Demonstrating smart buildings and smart grid features in a smart energy city


Boran Morvaj
ETH Zurich


Luka Lugaric
Dubai Supreme Council of Energy


Slavko Krajcar
University of Zagreb

Demonstrating Smart Buildings and Smart Grid features in a Smart Energy City

B. Morvaj, *Student, IEEE,* L. Lugaric, *Graduate Student Member, IEEE,* S. Krajcar, *Senior Member, IEEE*

Abstract-- **The paper gives an overview into the features and paradigms of a smart energy city in the framework set for the evolution of existing cities and their transformation to smart cities. The potentials of smart buildings has been scrutinized and put into perspective as the basic building block of cities. A draft model has been developed in Anylogic using system dynamics to demonstrate basic features of several smart houses, equipped with (1) demand side management capabilities, (2) micro renewables (solar and wind), (3) micro energy storage, (4) basic electricity-price based consumption controller. The smart building responds to price signals from the market.**

The system shown is being coupled with parallel initiatives of smart metering, micro-size renewables and energy management initiatives at the Faculty of Electrical Engineering and Computing, Power Systems Department.

KEYWORDS: **demand side management, price based consumer response, smart building, smart grid, renewable energy sources**

I. Introduction

THERE are numerous definitions of the term 'city' depending on countries, but the most common one defines 'city' as a relatively large and permanent settlement [1]. A city has highly dense population and its inhabitants, citizens, mostly live from work connected with industry, commerce and services. Operationally, cities are based on a number of core structures: energy, water, transport, information and telecommunication infrastructure, business market, city services, citizens and sanitation.

In 1950s, around 30% of the world population lived in the cities whereas in 2010 it was established that the percentage increased to 50% and is projected to be 70% by the year 2050 [2]. Cities are becoming economic, political and technological power centers [3]. With the increase of population and number of businesses cities now face the challenge of combining competitiveness on a global cities scale and sustainable local urban development. Also, there is a big strain on the environment and the emission of the greenhouse gases that must decrease. Cities occupy only 2% of the Earth's surface but emit almost 80% of global carbon dioxide and significant amounts of other greenhouse gases [4]. In addition to improving their competitiveness, innovation potential, governance and delivery of services to the citizen, cities also must improve environmental performance and energy efficiency. The EU Climate Action and Renewable Energy package obligates European Union member states to decrease greenhouse gas emissions by at least by 20% compared to 1990 levels by 2020. In 2009, over 400 European cities pledged to go beyond 20% CO2 reductions, as established in one of the basic tools established by the EU, targeted at the level of cities - Covenant of Mayors [5].

To decrease emissions and increase their energy, economy and information efficiency, cities must undergo a change in their organization and infrastructure, while maintaining secure and continuous access to critical infrastructures. Critical infrastructures are systems and assets, whether physical or virtual, so vital to the community that incapacity or destruction of such systems and assets would have a debilitating impact on local security, economic security, public health or safety, or any combination of those matters [6].

Electric power systems are a critical infrastructure underlying all other infrastructure systems. Disruptions in the power system have severe economic and social consequences, even for short periods of time [7]. Therefore disruptions must be avoided if possible. Today, electric power infrastructure is using more and more information and communication technology (ICT) elements. Renewable energy sources are accessible to an increasing number of people. Solar photovoltaic panels are falling steadily in price and size [8] so it is becoming a plausible possibility to create a cluster of distributed generation installation, so called virtual power plant, and using demand side management to enable near-uninterruptible power supply. This would require an intelligent and advanced control system to take the full advantage.

The electrical energy system is a critical infrastructure underlying many other critical and non-critical infrastructures is the focus of this paper. However, it is not the only system that needs to be improved - for the cities to cope with the incoming challenges; they need to improve all systems simultaneously. The whole city must be upgraded to a so-called "smart city".

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II. Concepts and Definitions

A. Smart city

We define a smart city as a city that continually increases its performance in satisfying all needs of its citizens.

This is aligned with definitions in literature [9], where a smart city is a city that combines ICT with its physical infrastructure to improve conveniences, facilitate mobility, add efficiencies, conserve energy, improve the quality of air and water, identify any problems in the operation of city systems and fix them quickly, recover rapidly from disasters, collect data to make better decisions and deploy resources effectively and efficiently. It cannot be viewed as a sum of parts but holistically as a network of interconnected infrastructures dependent on each other. It can be debated whose infrastructures and systems are the ones that make the core of the smart city but usually they are often narrowed down to the following:

1. Citizens,
2. Water and energy.
3. Communication,
4. Business,
5. Transport,
6. City services,

Energy production currently accounts for between 30 and 40 percent of all water withdrawals in the OECD [10]. Also energy use is responsible for approximately 75% of greenhouse gases emissions and utilities. Additionally, according to the European third legislative package, consumer choice, fairer prices, cleaner energy and greater security of supply are focal points in both short term and midterm development of cities. Therefore, in a smart city it is very important to increase energy efficiency and decrease total energy consumption, simultaneously maintaining an open and fair internal energy market. To accomplish that, the smart city must implement the smart grid concept and technologies into its energy infrastructure.

