], marshalled as XML, for encoding metering data and control messages.

B. Home and Building Gateways

The devices installed in buildings and homes are interconnected together and to the outside world through the gateway (GW). The objective of this component is to act as proxy to the Home Area Networks (HAN), providing a single access point to a set of devices. Ideally, one GW per building or house would provide access to the entire set of devices. However, due to the heterogeneity of the devices inside such networks, it is not uncommon that multiple gateways co-exist in the same environment, and it was actually the case in some of the pilots of the project. A solution to provide uniform access to all the devices in the building is the HomePort system [6].

C. Middleware Plugins

The middleware plugins (MPGs) come in two types, and are the entry points to the middleware for everything deployed outside it. The MPGs of the the first type connect the middleware to the GWs, which offer access to the HANs and their devices. The MPGs of the second type are required to contact external applications, such as weather forecast. As these services are provided in heterogeneous ways, the MPGs act as adaptater between the services' custom protocols, and the one used in the ENCOURAGE middleware.

[2]https://www.amqp.org/
[3]https://www.rabbitmq.com/

D. Virtual Devices and Database

The Virtual Device (VD) module is used for processing incoming messages, storing them in a database (DB), caching current status of devices, and routing messages between modules. The virtual representation of devices in the middleware allows easy access to their current status, sending data and receiving control commands. When data from a device is received in the middleware, the VD updates its virtual representation accordingly. The VD thus acts as a server side cache for applications, avoiding having each application contacting the HAN to query its devices, thus lowering delay.

The VD module is configured to route messages to correct devices based on the previously described routing keys. Examples of routing implemented by the VD are sensor data forwarded to the SC module, or direct control messages delivered to the appropriate MPG, which then forwards them to the correct GW and finally a HAN device. Another functionality of the VD module is to log all events happening in the system, such as exchanged messages, and store them in the ENCOURAGE DB, to enable offline analysis of the Smart Grid performance.

The Database Handler (DBH) abstracts access to the database by providing generic connectors for handling various kind of queries, for example used by the VD module to log information.

E. Configuration and Diagnosis

The Configuration and Diagnosis module (Conf&Diag) manages the configuration of the Middleware, HANs, MPGs, GWs and Devices. At system start-up, it is assumed that each component has a minimal configuration specifying how to access the Middleware and in particular the Conf&Diag module. When receiving an initial request, the Conf&Diag module looks up the identifier it contains, and replies providing a configuration stored into its local database. This ensures that in case of failure each component can restore its configuration properly. When configurations are updated, previous ones are saved to allow comparison and forensics analysis. Among the data contained in the Conf&Diag module, there is information to contact external services, and to interact with end users of the system through user interfaces and in-wall devices.

For scalability and operational issues, a specific workflow is given for the set-up of new devices and new GWs. In fact, adding new devices can change the control strategies in use. Moreover, when adding new customers to the system, setting up new devices should be as automatic as possible. For this purpose, the initial (default) configuration of a HAN device can be accessed by specifying just a unique identifier, the device type, and its macrocell id. The Conf&Diag module also copes with generating and storing alarms regarding abnormal behavior of the system. For example, should two devices get assigned the same unique identifier, the Conf&Diag will generate an alert message for the user, and will save this event for future analysis.

F. Complex Event Processing

The Complex Event Processor (CEP) is a module capable of generating, from asynchronous and independent events of different types, a complex (synthesized) event. The module's goals are to allow temporal reasoning and enhance system performance. When receiving new events, it compares them with previous ones in a temporal window, and distills basic events into complex ones. To this aim, it contains processing elements that can be configured by external applications through declarative *rules*, to define how multiple events are consolidated into a single, complex event. A simple example could be to detect smoke and heat within a short time interval, and signal the possible presence of a fire. The CEP module is also used as a filter, to generate less frequent events but of more significance than the simple ones produced by devices. The SC modules can for example choose to subscribe to CEP events to reduce the number of events they receive, thus saving them resources.

