Energy Management Modelling Under Real-time Approach

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***Abstract*—The paper describes modelling, design and testing of the developed Energy Management Strategy (EMS) system simulation model. The project was carried out by NTNU and IPE contributing to CloudGrid, with the aim to develop a new real-time simulation model with price-based Demand Response (DR) program for future implementation as consumer flexibility tool. Real load data were used as the basis of the model that was tested in Real-time Simulator in Norwegian National Smart Grid Laboratory at NTNU, with an algorithm and measurements provided from IPE member side.**

***Index Terms*--Demand Response, Demand Side Management, Energy Management Strategy, Flexibility.**

I. Introduction

The climate and energy targets for 2020 to 2030 binding on the EU Member States provide for the following: 1) cutting of GHG emissions by at least 40% compared to 1990 levels; 2) increasing the share of renewable energy consumption by at least 27% of the total energy consumption; 3) increasing the energy efficiency goal by at least 27% compared to the estimated energy consumption in the future [1]. The main purpose of the Energy Efficiency (EE) is rational use and management of energy resources to promote sustainable development of the national economy and restrict climate changes. In order to contribute to EE, the costs of electricity for consumers must be reduced.

According to the European Commission report [2], home automation technologies enable consumers to optimize electricity consumption as well as help match it to their consumption needs. These technologies can improve market flexibility as consumers would consume less electricity during the energy system peak times and more electricity in subsequent periods when there is enough electricity and capacity in the grid. Such flexibility can ensure the optimal use of the distribution grid as well as reduce the need for transmission system operator to increase the grid capacity and hence tariffs. The aim of this paper is to show the results of algorithm testing under real-time approach and to prove model ability to provide solutions for Energy Management Strategy (EMS) in price-based Demand Response (DR).

II. Technology and Incentives

Demand Side Management (DSM) is the planning and implementation of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape i.e., changes in the pattern and magnitude of a utility load [3], [4].

DSM encompasses the entire range of management functions associated with directing demand-side activities, including program planning, evaluation, implementation, and monitoring [5], [6]. Belonging of the DSM branches to DR and EE is shown in Fig. 1. EE is using energy with least amount of waste energy produced [7], [8]. This means reducing the cost of overall energy consumption with same or greater performance output; generally, it is a passive efficiency. Active efficiency can be achieved with DR. DR is the change in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.

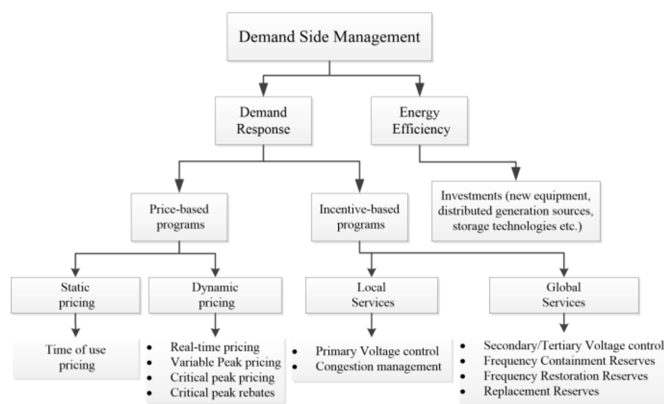

Figure 1. Demand Side Management core elements

In this research, we are taking into account solutions for EMS in the price-based DR. Using these solutions users can create their own load response to hourly changes in electricity market prices by shifting hourly loads from higher price periods to lower, resulting in user profit.

III. Electricity Consumption Aggregation and Management

The IPE pilot technology was used for energy consumption data accumulation and analysis. The technology has an aggregation capability and is aimed to optimize

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electricity consumption, reduce electricity bills for consumers and improve energy efficiency [9].

A. Technology

The technology is a set of tools that enable the user to gain financial benefits from electricity market price fluctuation using modified existing load work patterns based on price signal. Tool set consists of processing and data storage equipment – control panel, and measurement and command execution equipment – smart sockets, ensuring smart load management and monitoring (see Fig. 2).