B. Smart grid

A smart grid is a concept that combines ICT and electrical power grids. Its main feature is establishing two-way communication in all nodes of the grid using advanced metering infrastructure. With customer involvement (passive and active) it can improve overall energy efficiency and reliability of the grid, and decrease energy consumption. It also enables control and optimization of renewable energy sources and demand side management programs by delivering real-time information to control nodes, enabling near-instantaneous balance of supply and demand at the level of individual consumers – buildings, even appliances.

C. Focus on buildings as energy units

Cities occupy only 2% of the Earth's surface yet produce over 70% of greenhouse gas emissions [13]. 70-80% of these emissions come from buildings; hence buildings are the basic unit of observation when considering infrastructure systems.

Today, most of the buildings are passive consumers of energy and cannot communicate with the outside world. Also, the percentage of buildings emission compared to the total of the city is increasing. To be aligned with policy goals as outlined earlier, utilities must transform the consumer from passive, unresponsive users of energy to an active participant in the power system. Furthermore, due to peak demand as much as 20% of total generation capacity is used for only 5% of time in today's power grids [VII] and with demand response peak value can decrease by 20-50% and overall consumption of electricity can decrease by 10-15% [11] which creates huge financial savings. For these savings to start accruing, current buildings must be upgraded to smart buildings which can communicate with its surroundings, and users can view their energy consumption in real time and be an active member of the demand side management.

D. Smart Building

The term smart buildings have been used for more than a two decades to introduce the concept of networking devices and equipment in the building, and energy efficiency. In second half of 1970s it was a building that was built using a concept of energy efficiency and in 1980s it was a building that could be controlled from a house PC.

Today, smart buildings use the 1970s and 1980s concept with additional subsystems for managing and controlling renewable energy sources, house appliances and energy consumption using most often a wireless communication technology. ICT enables smart buildings to communicate both with its inside devices and appliances, which they can also control, and with its surroundings. Furthermore, they can adapt to grid's conditions and communicate with other buildings, hence creating active microgrids or virtual power plants.

As shown in Figure 1, in general the smart building consists of:

- Sensors - monitoring and submitting messages in case of changes;
- Actuators - performing a physical action;
- Controllers – controlling units and devices based on programmed rules set by user;
- Central unit – enabling programming of units in the system;
- Interface - the user communication with the system;
- Network - allows communication between the units
- Smart meter - offers two-way, near or real-time communication between customer and utility company

Sensors, actuators, controllers, central unit, interface with network standard make a building automation. The smart energy building has in addition to mentioned components also energy storage and small renewable energy source.

