Smart city — Platform for emergent phenomena power system testbed simulator

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Smart City - Platform for Emergent Phenomena Power System Testbed Simulator

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Abstract-- **Due to climate change issues, fossil fuel depletion and increasing economic pressure, "smart" cities will have significantly altered physical, social and economic systems, built upon smart infrastructure. Key infrastructure is energy, with focus on electricity. The paradigm of physical, data transfer and information flow layers of the smart city power grid is shown. Challenges of the new urban development arising from the presented paradigm of the future power grid are defined and tools for approach to creation of an testbed simulator with respect to new hazards defined. The goal is to create a platform for analyzing emergent phenomena in future power systems, based the electricity infrastructure of a smart city.**

Index Terms--**Power system security, Power system simulation, Intelligent control, Building Management systems, Cooperative systems**

I. INTRODUCTION

CITIES are defined as large and permanent urban settlements [1]. A city has advanced systems for sanitation, utilities, land usage, housing, and transportation. This concentration of development greatly facilitates interaction between people and businesses, benefiting both parties in the process.

Climate change mitigation requirements, globalization of innovation networks and broadband services are the driving forces of new urban development paradigms towards cities which use technology and communication to create more efficient urban areas [2]. Cities aim to improve their competitiveness, innovation potential, environmental performance, energy efficiency, governance and delivery of services to the citizen [3]. The underlying assumption is reliability and safety of critical city infrastructures.

Critical infrastructures of a city are systems which incorporate physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments [4].

Electricity is a critical infrastructure underlying all other depending critical infrastructures. Disruptions in the power system have severe economic and social consequences, even for short periods of time.

Electricity infrastructure is becoming co-dependent with information and communication technology (ICT) infrastructure. In parallel, small renewable and non-renewable generators are increasingly becoming important components in the grid at distribution network levels. This creates an opportunity for network operators to balance large power plants, local small generators and demand side management systems with high flexibility, in real time.

The goal of utilities is to maximize operational performance, whether using security or economy performance indicators. Designing an intelligent control system, capable of monitoring and controlling the new power grid (also called “smart grid”), both during normal operation and during major disruptions is vital to increasing the performance of the grid under extreme conditions, hence securing proper functioning of other critical infrastructures and the city itself.

Due to its complexity, the power system cannot be fully protected against disruptions. Taking this fact into account mandates creation and use of algorithms, procedures and other measures which will keep critical consumers operational when a disruption in power system occurs. In addition, methods of faster detection of causes of disruptions, methods of restoration and use of local generation capacity in the transitional phase from a black-out to a fully operational grid must be developed.

As it is unfeasible to perform such developments in real life, a software based testbed for electricity infrastructure, which will be able to simulate physical grid properties, information flows and communication infrastructure is proposed. Research in this direction is in progress within a NATO Science for Peace project, started in partnership between Faculty of electrical engineering and computing and Politecnico di Milano.

The envisioned simulator testbed is to capture the scope of a so called "smart city" as an important observation unit.

II. DEFINITION OF SMART CITIES IN EU POLICY

Cities around the world occupy only 2% of Earth's surface yet emit almost 80% of global carbon dioxide as well as significant amounts of other greenhouse gases [5]. Energy use is responsible for approximately 75% of these emissions. Pillars of the EU’s overall policy are built upon the current context of climate change issues, increasing energy costs,

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concerns on security of energy supply and integrated sustainable urban development. Cities in the EU are driven to deliver results that go beyond targets "20-20-20 by 2020" established within the EU Climate Action and Renewable Energy Package. This is recognized by the "Covenant of Mayors" (CoM) initiative [6]. To facilitate these goals, the third EU energy legislation package was developed and in 2009 adopted [7]. Utilities and regulators are now required to create new capacities for consumer choice, fairer prices, cleaner energy and greater security of supply. Therefore, from national and municipal authorities and utility companies points of view, advanced energy management in cities is compulsory.

The new EU legislation paves the way for the roll-out of smart meters, widely considered as the basic means to advanced energy management. Smart metering systems are required to be fitted in 80% of homes where deemed cost-effective by 2020 [8]. According to the European Electricity Grid Initiative (EEGI) Roadmap 2010-18 and Implementation Plan 2010-12 [9] developed in cooperation with the European Commission, this is considered a first step towards creation of smart grids.