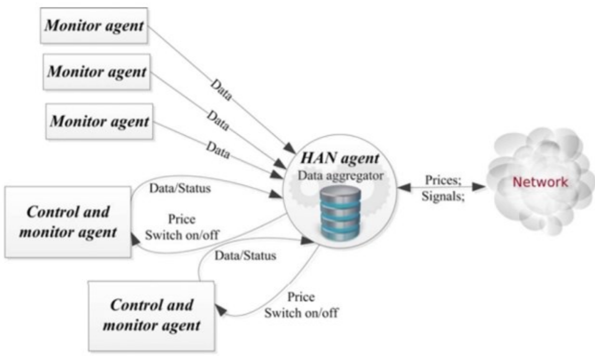

Figure 2. Energy consumption data analysis and aggregation

The technology is capable of automatic data collection and load management based on electricity market price. Comparing electricity market prices, a decision is made to carry forward electric device on going operation to a later time, when market price is lower. In practice, load management can be achieved through smart appliances, which use wireless radio signals for receiving load 'on/off' commands and command execution is performed by physically stopping the load supplied through the smart socket.

B. Consumption data analysis and aggregation

The approaches chosen are applied to accommodate various building loads, taking into account the limitations of the connected load, which includes the maximum load shutdown time and the minimum operation time, as well as take into account the impact of sensors (temperature, humidity, etc.) on the functioning load.

Load management and planning is structured considering the economic benefit, if there is a price difference between two hours, i.e., the system carries out the above-mentioned activities, reducing the total cost of electricity of the user and providing flexibility to the system (Fig. 3).

The IPE proposed system (see Fig.2) was verified during European Research Infrastructure supporting Smart Grid Systems, Technology, development, Validation and Roll Out (ERIGRid) Transnational Access visit [10]. Within this paper, all described tests match the Fig.3 green zone; however, other test cases described in EMS figure could also be performed under the proposed IPE technology. The main idea of the smart socket system and its control algorithms was divided into three parts: socket hardware development, software for data accumulation in Raspberry PI [11] as data server and algorithms for smart load control based on price signal DR. Two different types of load groups were confirmed to be use for DSM realization via IPE smart socket system (see Section IV).

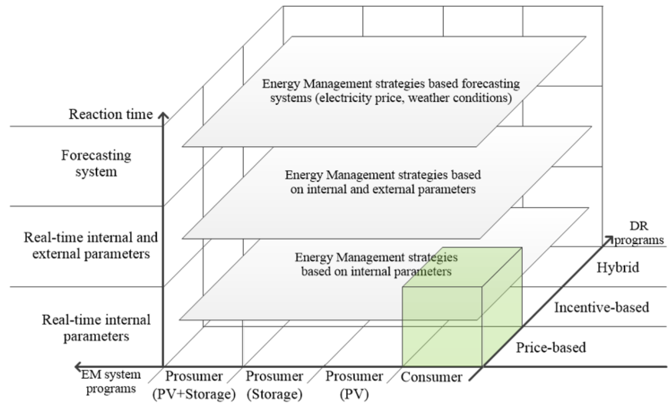

Figure 3. Architecture of Energy Management Strategies

A decision was made to test the algorithm part of the smart socket in OPAL – RT system before final parsing of software to the hardware. We propose the holistic testing under real-time system for the functions (algorithms) to set out the following objectives:

- Characterization tests – prove that the model can work under real-time conditions
- Validation tests – prove that algorithms are ready for hardware implementation and commercial realization

In Fig. 4, the holistic test case structure is shown that was developed during ERIGrid Transnational Access. Building simulation model under which we are using building load data from IPE building, electricity market price from Nord Pool (NP) day-ahead prices [12], Building Energy Management System (BEMS) where algorithms for control are applied (see Section IV) and two types of load groups controlled [13].