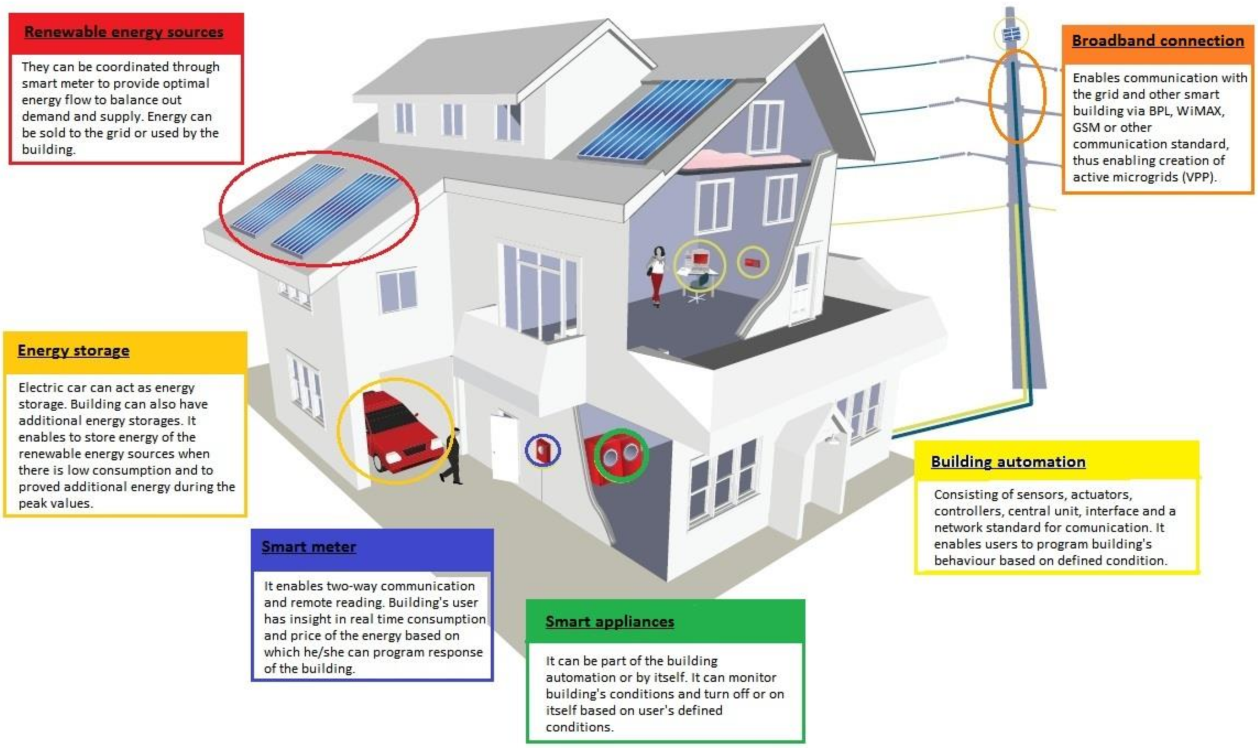

Figure 1. Smart energy building

E. Smart meter

Traditional meters can only provide one-way information and must be read in person by a meter reader. Smart meters are digital meters that offer two-way communication allowing for more interactivity between the consumer and utility. A smart meter can be water, gas, electricity and heat meter. In this paper it refers to a smart electricity meter.

Characteristics of a smart meter are:

- Near or real-time measuring of a consumption of the electricity usage and the amount of the electricity generated locally;
- Can be read both remotely and locally;
- Utilities could use the smart meter limit the amount of electricity going to or from the smart building or even completely disconnect the customer.

The smart meter acts like a gateway for the smart building to communicate with the rest of the grid. GSM, Broadband Over Power Line (BPL), WiMAX, Internet and other wireless communication standards can be used as a standard for the communication.

This communication is bidirectional. Utilities can read the meters remotely in real time and they can send price signals to the end customers. Customers have an overview of their consumption and price of the electricity in real time. By that way customers can respond to the occurrences in the grid which is the concept of the demand response.

F. Demand response program

Demand response programs can be described as a means to encourage consumers to reduce consumption, hence reducing the peak demand for electricity. We emphasize this must be done at minimal or no loss of living comfort to the consumer.

Utilities use demand response capabilities when there is a shortage of supply for a relatively short time. Demand response programs provide customers with signals upon which loads can be adjusted. This is done by programming the central unit of the building automation to turn off specific load(s) in the building when specified condition is fulfilled (e.g. when the price is higher than some value or if the energy consumption exceed the specified value), in line with preset user preferences regarding time of use of certain appliances.

Demand response (DR) programs can be classified into three groups [12]:

- Incentive-Based: represents a contract between utility and customer to ensure demand reductions from customers at critical times. This DR program gives participating customers incentives to reduce load during the agreed period which may be fixed or time-varying. Examples of the programs in this group are Direct Load Control and Interruptible & Curtailable Load.
- Rate-Based: a voluntary program where the customer pays a higher price during the peak hours and lower price during the off-peak hours. The price can vary in real time or a day in advance.

- Demand Reduction Bids: refers to relatively large customers to reduce their consumption. In this program customers send a demand reduction bid, containing demand reduction capacity and the price asked for, to the utility.

It is predicted that demand response programs in Europe could save 202 TWh annually and reduce the emission of CO2 by 100 million tons, avoid €50bn worth investments related to peak generation capacity and save €25bn annual on electricity bills for customers [9].

III. MODEL

In the present grid, supply reacts to demand. If there is an increase in demand, additional regulating power plants need to be turned on which can be unfeasible. This is avoided in the smart grid paradigm since it presents an ability to control both the demand and supply side of the grid. The smart grid vision assumes all buildings have a small renewable energy source installed and in case of increase of demand it can act as a small power plant both externally to the grid and internally for its own consumption.