A smart grid is an "intelligent" utility distribution network that uses two-way communications, advanced consumption meters and computers that help educated customers to improve energy efficiency of their building, improve overall efficiency and reliability of the distribution grid, facilitate connection of distributed generation facilities to the system and optimize the integration of renewable energy sources.

The established policy framework within EU has therefore put cities as the basic unit for increasing energy efficiency, implementation of renewable energy sources, CO2 reductions and overall reduction of dependency of fossil fuels, which is today a global inclination. The EU is investing considerable efforts in implementing strategies for urban growth within the initiatives for arresting climate change by creating what is being referred to as Smart Cities [10, 11].

III. POWER SYSTEM AS COMPONENT OF A SMART CITY

According to aforementioned definitions, everyday operations in a smart city must include:

- reliable and secure energy and water supply;
- efficient city and intercity transport;
- developed broadband IT infrastructure;
- efficient public administration;
- 24/7 access to public data;
- high quality and availability of intellectual and social capital:
- competitive, productive and open local economy.

Satisfying these requirements imposes a new, proactive development framework for cities - from passive users of built infrastructure cities must become an active participant of networks, with the goal of achieving better living conditions for citizens. For purposes of this paper the focus is on the basic infrastructure for urban living – buildings.

Buildings are the basic components of cities, which utilize multiple types of infrastructure systems. Therefore a building defines a system boundary at which new information has to be collected and where, ultimately, new control systems and procedures will be implemented in order to achieve aforementioned goals and bring new value to citizens.

This new information becomes a part of our knowledge on supply and demand control. Use of this knowledge in networking buildings and advancing infrastructural systems in the process is vital to creation of smart cities.

Levels of observation at the new power grid, along with pertinent features are shown in Figure 1.

A. *Smart buildings*

The definition of the term smart building has been used for more than two decades, and has been constantly evolving. In the 1980s "smart" was a building with implemented passive energy efficiency measures. In 1990s it was buildings with central, computer operated infrastructure systems. Today it includes all previous meanings with the addition of networked appliances, advanced energy management and renewable energy sources.

Smart buildings communicate with its surroundings (i.e. the energy distribution networks), and can adapt to conditions in the network, which they can monitor and receive signals from. Smart buildings communicate between themselves, exchanging both information and energy, thus creating active microgrids which, except consumption, can include small renewable and non-renewable energy sources.

In general, the smart building consists of [12]:

- Sensors - monitoring of selected parameters and submit data to actuators;
- Actuators - which perform physical actions (i.e. open or close window shutters, turn on appliance, etc.)
- Controllers – monitoring inputs from sensors, managing units and devices based on programmed rules set by user;
- Central unit – used for programming of units in the system;
- Interface - the human-machine interface to the building automation system
- Network - communication between the units (RF, Bluetooth, wire);
- Smart meters - two-way, near or real-time communication between customer and utility company.

Today's buildings incorporate principles of energy efficiency. This is manifested in choice of materials, architecture, construction procedures and other passive and active energy efficiency measures. However, without a system for real time monitoring, control and communication with the grid, the building cannot fully adapt to grid conditions.

Installation of renewable sources on buildings creates further complexities as the building becomes an active generation component of the grid. Depending on features and user settings, a smart building uses algorithms to reach a decision on whether to use generated energy from renewables within the building or to sell energy on the market. If any energy storage capacity is present, it should also be accounted