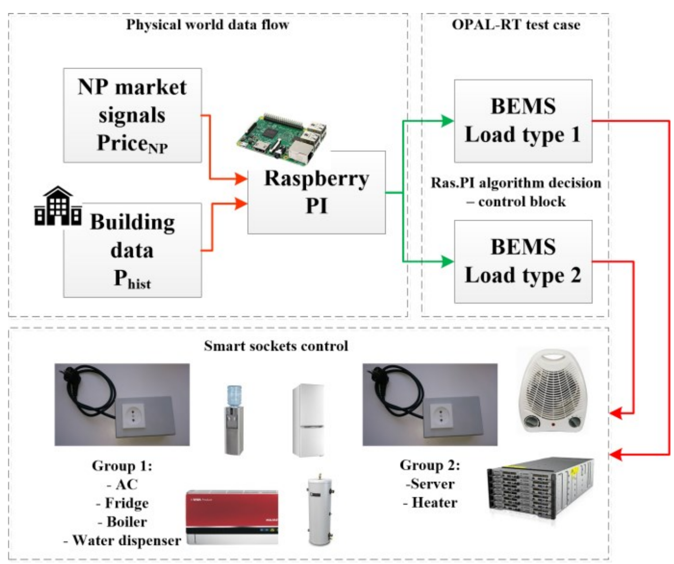

Figure 4. Building simulation model

The paper focuses on the results from flexible load tests to show the potential impact on different load type and algorithmic approach to energy efficiency and DR realization [13].

IV. Test Cases

EMS model is based on continuously collected historical consumption data of a real commercial type building – IPE building. The model has flexible loads implemented with load control based on electricity market price from NP and local load peak reduction. EMS model contains two flexible load types – hour ahead and +3h horizon.

A. *Flexible load types*

First flexible load type is hour ahead load type; this type incorporates limitation of next hour shift range. Shift limitation is tightly based on temperature sensors and heating/cooling elements within used loads under this group. In the EMS model, under hour ahead type loads are - boilers, fridges, AC (Air-Conditioning) and "Venden" water dispenser. Shift performance is created by increasing overall consumption hour after shutdown hour by increasing unit operation power or extending its intended working period. Sequential load shifts can occur if the load is available and the price is right. Each hour electricity market price Pr_h (in EUR/MWh)) is compared with the following hour price Pr_{h+1} (in EUR/MWh) in search of minimum value, where time in hours is h (in hours):

$$\sum_{h=1}^{24} \mathrm{Pr}_{h+1} - \mathrm{Pr}_h \leftarrow \min \tag{1}$$

First flexible load type has the following constraints, where $Load_{a,h}$ (in kWh) is the available load at actual hour:

$$\begin{cases} \mathit{If}\ \mathrm{Pr}_{h+1} - \mathrm{Pr}_h > 0,\ \ Load_{a,h} \leftarrow Load_{a,h} \\ \quad Else\ Load_{a,h} \leftarrow 0 \end{cases} \tag{2}$$

When constraint results in (2), reports better price for actual hour than the following next hour, the load is not shifted and used at that moment. Otherwise, load usage is shifted to the following hour, while actual hour load for this load type is 0.

The second flexible load type is +3h horizon, similar to previous load type, but with an extended shift period of 3 hours forward from the initial hour. This load type includes loads with continuous consumption periods and planned forwarded actions. In the present EMS model, this group type includes the following loads – heaters and servers. A shift is performed by moving entire consumption from the initial hour to the following three hours. Multiple shifts can occur per load, but if one shift is ongoing another shift on initial shifting load cannot occur in between shifting process. Each individual hour Pr_h (in EUR/MWh) is compared to the three following hours Pr_{h+1}, Pr_{h+2}, Pr_{h+3} (in EUR/MWh) in search of the minimum value:

$$\sum_{h=1}^{24} \begin{Bmatrix} \mathrm{Pr}_{h+1} - \mathrm{Pr}_h \\ \mathrm{Pr}_{h+2} - \mathrm{Pr}_h \\ \mathrm{Pr}_{h31} - \mathrm{Pr}_h \end{Bmatrix} \leftarrow \min \tag{3}$$

The second flexible load type has the following constraints, where price difference ΔPr (in EUR/MWh) is compared and decision of flexible load $Load_{b,h}$ (in kWh) use at actual hour or shifted to desired shift time $Load_{b,h+i}$ (in kWh) is made:

$$\begin{cases} \mathit{If}\ \min(\Delta \mathrm{Pr}) > 0,\ \ Load_{b,h} \leftarrow Load_{b,h} \\ \quad Else\ Load_{b,h} \leftarrow 0, \\ \quad Load_{b,h+i} \leftarrow Load_{b,h} + Load_i \end{cases} \tag{4}$$

The main target is to achieve minimum total costs C_{total} (in EUR), this cost contains shifted load expenses $C_{shifted}$ (in EUR) with both flexible load types and rest of the base load costs $C_{base.load}$ (in EUR):

$$C_{total} = C_{shifted} + C_{base.load} \leftarrow \min \tag{5}$$

B. *Flexible load description*

EMS model contains six different loads, divided into previously mentioned flexible load types. Fig. 5 depicts single unit shift process from each load group within an 8-hour scope. Areas colored in blue represent the shifted load.