In this respect, the smart city, with its smart grid will require coordination mechanism (operator) that will enable integration and cooperation of various energy sources and loads (buildings or smaller) using the energy management to provide optimal energy flow. The model consists of 2 levels:

- First model level is a smart building modeled as an agent that responds based on price signal from the grid/market operator;
- Second model level acts like an environment of the smart building agent.

Main level represents the utility, and its energy management of the smart grid and consumption. In this model we try to present aspects of energy management both from utilities and customers using controllable loads, renewable energy sources and energy storage. The model consists of 5 smart buildings; each equipped with a small renewable energy source, in this case photovoltaic panels, and energy storage in the form of batteries.

A. *Energy management algorithm*

In the model, energy management is implemented through demand response management. Demand response program is based both on the price signal's value response and direct load control from the utility. Since the scope of this paper is not modeling of the energy market, in order to simplify the behavior of the value of the price signal, it changes by the following rule: if the supply is lower than the demand the

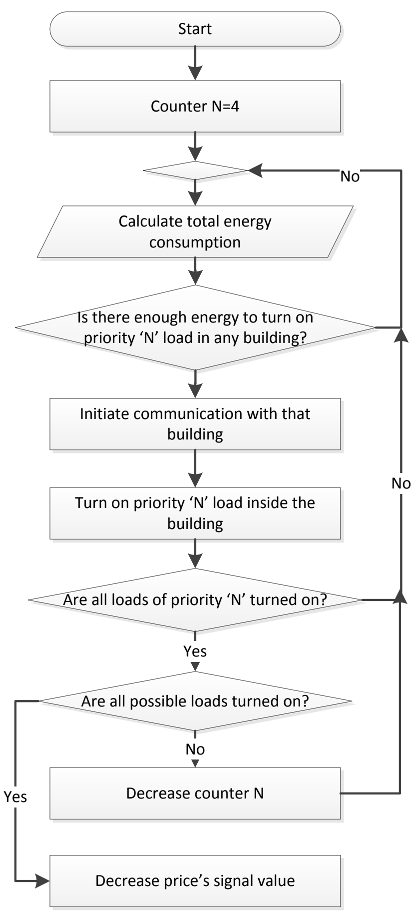

Figure 3. Algorithm for regaining energy from the main model level

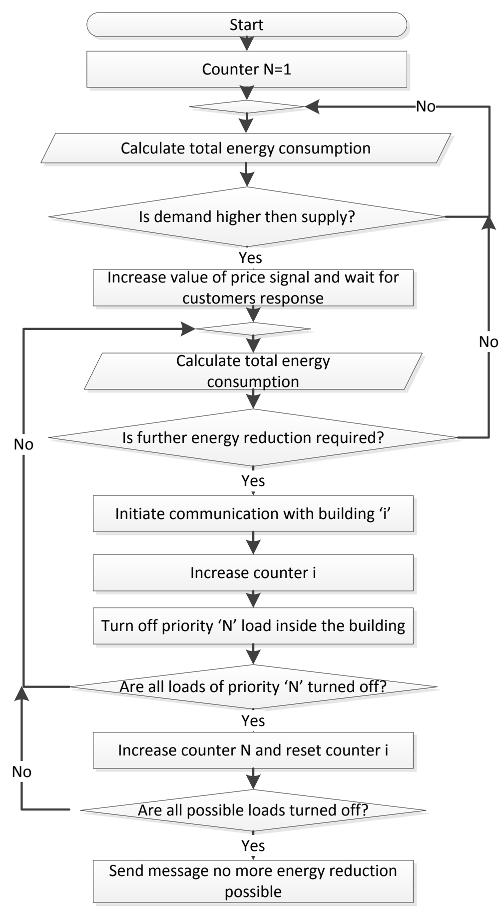

Figure 4. Algorithm for reducing energy consumption from the main model level

price signal's value increases linearly and vice versa- if the supply is higher than demand price signal's value decreases linearly.

The imbalance of supply and demand can be the result of the increased or decreased consumption and increased or decreased output of the renewable energy resources. In case of the shortage of the supply, the price signal's value increases and (some) buildings respond by turning off controllable load(s).

Not all customers will respond in the same way to increase of price signal's value and in order to simulate that, uniform distribution was used. Uniform distribution is a probability distribution in which all intervals of the same length of the distribution's support are equally probable. The support is defined by the two parameters that define minimum and maximum values.

Human behavior cannot be deterministically described. Some customers will set their building automation to act on smallest price signal's value change by turning off specified loads. Others will set their building automation to respond on higher price signal's value and may not respond at all. In this model it was assumed that all customers will respond but not in the same way. Uniform distribution simulates that behavior.