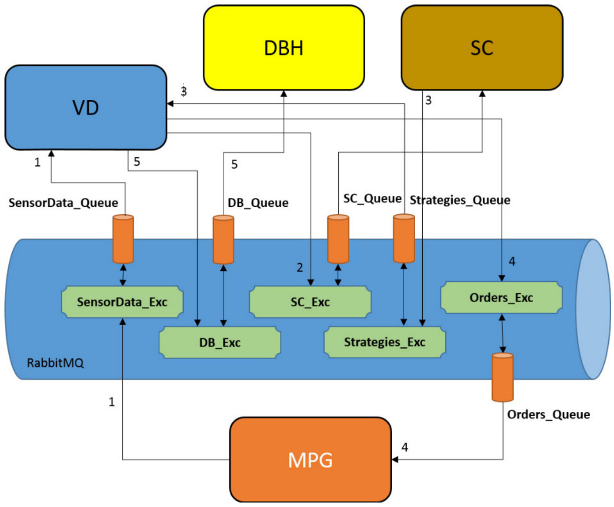

Fig. 3. Scenario for the performance tests of the Smart Grid.

G. Performance Evaluation

A testbed was implemented to evaluate the performance of the middleware. In particular, it focused on the VD module, as it is the corner stone of the architecture, routing all messages between the components. To provide realistic results, the configurations was aligned with low-end virtual machines available on most cloud provider: 4 GB of RAM, a dual-core CPU running at 2.80 GHz, Linux operating system (see for example the `t2.medium` configurations available at Amazon[4]).

The test scenario featured the messaging bus, a VD module, a DBH module and a SC module, running on different computers. In addition, a number of simulated MPGs were used, providing data from simulated devices and receiving control messages from the SC. The workflow related with Smart Grid operations is represented in Figure 3. Each time a MPG sends a message to the system, the message is delivered to the VD module (1). The VD module decodes the message, forwards it to the DBH module for logging (5), and to the SC module (2). The SC module is simulated by means of a process waiting 100 ms after receiving a message, and then sending a control message to a random device through the VD module (3). The

[4]http://aws.amazon.com/pt/ec2/pricing/

VD module decodes it, logs it using the DBH module (5), and sends a message to the MPG corresponding to the device targeted by the SC (4).

The experiments were made over Wide Area Networks: the MPGs were deployed on private houses in Portugal, the messaging bus was hosted in a university campus in Barcelona, and the SC and VD were executed on computers in the Polytechnic Institute of Porto, Portugal. Each test featured 10000 messages from the MPG, and was repeated 20 times. Different message sizes were experimented with (1, 4, 50 measurements in each message sent from MPG to VD). The results hinted that the performance is independent from the number of simulated MPGs and from the number of devices. The only parameter that impacted the performance of the system was the total rate of messages incoming to the VD. The rest of the evaluation was based on 1 MPG and 242 devices (the number of devices deployed in the pilots).

Many experiments, described in detail in [7], led to the definition of maximum message rates that can be supported by the platform without getting saturated. In particular, the findings hinted that for small messages (1 and 4 measurements in each message) up to 130 messages per second could be supported. For larger messages (50 measurements per message), 40 messages per second could be supported. The mean delays measured in these configurations were always less than 0.5 s.

Current case studies suggest that a Smart Grid should exchange one message with the user premises each 15, 30 or 60 minutes for monitoring only, and one message each 12, 10 or 4 seconds when SC is taken into account [8]. Let us consider a worst case scenario (one message each 4 seconds), considering 130 messages per second containing 4 measurements each, the ENCOURAGE system can support up to 520 HANs. Considering that the system configuration is the same as the lower-end (`t2.medium`) virtual machine of Amazon, whose cost amounts to 0.060$/hour[4], each server of the setup has a cost of around 35 Euros / month, for a total of 280 Euros / month (VD, messaging bus, DB, SC). Since the setup can support at least 500 HANs, it is possible to cap the Operating Expenses of the ENCOURAGE Smart Grid to 0.60 euro per month per HAN.