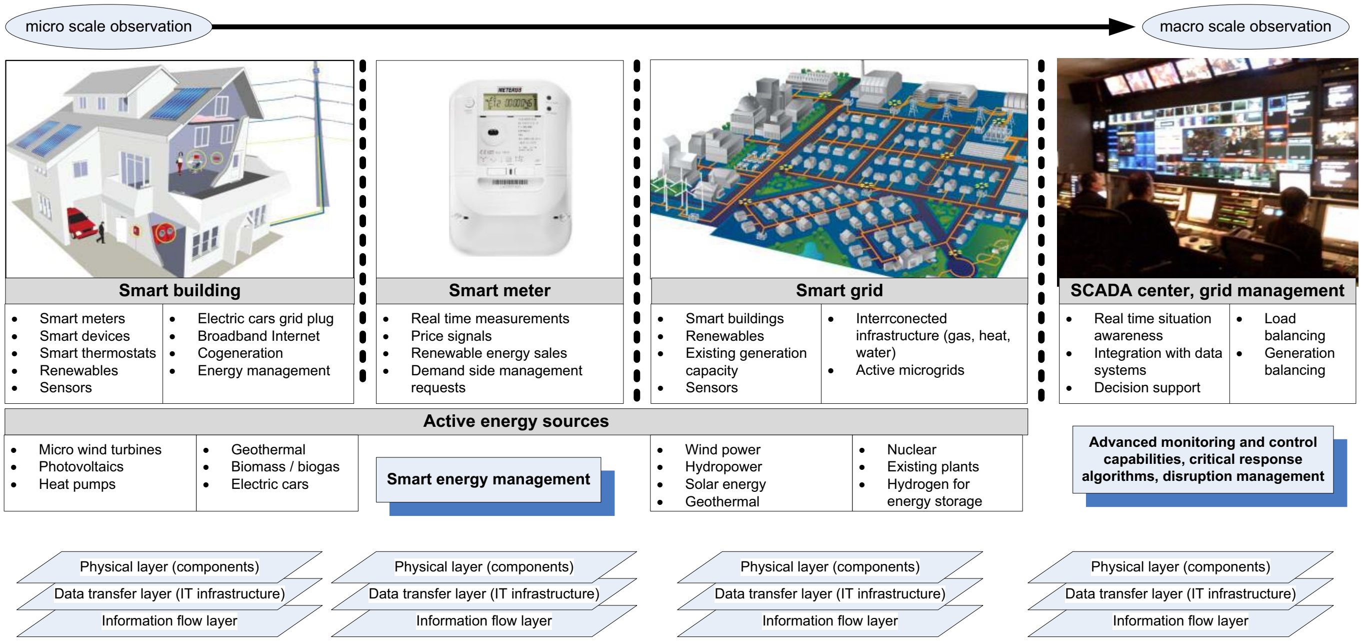

Figure 1 - Smart city electricity infrastructure components

for as a grid asset.

Multiplication of this kind of buildings creates local networks capable of acting as distributed generation but also as self-sufficient energy communities, without the need for external remote supply of electricity. Interconnecting such local networks of active energy consumers a smart grid.

A precondition is installation of the basic measurement and communication and control device in every building - the smart meter.

B. Smart meter

Traditional meters provide one-way information and are either read in person by a meter reader or remotely, up to a frequency of one readout per month, if applicable. Smart meters are digital meters that offer two-way communication allowing for more interactivity between the consumer – the smart building and the utility. The concept is already expanding to water, gas and heat networks.

Characteristics of a smart meter are:

- real-time measurement of energy consumption and electricity generated locally;
- two-way communication with the utility whereas the utility can read data from meters remotely and can send information to the meter;

Existing public networks such as RF, satellite, Internet and/or telephony (cellular or landline) networks can be used to provide for communications between meters and utilities. One key advantage of these systems is the ability to enable bi-directional communication between smart electricity meters and utilities across a wide area, whether with high or low population density. Upfront costs of deployment are possibly lowered since the utility does not need to build private communication infrastructure.

Three key limitations include:

- being subject to the coverage provided by the public networks,
- changing protocols, and
- operational costs.

Utility companies have detailed data on events at the power plant or on their transmission line, but due to traditional paradigm of consumers as passive users of energy, have little information on energy consumption at points of use - the buildings. Smart meters enable full information awareness to the utility as well as enabling active consumers to become participants in the grid load. In turn, these meters can receive real-time data on grid conditions, load and pricing from the market.

Smart meters are a stepping stone to smart grids, a dynamic ‘energy Internet’ or ‘information utility’. Following the transformation process of the telecom industry with the introduction of mobile telephony, smart meters are expected to trigger new energy market models as features of smart grids reach implementation stage.