Since not all customers respond to the change of price signal's value, so consumption reduction will not be enough, driving the utility to use direct load control to directly turn off controllable loads.

In this model it was assumed that all the customers made a contract with the utility to allow for the utility to directly control predefined loads. Direct load control can also be used if there is a need of quick response.

In case of lower demand compared to supply, the price signal's value decreases thus encouraging the customers to store the energy from the renewable energy sources and to turn on the loads that they may have turned off before due to the price signal's value increase.

Algorithms for reducing energy consumption and regaining energy capacities are shown in Figure 3 and Figure 4.

A. *Buildings*

Each smart building has (controllable) loads, energy storage (battery), a small renewable source (PV) and a building automation. Each building is a part of a demand response program and utilities can turn off up to 4 loads in the building if needed. Each building has a priority list of these 4 controllable loads. The priority list is a list where loads are scaled from the least important, the ones that the owner of the each building thinks it will make the least impact on his/her comfort and will be turned off first if needed, to the most important, the ones that will be turned off last and turned on first. The list goes from the number 1, which marks the least important load, to the number 4, marking the most important load. Graphical overview of this model is shown in Figure 5.

Every smart building is simulated as an agent, as shown in Figure 6. The building has built-in automation systems (AS). AS is programmed to turn off specific loads based on price signal's value based on uniform distribution, as explained before. Turning off and on these loads is also based on the

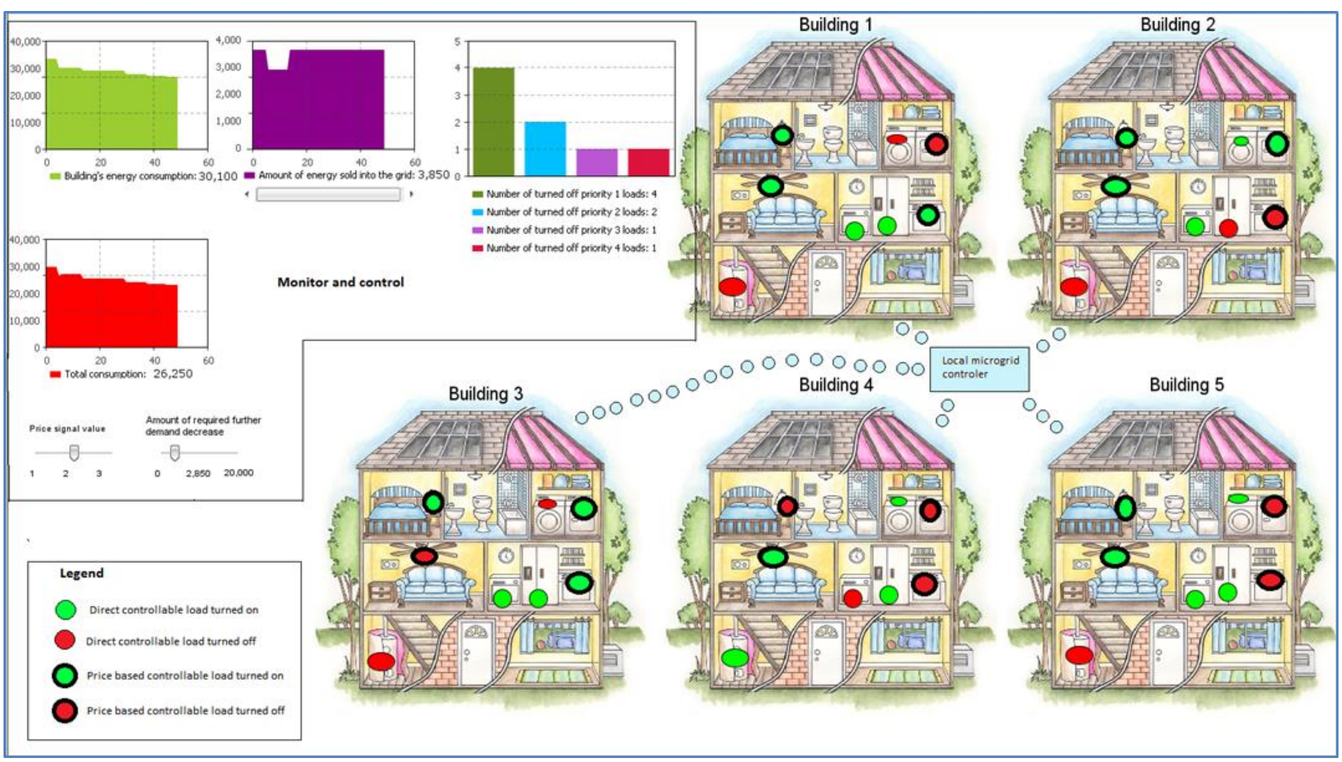

Figure 5. The main model level - 5 smart buildings with inbuilt building automation, small PV and smart metes. Each building is agent-based. Green circles inside buildings represent visually which loads are turned on.

priority list.