IV. SUPERVISORY CONTROL

The objective of the Supervisory Control (SC) module is to design and test strategies for managing supply and demand of energy in the Smart Grid. Essentially the SC is supposed to regulate energy flows to maximize consumption of energy produced locally, minimizing power trades with the grid. Building loads can be optimized either directly by shedding, shifting or rescheduling power consumption patterns, or indirectly by using electricity price signals to drive users' behaviors. As a title of example of the complexity involved with its operations, the SC module can shift the schedule of the Heating Ventilation and Air Conditioning (HVAC) systems, but in doing so it must take into account the thermal changes inside the building that might contradict with desired comfort level set by end users. In this context, it is clear that larger comfort intervals can provide the SC with more flexibility to operate, and thus allow it to provide stronger improvements to energy utilization.

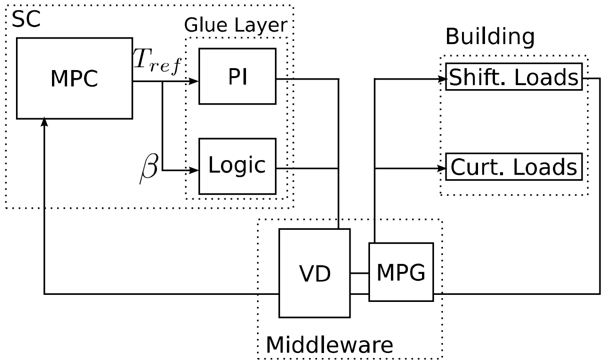

Fig. 4. The structure of building level control

Another objective was to be able to have a single SC strategy that could be used for the all houses and buildings. This was first made possible by deploying the SC module as a middleware application, where it could be seamlessly connected with the desired houses and buildings through the VD module and adequate middleware plugins. The second way to achieve this goal was by developing a dedicated language serving as a glue between the SC module and local devices. The overall structure of the control system is shown in Figure 4. This language also enables handling of curtailable loads, for example by controlling lighting systems. The main target is then not to enhance flexibility of the loads but to lower the energy consumption. The method uses a strategy consisting of an indirect control of the energy consumption. A model predictive controller (MPC) is formulated that systematically finds the energy consumption pattern of flexible loads provided that knowledge about other loads and productions and the building dynamics information is available in the middleware DB. Flexible loads are mainly shiftable ones, and to some extent curtailable ones. A cost is formulated based on power consumption and energy price, which is then minimized by the MPC. In the proposed scheme electricity can also be sold to the grid and consumption can be curtailed when convenient. The MPC layer connects to the glue layer by commanding a general reference signal to the local single loop controllers, which can be for example a room temperature PI controller. It is designed in a receding horizon fashion to incorporate building energy flexibility based on a dynamical model, future preferences and disturbances.

The MPC is based on iterative, finite horizon optimization of a plant model. At time$k$the current plant state is sampled and a cost minimizing control strategy is computed (via a numerical minimization algorithm) for a relatively short time horizon in the future: $[k, k+N]$. Specifically, an online or on-the-fly calculation is used to explore state trajectories that emanate from the current state and find (via the solution of Euler-Lagrange equations) a cost-minimizing control strategy until time $k+N$.

Dynamics of a house and its heating loads are governed by the following first order model. This model is accurate enough for control design purposes in practice.

$$CT = UA(T_{out} - T) + Q_{heat}$$

Where:

U: thermal transmittance $[kW/m^2\ °C]$
A: surface area $[m^2]$
T_{out}: outside temperature $[°C]$
T: room temperature $[°C]$

The optimization Problem is formulated in a receding horizon framework. Purchase from the utility grid and deviation from comfort temperature profiles are penalized in the cost function. The other term in the cost function is related to curtailment penalty.

$$\min \sum_{k=1}^{N} \begin{array}{l} \alpha * \rho_{discmf}|T(k) - T_{cmf}(k)| \\ + (1-a) * (\rho_{buy}(k)w_{buy}(k) - \rho_{sell}(k)w_{sell}(k)) \\ + \rho_{curt}(k)\beta_{curt}(k)Q_{curt} \end{array}$$

Here k is the time instant and N is the prediction horizon. ρ_{discmf} and ρ_{curt} are coefficients of penalty for thermal discomfort and power curtailment of the appertaining curtailable loads, respectively. Control variables are curtailment coefficient β_{curt}, and the selling power to the grid $w_{sell}(k)$. Predicted signals and system disturbances include comfort temperature profile $T_{cmf}(k)$, the buying and selling price from the grid $\rho_{buy}(k)$ and $\rho_{sell}(k)$, the discomfort penalty ρ_{discmf}, the curtailment penalty ρ_{curt}, and the curtailable and inflexible loads Q_{curt}.