C. Smart grid

It is widely accepted that due to peak demand as much as 20% of total generation capacity is used for only 5% of time in today's power grids. A smart grid implies integration of actions of generators, transmission and distribution system operators, monitoring and control centers, suppliers and consumers through exchange of information in real time. Some of the widely quoted features are still under development while some have been implemented [3]. Existing and planned implementations of smart grids provide a wide range of features:

- Increased hosting capacity for renewable and distributed sources of electricity;
- The integration of national networks into a market-

based, pan-continental network;
- Increased quality of supply;
- Active participation of end consumers in markets and energy efficiency;
- Anticipation of new developments such as a progressive electrification of transport;

A multitude of technological and economic challenges is still ahead of full implementation of all smart grid features. The transition from the current grid to the smart grid is subject to individual plans of countries, each defining its own smart metering features depending on the business case performed [13]. A cross-section of currently known initiatives for transition to smart grids is presented in this paper, with regard to potential for modeling a simulation testbed for emergent phenomena.

D. *Transitional phase*

Renewable energy sources at distribution and transmission network level are already common. The ongoing process is implementation of renewables and other micro sources on buildings, coupled with introduction of smart devices and smart meters, which is a precondition of creation of smart grids. The costs of such initiatives is high, hence new developments are currently implemented in phases, in the form of multiple pilot projects [14, 15]. Networking developments along with national smart meter rollout campaigns and incentives for renewables will create full scale smart grids, which are the basic infrastructure of smart cities.

Figure 1 shows that at each domain of the smart city electricity infrastructure – smart building, the metering system, smart grid and the grid management system, three basic layers can be observed, as follows:

1. Physical components – devices and other physical infrastructure, such as power lines, photovoltaic panels, wind turbines, GSM towers, sensors, etc. that are used to deliver essential services;
2. Data transfer layer – consisting of data transfer media, computers and telecommunication networks that are used to gather and transfer data to and from physical components;
3. Information flow layer – Next generation supervisory control and data acquisition (SCADA) systems are the main part of this layer, with added functionality of energy management systems (EMS). Data processing and decision making are performed at this level, where a human operator is also involved in the process. Commands are issued via the data transfer layer to physical components in order to optimize operation.

The presented paradigm of the smart city electricity infrastructure with three underlying layers has strict survivability requirements on a twenty-four-hours-a-day, seven-days-a-week (24x7) basis for each layer. Here survivability means the capability of a system to fulfill its mission in a timely manner, even in the presence of failures, attacks, or accidents. In difference to fault tolerant systems (such as the electricity grid) which are generally engineered to tolerate random natural failures, system survivability must also consider unpredictable faults which may be caused by emergent phenomena such as terrorism, natural hazards, large disruptions, market disturbances, international policy shifts, etc.

IV. APPROACH TO DEVELOPING A SIMULATION TESTBED

A development of a software based testbed for SCADA infrastructure in the area of power systems has been proposed, with the ability to simulate physical grid properties, communication infrastructure and information flow capabilities of power grids of the future, which will also enable modeling of human operator behavior within the system.

The basic justification of creating the proposed system is the fact that a holistic simulation platform for emergent phenomena which include dependent systems does not exist yet. The proposed platform will be used for analyzing impacts of emergent phenomena in power systems of the future - the smart grid, as well as to develop contingency plans for reactions.

Without integrated control or inappropriate risk management systems, the ability to deal with disturbances which are beyond the conventionally built-in redundancy (the n-1 criteria), creates a risk of disruptions which are hugely damaging to the developed economy of a smart city even for short periods of time. Disturbances such as terrorism, natural disasters such as floods, fires and lightning, as well as market disturbances which can raise the price of electricity act to the detriment of the whole society. This cannot be analyzed in real life. Any contingency plan developed without a proper simulation testbed is based only on expert observations, since actual simulation of any response would require the system to become critically unstable, which would mean a system blackout. The proposed testbed provides a solution to this problem.

Based on challenges and the concept presented, the main questions which arise and will be the target of the new testbed are:

- How can compromised lines of communication impact the electricity market and the physical power system monitoring and control?
- How do market disturbances impact the physical power system?
- What happens in individual power system components and how a human operator responds in case of exceptional events such as:
    - Natural hazards;
    - Unplanned disruptions of trans-national power flows;
    - New generation capacities being installed (renewable energy);
    - Part of information from the physical system becomes unavailable;
    - Part of information from the electricity market system becomes unavailable;
    - Terrorist (including cyber-terrorism) attacks to either of the systems;

  - Energy security policy changes;
  - General security politics changes;
- What should the next generation SCADA have in order to improve performance of the human operator when the power grid reaches an unstable state?
- Who needs which information and for what purpose in case the power system becomes unstable?
- How can the power system and its components (physical grid, electricity market infrastructure and ICT) be defended and their security increased?
- How to optimally distribute limited resources for improving security?
- How does the smart grid with enhanced security contribute to the security of a smart city?