In the case of the higher price signal's value, the AS initiates consumption of energy directly from the renewable energy source if it is available. If the price value rises, the AS turns off controllable loads based on the priority list. In the case of the lower value of set price signal the AS first turns on, also based on the priority list, turned off controllable loads and on further price's value decrease stops using directly energy from renewable energy source and stores energy from renewable energy sources if available.

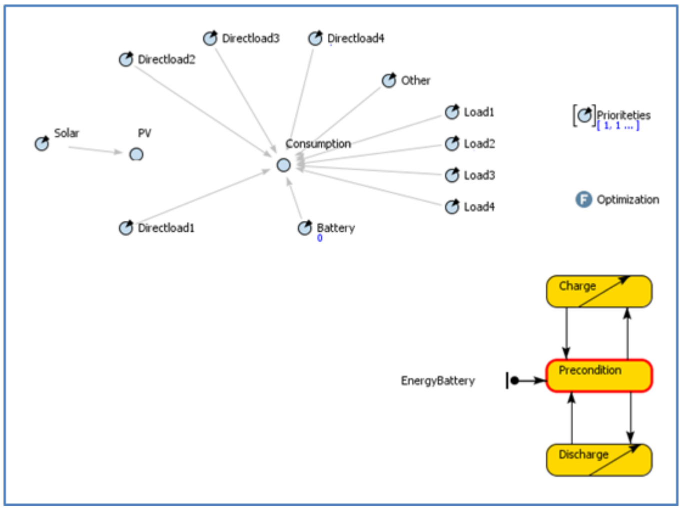

Figure 6. Smart building agent implemented using discreet modelling and system dynamics. Each agent has 4 direct controllable loads and 4 controllable loads based on price signal's value.

IV. SIMULATION

A. Simulation tool and concept

The simulation was performed using Anylogic 6 [14]. AnyLogic is a general-purpose modeling and simulation tool for discrete, continuous and hybrid systems. The simulation uses an agent based and system dynamics modeling. As mentioned before the model consists of 2 levels. First one is a smart building that is modeled as an agent that comprises system dynamics and responds based on price signal's value, and the other level is the main level, that acts like an environment for the agent – smart building. Main level represents the utility, and its energy management of the smart grid and consumption.

B. Scenarios

The following scenarios were used to analyze the response:

1. At a specific time there is a higher demand than supply which causes the increase of value of price signal.
2. After scenario 1 there is a sudden drop in supply which could be caused by some malfunction. The price signal's value increases.
3. After an hour the malfunction is fixed and the state reverts back to scenario 1 condition followed by decrease in price signal's value.
4. After the conditions return to default, the demand decreases and the price signal's value decreases also.
5. There is a decrease in demand which causes the price signal's value to decrease.
6. After the conditions return to default, the demand increases and the price signal's value increases.

C. Results

In the first case, only price based response was monitored using previous stated scenarios. The results are shown in Table 1 and Figure 7.

TABLE I
PRICE BASED RESPONSE OUTPUT OVERVIEW

Scenarios	Required output[W]	Obtained output [W]
1	27790	28490
2	23870	23660
3	27790	27970
4	31150	31150
5	35140	35000
6	31150	31150

Only in scenario 2 the obtained output was lower than required and scenario 5 was close enough to the required output. This means that only in scenario 2 no further reduction was required, while scenarios 1 and 3 required additional reduction. It can be noted that values of scenario 1 and 3 are not the same even though the required output is same. This is due uniform distribution which simulates different customers' response.

In the second case, both price based responses and direct load was used. The results are shown in Table 2 and Figure 8.

TABLE II
PRICE BASED RESPONSE AND DIRECT LOAD CONTROL OUTPUT OVERVIEW

Scenarios	Required output [W]	Obtained output [W]
1	27790	27356
2	23870	23660
3	27790	27356
4	31150	31150
5	35140	35000
6	31150	31150

In this case, when using both price based and direct load control all required outputs were satisfactory. In scenario 1 and 3 direct load control was needed to provide additional reduction to price based customers' response.