V. Pilot Results

This section describes three of the pilot demonstrations that made use of the middleware to implement energy optimization strategies in buildings and households.

A. *Vestervej*

This pilot consists of one residential house. It is equipped with a heat pump based heating installation where floor heating tubes are embedded in a concrete deck at approximately 50 mm. A 6 kW solar system is also installed on the south facing roof. The electricity consumption is approximately 16,000 kWh per year, from which approximately 9,000 kWh are used for heating. The house is equipped with temperature and movement sensors in the kitchen, the living room, the bath room and the toilet. It also includes electricity meters that measure the total consumption, total production via PV cells, and heat pump consumption. All these data are sent to the SC module through the middleware.

Figure 5 shows the control structure at Vestervej. The SC module outputs a reference temperature to the heat pump, transmitted through the middleware. This reference is used internally by the heat pump for controlling the hot water outlet. As describedin Section IV, the SC controller is composed of a MPC component and a “glue layer”. In this pilot, the glue layer consists of a room temperature feedback controller and a number of finite state machines. The room temperature controller is a PI controller with a slow integration part, due to the fact that the time constant for the floor heating system is approximately 24 hours. The high level controller sets the reference for the room temperature controller. The finite state machine generates a signal informing the high level controller regarding the presence of users in the home (Some One Home).

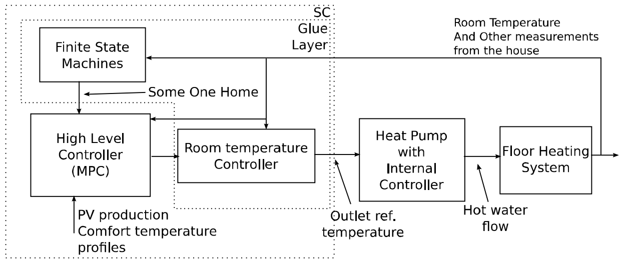

Fig. 5. The control structure

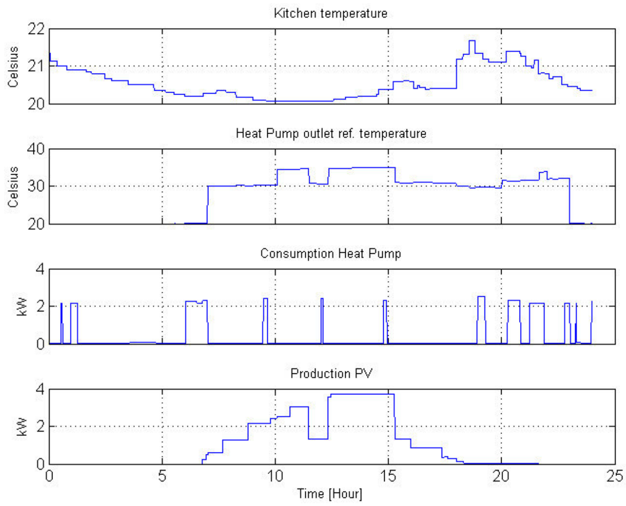

Fig. 6. Measurements for the 26th of March 2014

Figure 6 shows measurements of the different signals for 24 hours. At about 10 o’clock the production from the PV cells rises to a level higher than the consumption of the heat pump. The SC controller reacts by increasing the outlet temperature to make the heat pump use this locally produced electrical energy, storing it inhouse in the form of the higher room temperature.