There have been attempts to answer some of these questions, either fully or partly, but so far there has not been an attempt to create a simulation testbed including all relevant components which would enable further scenario-based exploration or a holistic system analysis.

The proposed testbed will make use of commercially available software for modeling. Software selection is as follows:

- PowerWorld Simulator for general power system modeling;
- Anylogic for agent-based and system dynamics modeling of communication infrastructure and information flow.

The selection is based on best available information from projects which are related to the one or more challenges as presented here. This will enable researchers to concentrate on modeling individual components of the system, which enables combining specific researcher knowledge into a larger, more diverse system. The end result, individual components working together, will enable exploration of holistic system performance, instead of the older approach to modeling the whole power system top-down using a system of complex equations to describe system behavior. Also, the man-machine behavior is relatively easy to model using agent-based architecture. Agent-based modeling has also been extensively used to include social dynamics into technical systems, and for the complex distributed networked systems. Thus agent-based modeling can enable accounting for the human factor and interrelated systems within the simulation.

The proposed architecture enables simulations with real-life data incorporated. The proposed workflow layer is built external to SCADA systems and interfaces with the SCADA by processing and controlling inputs and outputs via the testbed.

As shown in Figure 2, the envisioned testbed is to be composed of three basic layers:

- Physical grid;
- Communication infrastructure;
- Information flow.

Testbed is envisioned to be capable of accepting various sources of major disturbances with interpretation and modeling of their influences on the all three components.

The solution is functionally integrated via the input/output interface – this is the actual simulation testbed and it