The price based response was not always sufficient in reducing consumption to the required amount. In scenarios 1 and 3 additional direct control was required. Due to the direct load control, amount of saved energy is $(28490\,W - 27356\,W) * 3h + (27970\,W - 27356\,W) * 3h = 5244\,Wh$ compared to only price based response. That may not seem much but with a larger number of smart buildings this savings accrue quickly. In scenario 5, when there was higher supply then demand, due to storing energy from PV to battery, additional $(35000\,W - 31150\,W) * 3h = 11550\,Wh$ was used.

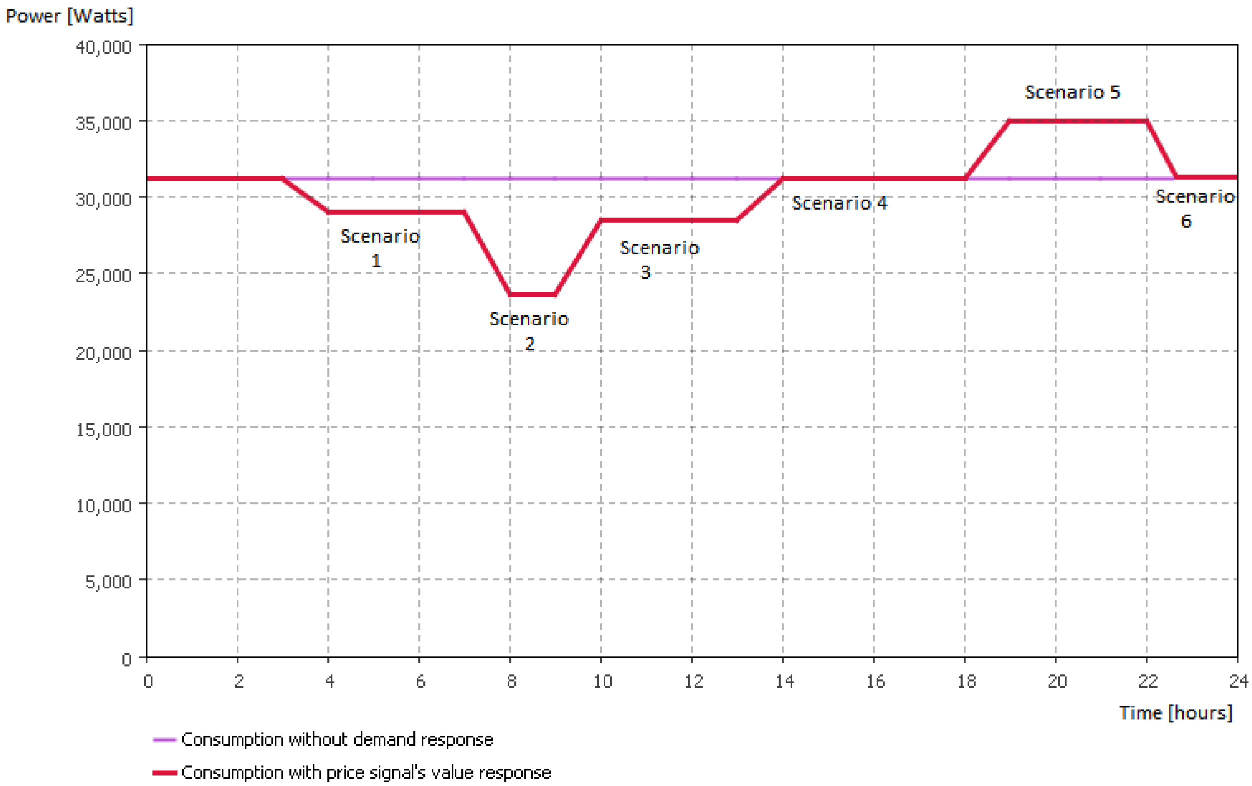

Figure 7. Comparison of price based demand response and no change in consumption.