B. *Jadevej*

This pilot is the main demonstration site for the SC controller, located in a residential area. This site consists of eight residential buildings, which are detached houses located in the Gistrup area, Northern Denmark. Each house is equipped with photovoltaic (PV) cells that can produce up to 4kW of electricity, and that can cover part of the electricity consumption of each individual house. The rest can be purchased either from other producers in the distribution domain, or from the Grid, depending on the price offered by each provider.

The heating system of the houses consists of an electrical floor heating, and measurements showed that the heating system, electric water heater, appliances, and lighting respectively account for the highest to lowest power consumption in each house. A satellite view of the houses taken from Google Maps is depicted in Figure 7.

All the houses are similar and very well insulated. They are occupied by different types of family, young couples, families with children and retired people who are in couple or single. This diversity makes it possible to test different consumption

Fig. 7. Aalborg demonstration site. Houses denoted with red circles are equipped with PV cells.

profiles for load control and energy exchange between the houses, which is the normal case in a medium to large scale power island.

Figure 8 shows a simulation scenario for energy management of one building. Parameters of the building model are chosen based on data from a low energy building that is very similar to the houses in the Jadevej case study. The model is aligned with real scenarios, for example with the Elspot trading system: the sampling time is one hour, which corresponds to the time interval of variations in predicted price profile, and predicted signals are assumed to be available one day ahead. The power price is determined by balance between supply and demand and fixed from 12:45 CET each day to be applied from 00:00 CET the next day[5]. Therefore, the MPC prediction horizon is set to 1 day. The particular price signals that were used, are taken from the Nordpool database for a period of one week in February 2013. Weather data are taken from the Danish Meteorological Institute (DMI). Data on PV cells production were measured in the houses pertaining to the pilot.

Simulation results over one week show that the proposed controller can enable 33% savings compared to an energy minimizing MPC that considers a constant price for the whole day. Compared to an MPC that only optimizes comfort, it enables savings of approximately 50% in electricity consumption cost. However, these savings are excluding energy taxes, which in Denmark amount to 0.82DKK/kWh.

C. Terrassa

The last pilot demonstration described in this work took place in the urban campus of the Universitat Politècnica de Catalunya (UPC) in the city of Terrassa (Barcelona). Its macrocell includes facilities where different activities take place, such as educational, residential, commercial, industrial and other public buildings. The tests of the ENCOURAGE project were carried out in 3 cells, which can be a building or a room pertaining to a single user (see Section III-A).

The first cell is the building of Escola Tècnica Superior d'Enginyeries Industrials i Aeronàutiques de Terrassa (ETSEIAT), an academic building with an area of 11,600 m^2, used by 2,600 students and 240 lecturers and administrative staff. The areas selected for the experiments are all located on the third floor and include a computer room, a lecture room and an office.

[5]See http://www.nordpoolspot.com/

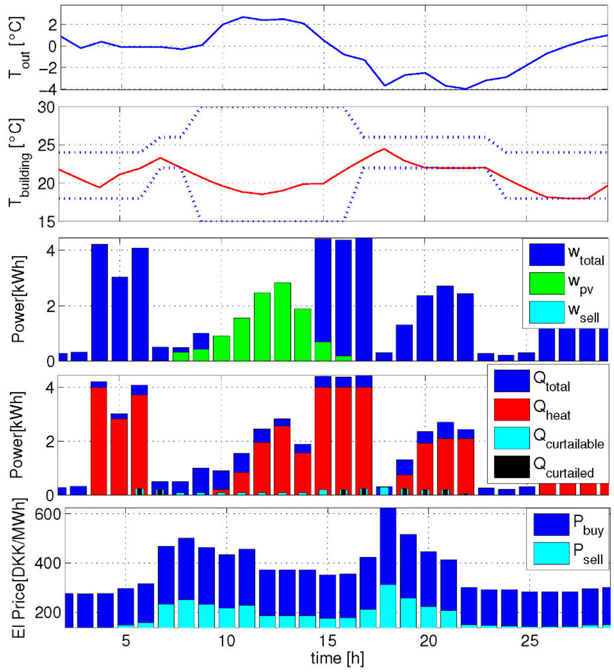

Fig. 8. Energy management of one building in a day. Building temperature is limited between two temperature profiles which are customized based on the user

The second cell is an apartment for lecturers, located in a 5 stories building having two apartments on each floor. The total area of the apartment is 65 m^2, with three rooms between 8 and 11.5 m^2, a dining room with almost 16.7 m^2, a kitchen, a bathroom and a corridor. All rooms have windows with natural light.