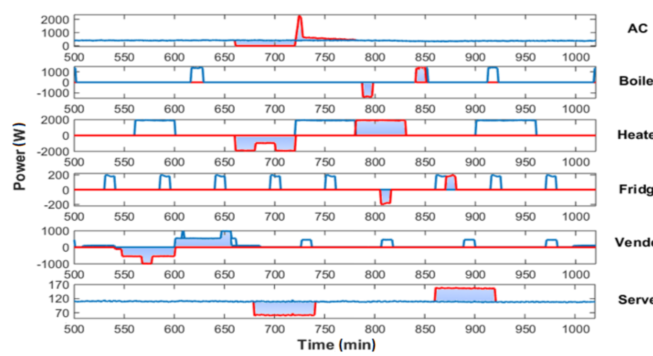

Figure 5. Load shift per unit type

Boiler is an hour ahead flexible load type, shift to the next hour creates an extended period of consumption. This load is non-continuous and availability each hour is estimated based on water temperature and recent user interaction. Boiler continues its working pattern during off-work hours.

Fridge as a part of hour ahead flexible load type is limited to next hour shifts. The load is highly repetitive and user interaction does not create any significant pattern changes. Availability is expected every hour and shifting is performed by extending working period. Similarly, to boiler, this load keeps its work during off-work hours.

AC is a unique load in hour ahead load type group. According to IPE collected data, AC consumption is greatly under its limits, because this shift to the next hour is performed by increasing AC initial consumption by 80% of previous hour consumption, which is approximated by ambient temperature at the set hour. This load is work hour only load, because of its high consumption.

"Venden" water dispenser has last hour ahead load type. This load has two discrete passive cycles and an active user interaction use cycle. Availability of this load is not determined beforehand, because the high availability load can be expected every hour of the day. "Venden" similarly to AC is strictly work hour load and is switched off, otherwise.

Heater load is in the +3h horizon load type. Based on tested units with two heating setting and IPE gained user experience, the shifted load can be divided up to two hours in the 3-hour further horizon. The shifted load can be added to sequential and non-sequential hours. Heater load availability is highly based on user interaction and under certain outside temperatures this load is likely to be expected. This load only occurs during work hours, since user interaction is mandatory.

Server active load is part of +3h horizon flexible load type. Unlike heater load, server active load can be shifted exactly to a desired best market price in the 3-hour further horizon, because of non-direct user comfort interference. Load availability is not estimated; at the moment of active load activation the decision of shift is determined.

Test case results of each appliance group used can be seen in Table I, Table II and Table III.

TABLE I. TWICE MAX PRICE SHUTDOWN

Load	Savings (EUR)												
	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Total***
AC[a]	1.73	2.36	1.63	1.97	3.60	1.34	1.14	1.68	3.40	2.58	1.80	1.55	24.79
Boiler[a]	0.22	0.21	0.19	0.25	0.22	0.23	0.10	0.28	0.27	0.33	0.13	0.08	2.51
Heater[a]	0.23	0.89	0.70	1.15	0.32	0.12	0.10	0.09	0.58	0.94	0.84	0.53	6.50
Fridge[a]	-0.05	0.24	0.24	0.23	0.29	0.00	0.00	0.00	0.27	0.27	0.25	0.22	1.97
Venden[a]	-0.04	0.22	0.16	0.26	0.18	0.25	0.12	0.37	0.30	0.32	0.25	0.15	2.55
Server[a]	0.02	0.04	0.03	0.04	0.05	0.05	0.03	0.05	0.04	0.03	0.02	0.01	0.40
Total	2.12	3.98	2.95	3.90	4.66	2.00	1.49	2.47	4.85	4.48	3.30	2.54	38.71

a. Represents 10 units in group.