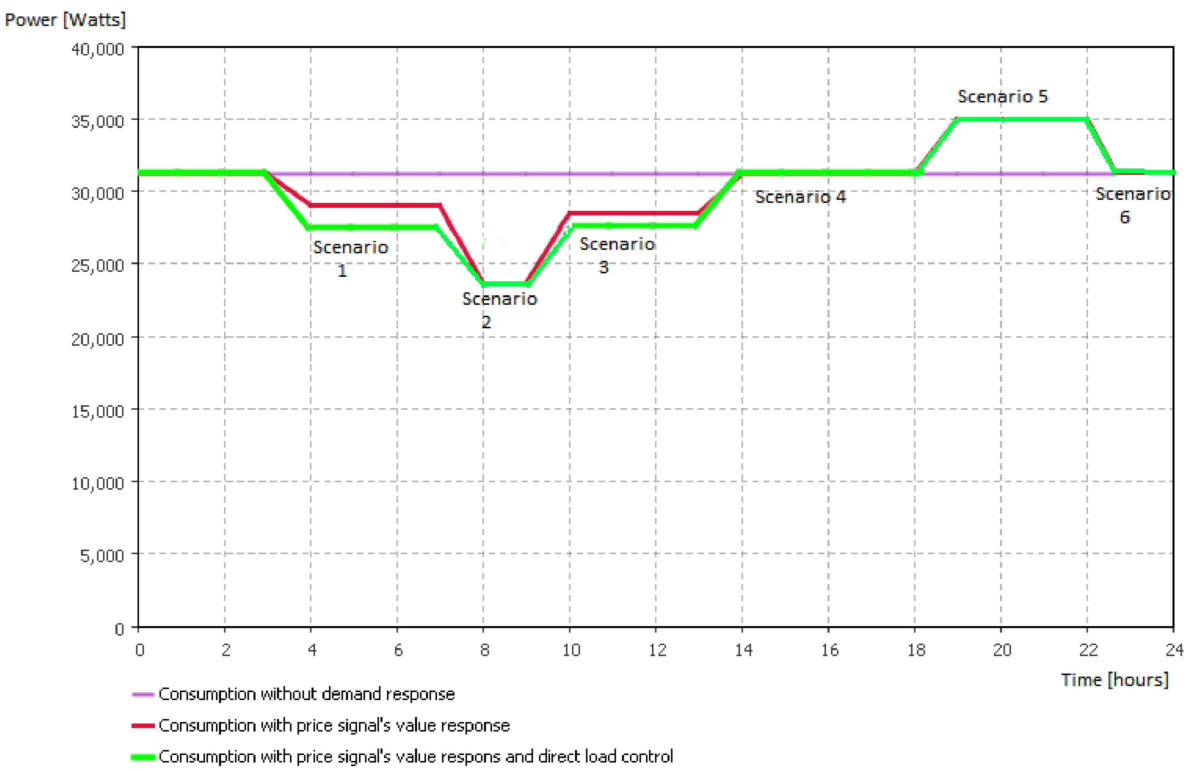

Figure 8. Comparison of price based response, price based with additional direct load control and no change in consumption.

V. Conclusion and Further Development

In the context of this work, the motivation was to create a first stage model for analysis of interactions within an envisioned smart city. Our aim was to develop a system which is operable for further development towards including other critical infrastructures and ultimately a larger scale simulation between different systems vital to a smart city. At this stage electricity was investigated through a small scale smart grid consisting of 5 smart buildings.

The model acts in accordance with expected behavior, according to current and future features of smart grid, including utilization of renewables, energy control on demand and supply side and price-based signaling. To demonstrate and validate the simulation, we have run several scenarios, where one can clearly see that the running simulation is behaving in accordance with what we set out to achieve. We consider this as a proof of concept solution on building-level scope of observation.

Further development of the model will refine the existing concepts as the NATO Science for Peace project this work is part of produces new algorithms to describe the behavior of a smart city. Particular focus will be given to ways of distributed control over a large number of buildings, each consisting of both controllable appliances (price based and direct control), along with renewables installed in each building.

Expansion to citywide scale, including several hundred or thousand buildings, along with modeling of water distribution, transport and other critical systems within a city will enable full scale simulation of emergent phenomena and ultimately investigations on the impacts of the smart city, grid and building paradigm in the overall future of cities globally.

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VII. Biographies

Boran Morvaj was born in 1990. He is a student member of IEEE and currently he is an undergraduate student at the Faculty of Electrical Engineering, University of Zagreb. He is studying Electrical Power Engineering. He has been working on "Emergent phenomena testbed simulator for improving SCADA performance in power system security management project" since March 2010. He is a co-author of paper "Smart cities, buildings and distribution grids- perspectives and significance for sustainable energy supply", presented at CIRED.

Luka Lugarić received his Master Electrical Engineer degree in 2007 and is currently a PhD student He participated in several research projects in South East Europe region and is currently employed at the Faculty of Electrical Engineering, University of Zagreb as a researcher. He also performs consultant services UNDP. Current career highlights include published journal papers in the field of power systems and successfully finished projects for Croatian companies, Government of Croatia and UNDP.

Slavko Krajcar received his MSc degree in 1980 and a PhD degree in 1988 in the field of planning the distribution networks at the same university. He is working in the Faculty of Electrical Engineering as a full professor. A lecturer in a dozen undergraduate, graduate and PhD courses, he has also authored more than 100 R&D papers, the majority of which are implemented in practice. He is Senior Member of IEEE.