The third cell is a student apartment located in the Students' Hall of Residence, which is a five-story building with about 200 accommodations: 36 single rooms with a kitchen, 122 single rooms with shared kitchen and 20 double rooms with a kitchen. All rooms are distributed surrounding a central courtyard. The apartment involved in the demonstration is a single room with a total area of 19.88 m^2.

Each cell was equipped with sensors to measure the energy consumption, the temperature, the humidity, and the presence of people. The ENCOURAGE middleware facilitated the fusion of data from sensors of different brands. The centralized collection of information in the middelware also facilitated the development of strategies and their deployment to implement Smart Grid functionalities. Information from sensors and other devices was transmitted to MPGs through HAN gateways, and the VD module took care of storing the data in the DB. The VD module also distributed monitoring information to an internal service that procesees it to compute a set of Key Performance Indicators (KPIs), to develop user awareness regarding energy usage. The KPIs were developed using a standardized methodology based on 3 steps [9]: define the main strategic objectives and scenario requirements, identify the questions to answer, and finally design KPIs that will answer the former questions. This process identified 6 strategic objectives, developed 15 questions and 37 KPIs were needed to answer all the questions.

Out of the 37 KPIs, 19 of them were selected for user awareness strategies, which targeted two groups of people: building energy managers and end users. The approach was different in the different cells due to their specificity. In the academic building it made sense to provide building energy managers with technical information to help them characterize and diagnose the building. The analysis assisted energy managers in identifying actions and deriving control algorithms to reduce the energy consumption. In the student and lecturer apartments, no dedicated person fulfills the role of energy manager, and the end user was expected to play both the role of consumer and of manager. As non professionals, less technical information was provided to them. In both cases, the information was presented to energy manager and users alike through a web interface.

The use of the KPIs helped energy managers from the academic building to identify excessive consumption during periods where the rooms were supposed to be empty, bad user behaviors, and strategies to reduce the building energy consumption. For example, an excessive consumption was detected during periods where the rooms were supposed to be empty, and it was originated from the computers in standby mode in the PC rooms. By cutting electricity at nights in the PC rooms, it was implemented a reduction of 35% of energy consumption in these rooms. The energy managers estimated that if this strategy was applied in all building PC rooms, the potential energy consumption reduction would be about 6% [9] at the building level.

Energy managers also identified that the energy consumption in the lecture rooms was the same whether it was in use or not, since lights were not turned off after lectures. Moreover, the rooms were sometimes used by students for meetings or group work, instead of the rooms dedicated for that purpose, leading to non-optimized usage of building space. Instead of showing KPIs through web interfaces, the user awareness strategy applied in this context gave advice directly to the users to encourage good practices in the use of buildings. Messages were sent through Twitter, which allows posting messages either privately or publicly, with a maximum length of 140 characters. A database with a set of rules and associated messages was created. Two types of messages were created, to report past events and to report real time events. The messages were based on KPIs and sent to a Social Network Processor (SNP), which evaluated the KPIs through a set of rules to produce the messages. Messages reporting past events were sent periodically (daily or weekly) depending on the rules satisfied. Messages reporting real time events were generated whenever a set of events occurred. Examples of the rules and messages are shown in Table I.

The experiments revealed that in the lecture room the usage of Twitter messages improved user behavior and reduce the energy consumption by 32.51%. However, in the office and PC rooms the results did not produce any savings. Three potential limitations to this strategy were also identified: (i) Difficulty to reach all users, as not all of them use Twitter; (ii) The number of testing rooms was too low (3 rooms); (iii) The students did not perceive the problem, and it was hard to engage them.