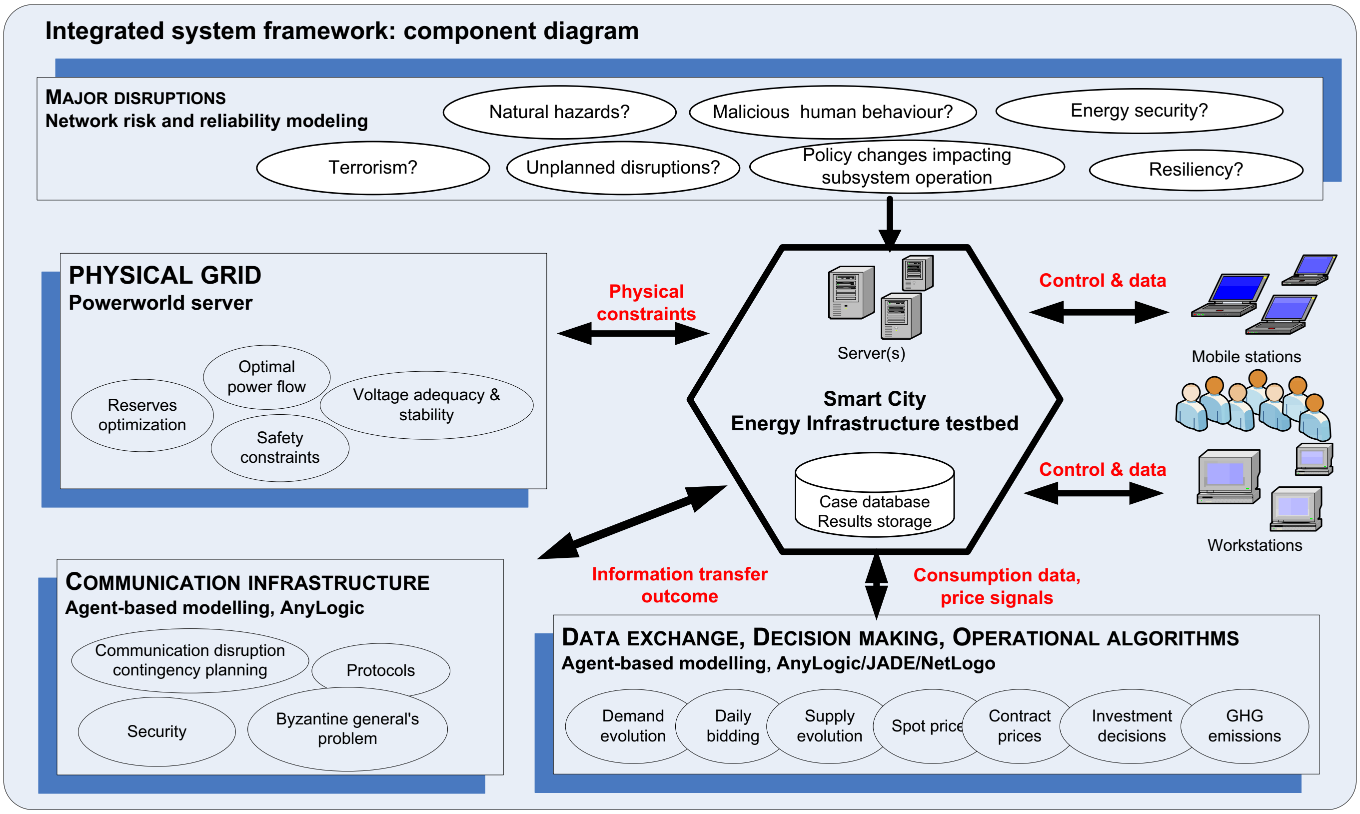

Figure 2 - Components of the proposed testbed development

constitutes the core of research activities - integration of various system components. Conceptually, the system is integrated in the way that results of the data exchange and processing are routed through the simulated (compromised or safe) communication infrastructure, after which calculations in the physical systems are performed. This produces physical constraints which are forwarded to the central operator so that grid components can react and try to even out imbalances. This is an iterative process until the whole system reaches equilibrium – an end state which can become an input to analyst (human operators) for creating contingency plans. Major disruptions which can occur are also shown in Figure **2**, and will be the focus of case studies after the testbed is operational.

Inputs are controlled by human operators, and executed in all components within the testbed at the same time. Human operator has an overview of the outputs, which can both be filtered (to prevent information overload) or examined in detail if so requested. Human operators control all parameters in the system – both the ones systems are designed for (i.e. power system lines or market bids), but also background parameters such as whether a communication line has been compromised, or if there's a malicious trader operating in the market, etc.

Once created, the testbed has essentially two goals:

(1) identifying whether an incoming operation applied on any testbed component will lead to a pattern of consequences which will endanger the stability of the power grid, which is pre-defined within the workflow based on domain specific security knowledge; and

(2) analyzing and predicting the propagation of an emergent fault in physical grid and the data exchange and processing system.

Commands issued to the testbed are routed to components through the interfaces which will be developed within the project, in order to perform computations and observe outputs simultaneously from all components. The state information monitored by the testbed layer is also forwarded to the database for further data mining and pattern recognition. Once the testbed has identified the system is in an unsafe state, operational algorithms will be developed to enable recovery from possible adverse actions – the end result being contingency plans for unplanned disruptions, such as in case of terrorism, natural hazards and other unplanned disruptions which are generally hard to either simulate or plan against in the real world.

Since the testbed is simulated and therefore non-intrusive to the existing critical infrastructures, advanced knowledge of behavior from individual component domains can be easily applied to determine both vulnerabilities as well as options for increasing security performance.

Developed testbed will contain mathematical and agent-based models of devices, operators, market concepts and IT infrastructure derived from domain knowledge. At run time, the simulations on the testbed verify the behavior of the physical system and identify potential faults.

V. CONCLUSIONS AND FURTHER DEVELOPMENT

This paper has looked into the role which advanced power system, the smart grid, plays in the framework set for 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. Based on observations, a simulator testbed for emergent phenomena has been proposed, in order to create a tool for investigation of structural criticalities, system vulnerabilities, restoration algorithms and overall control of the power system taking into account new functionalities being developed worldwide.

With respect to the developments presented, model refinements are necessary for a more realistic description of the system. The indications derived from current literature review, and an approach developed in accordance with current developments.

Further research efforts may be worthily directed to:

- Identifying appropriate indicators of the physical behavior of the system, to be used as representative weights of the network state. These indicators should capture the main characteristics at all three levels of abstraction - physical, data transfer and information flow, so that their criticalities better account for overall state of the system.
- Considering the trade-off between realistic and abstract modeling (including physical laws and system dynamics), in an attempt to reduce the model parameters and speed up the simulation on one side, and to increase the degree of sophistication of 'quick and simple' methods to satisfactorily describe the system behavior, on the other side.
- Optimizing the technical implementation of the models, relying on the evolution of both hard- and software simulation tools.