TABLE II. LOCAL LOAD PEAK SHUTDOWN

Load	Savings (EUR)												
	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Total***
AC[a]	0.92	1.23	0.76	0.74	1.19	0.56	0.53	0.69	1.33	1.11	0.82	1.02	10.89
Boiler[a]	0.01	0.08	0.03	0.01	0.01	0.00	0.01	0.05	0.00	0.04	0.06	0.12	0.42
Heater[a]	0.11	0.59	0.34	0.15	0.11	0.00	0.00	0.00	0.02	0.24	0.31	0.55	2.43
Fridge[a]	0.22	0.22	0.21	0.19	0.22	0.25	0.23	0.27	0.23	0.23	0.22	0.23	2.73
Venden[a]	0.02	0.18	0.06	0.01	0.01	0.01	0.05	0.05	0.00	0.08	0.11	0.22	0.81
Server[a]	0.01	0.03	0.02	0.04	0.05	0.05	0.02	0.05	0.04	0.03	0.02	0.02	0.39
Total	1.29	2.33	1.43	1.14	1.59	0.87	0.85	1.11	1.63	1.73	1.55	2.16	17.67

a. Represents 10 units in group.

TABLE III. TWO LARGEST PRICE DIFFERENCE SHUTDOWNS

Load	Savings (EUR)												
	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Total***
AC[a]	1.77	2.25	1.29	1.96	3.66	1.38	1.13	1.85	3.06	2.25	1.50	1.47	23.57
Boiler[a]	0.12	0.19	0.12	0.20	0.24	0.26	0.13	0.42	0.21	0.23	0.16	0.14	2.43
Heater[a]	0.43	0.97	0.61	1.38	0.47	0.00	0.00	0.00	0.55	1.15	1.23	0.46	7.25
Fridge[a]	0.31	0.32	0.29	0.31	0.40	0.41	0.37	0.47	0.35	0.35	0.30	0.30	4.17
Venden[a]	0.16	0.36	0.18	0.37	0.31	0.54	0.24	0.71	0.38	0.41	0.36	0.28	4.32
Server[a]	0.02	0.04	0.03	0.04	0.05	0.05	0.03	0.06	0.05	0.04	0.03	0.02	0.45
Total	2.81	4.13	2.52	4.26	5.14	2.64	1.90	3.52	4.60	4.42	3.58	2.67	42.19

a. Represents 10 units in group.

C. *Flexible load description*

EMS model calculations are limited to real IPE building consumption data, reducing the active time for both flexible load types to working days; shift occurrence is limited up to two times within working hours from 8:00 to 17:00, where flexible load use is concentrated.

Three cases have been tested and results summarized. First case is twice shutdown at the highest market price in the working hours, the results are given in Table I. Second is the shutdown at a single hour – 11:00 to 12:00, the local peak load at IPE building complex, the results are presented in Table II. Lastly, up to two shutdowns between hours with the largest price difference in the working hours were considered (see Table III for the results).

V. Conclusions and Future Work

Fossil fuel free energy markets are designed to unlock flexible energy sources for energy consumers, where energy consumers can make an important contribution to reducing emissions by adopting efficiency and curtailment behaviors. The use of price signals aims at making EE choices more financially attractive. An intervention with real-time energy information seems to be more effective in savings, providing consumers with detailed energy-use information.

Under the study, the authors were focused on flexible load use. Flexible load shifting in comparison to a simple load cut-off provides lower benefit, but the main aim of these tests was to check if it is possible to gain benefits without losing user comfort level or to do it with a slightest impact on it. As authors are focusing their technology on office/commercial type buildings, the scope of shift-able devices is limited. On the other hand, device consumption level might be higher due to task difference in load types.

Summarizing all test results, we can conclude that best key performance for load shifting without comfort level decreasing are AC and "Venden" water dispenser, providing high income rate and high variability of load demand. Heater by itself could give a large benefit for the user; however, affecting this load may slightly decrease user comfort level and it cannot be controlled with the same flexibility as the AC. Stable savings in load shifting can be provided by planned server model calculations run or even OPAL-RT system test performance shifting in the closest hour horizon, with more powerful units increasing its potential benefit.

Test case results show that load shifting can be used as the main option for DSM realization, as its sole performance does not decrease user comfort level. However, the user must have high density of the same devices that could provide such type of savings. Therefore, DSM approach should be done with multiple implementations of peak-cutting, load cut-off and load shifting for greater increase in technology efficiency with proportional saving increase.

As a future work, the authors plan to show multiple test case implementations under different types of add-ons (solar generation, energy storage etc.) taking into account the possibility of using device load with other interactions (cut-off, shifting etc.).

Acknowledgment

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