TABLE I. EXAMPLES OF MESSAGES SEND BY THE MIDDLEWARE TO THE TWITTER PLATFORM(SOURCE [10]).

Rules	Message	Period
If PC room energy consumption from this week is higher than 1,05*PC room energy consumption from last week, then send one of these messages	Dear PC room users, the energy consumption has increased by [value]% this week. Remember to make the most of solar light whenever possible.	Weekly
	Dear PC room users, the energy consumption has increased by [value]% this week. If you see any unnecessary light turned on, please turn it off.	
If not scheduled lecture and current lectures room energy consumption is higher than 1,05*lecture room energy consumption per type of hour and no movement has been detected during the last half an hour, then send this message.	It seems that lights in the lecture room [name of the room] are turned on, and nobody is inside. If anyone is nearby, please turn off the lights.	Event-based (any time that users action match the rule)

VI. EXPLOITATION

As presented throughout this paper, the middleware was a key enabler for the development of strategies that enable energy savings in the different pilots of the project. It is thus one of the main concrete results of the project, and it is planned to re-use it in other projects, and to allow industrial actors to implement solutions to ENCOURAGE on top of the middleware. To facilitate this, the middleware was recently made open source[6], with the goal of enhancing the performance of Smart Grid applications using the middleware, and reducing development time by removing the need to specify and develop an entire ICT infrastructure.

Another exploitable result from the project is the set of measurement data that was gathered in the middleware DB. This data is expected to be used in on-going Smart Grid project as a basis for the development of energy optimization strategies. Two ongoing examples in this sense are the TotalFlex and Arrowhead projects, which are developing a market for flexible loads [11].

VII. RELATED WORK

In the last few years, a number of international projects have addressed the problem of defining a Smart Grid architecture. Among those efforts it is possible to highlight the results obtained in eDiana [12], ENERsip [13], and ADDRESS [14] projects.

The main goal of the eDIANA (Embedded Systems for Energy Efficient Buildings) project [12] is to enable sustainable urban life through rationalization in the use of resources while increasing comfort in urban environments by means of embedded intelligence and integration technologies. The eDiana project introduced the concept of Cells and MacroCells

[6]Available at https://github.com/cistergit/ENCOURAGE

(see Section III-A), which ENCOURAGE adopted in order to better organize the grouping of devices.

The ENERsip (ENERgy Saving Information Platform for generation and consumption networks) project [13] had the objective of optimizing energy demand, by coordinating consumption and generation. ENERsip provides an integrated architecture for near real-time generation and consumption matching in residential and commercial buildings and neighborhoods. ENERsip and ENCOURAGE address the same domains, although ENCOURAGE assumes the inbuilding domain to be abstracted through the gateways (end points in ENERsip terminology).

The ADDRESS (Active Distribution network with full integration of Demand and distributed energy RESourceS) project [14] focused on solutions to enable active demand and response. ADDRESS also deals with the operation of the distribution network taking into account active demand services, which rely on an aggregator to allow access to the energy markets by small prosumers [15]. This approach is also similar to the solutions currently being developed on the Arrowhead and TotalFlex projects [11].

The architecture of the ENCOURAGE middleware results from an initial architectural analysis described in [4], where functionalities and components were identified. An analysis of current approaches led to a message oriented architecture [16] describing a protocol based on standards, in particular built upon the Common Information Model [5], for compatibility with existing and future Smart Grid middleware, aligned with current efforts to converge to a common protocol [17].

Finally, a detailed description of the SC module and its application to the Jadevej pilot is provided in [18].

VIII. Conclusion and Further Work

This paper introduced the ENCOURAGE middleware, an open source implementation of an ICT infrastructure for the Smart Grid. Its different modules and their interactions were introduced, and an evaluation of its overall performance was presented. The Supervisory Control module developed in the project was then described, outlining the use of the middleware in its implementation and deployment. The results of the project pilots that used the middleware for developing energy saving strategies were then presented.

The future work will essentially consist in maintaining and further developing the middleware to support potential users in making use of it in future applications. To reach that objective, we are working towards building a community of users and developers to maintain and extend the ENCOURAGE middleware.

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