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VII. REFERENCES

[1] Kuper, A. and Kuper, J., eds (1996) *The Social Science Encyclopedia*, 2nd edition. London: Routledge.

[2] R. Rifkin et. al, "A third Industrial Revolution Master Plan to Transition Rome into the World's First Post-Carbon Biosphere City", Jeremy Rifkin Group, Rome, 2010.

[3] Z. Morvaj, L. Lugaric, B. Morvaj, "Smart cities, buildings and distribution networks - perspectives and significance for sustainable energy supply", presented at 2nd Croatia CIRED Conference, Umag, Croatia, 2010.

[4] Communication from the Commission to the Council and the European Parliament: Critical infrastructure protection in the fight against terrorism [COM(2004)702 final], Brussels, 2004.

[5] R.T.Watson, M.C.Zinyowera, R.H.Moss, „The Regional Impacts of Climate Change: An Assessment of Vulnerability", Cambridge University Press, 1997, p. 53

[6] European Comission, Covenant of Mayors [Online] Available: http://www.eumayors.eu/

[7] European Comission, „The Climate action and renewable energy package, Europe's climate change opportunity“, [Online] Available: http://bit.ly/T7boP

[8] Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC, Brussels, 2006.

[9] The European Electricity Grid Initiative (EEGI) Roadmap 2010-18 and Detailed Implementation Plan 2010-12, Brussels, May 25, 2010 [Online] Available: http://www.smartgrids.eu/

[10] N. Komninos, (2009). "Intelligent cities: towards interactive and global innovation environments", International Journal of Innovation and Regional Development, Inderscience Publishers, 2009., 1 (4): 337–355(19)

[11] K. Paskaleva, "Enabling the smart city: The progress of e-city governance in Europe". International Journal of Innovation and Regional Development, Inderscience Publishers, 25 January 2009 1 (4): 405–422(18).

[12] A. Moderink et al., "Simulating the effect on the energy efficiency of smart grid technologies", in *Proc. 2009 Winter Simulation Conference*, pp 1530-1541

[13] G. Kmethy, "IEC 62056 DLMS/COSEM workshop handouts", Metering/Billing CRM Asia 2010, Kuala Lumpur, Malaysia, 2010.

[14] Smart City Amsterdam [Online]
Available: http://amsterdamsmartcity.com/

[15] Google Map of Smart Metering Programmes across the World, Maintained by Energy Retail Association, United Kingdom [Online] Available: http://bit.ly/12EZGx

BIOGRAPHIES

Luka Lugarić studied at the Faculty of Electrical Engineering, University of Zagreb where he received his Master Electrical Engineer degree in 2007. During studies he also won a Rector's award for work in risk analysis of investments in renewables. 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 within the UNDP Croatia project "Removing barriers to energy efficiency" and ENCONET d.o.o. Current career highlights include several published scientific papers in the field of power systems and successfully finished projects for various companies, Government of Croatia and UNDP.

Zdenko Simic holds PhD degree in EE from University of Zagreb, Faculty of Electrical Engineering and Computing since 2001, where he is an associate professor. His work experience includes risk and reliability assessment for the nuclear and power systems applications, and renewable energy resource assessment. His research interests are on-line risk monitoring, optimization and multiple objective decisions related to the risk, reliability, operation and maintenance of complex technical systems, energy resources. He is the current president of the Croatian IEEE Power Engineering Society Chapter, and member of the IEEE Reliability Society and Croatian National Committee of CIGRE.

Slavko Krajcar graduated in 1973 from the Faculty of Electrical Engineering and Computing, University of Zagreb, he 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 and Computing since 1973, first as a teaching assistant and afterwards as an professor. He are taking courses in diploma study: "Energy Technology", "Electric Power Distribution Systems", "Electrical Facilities", "Economics of Energy", "Electrical Lighting", "Electric Power Systems Planning on Open Markets", "MV and LV Networks", as well as "Modelling in Competitive Electricity Markets" and "Planning of Distribution Systems" in postgraduate courses. He was written more than 100 R&D papers, the majority of which are implemented in practice. He was head of different national and international Projects. He is still leading a lot of different S&T Projects at Faculty.