# An Approach to the Modeling of Decentralized Integrated Energy Systems with Renewable Energy Sources

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***Abstract* — New conditions for the development of energy systems, the growing consumer involvement in energy demand management, the expansion of energy supply services, the adoption of highly efficient technologies for energy production, transportation, and distribution both for large-scale systems and small-scale distributed generation, whose share is increasing, on the one hand, have already built a certain level of mutual integration of various systems, and, on the other hand, facilitate their even greater integration at the level of control of their expansion and operation. The paper presents an approach based on the long-term meteorological observation data. A chronological method for the calculation of operating conditions of integrated energy systems is presented.**

***Index Terms* — Decentralized integrated energy system, elements of the concept, mathematical modeling, long-term meteorological observation data, renewable energy source**

## I. Introduction

The modern energy sector represents an infrastructural complex including fuel, electricity, heat and cooling systems. Despite various kinds of services rendered by the systems, their common goal is to create comfortable living and working conditions for the population and to effectively facilitate the development of the national economy. To perform their functions, each of the systems has its production, transportation and distribution structure connecting them with consumers. They often interact and compete in the existing market for energy services. This, in particular, refers to the electricity, heat, and gas systems. Despite their certain functional independence, these systems can interact with one another under normal and emergency conditions, at the level of interchangeable primary energy resources and use of energy carriers. This is indicative of their natural integration which gets even stronger in the course of the formation of intelligent, information and telecommunication systems. In combination, all of them represent a new structure in the form of a metasystem. This metasystem combines certain independence of the systems that constitute it and their coordinated participation in accomplishing the main goal to provide social and economic activity. Coordination of the accomplishment of this goal is ensured by the information system that represents an infrastructural framework of the metasystem.

The expansion of distributed generation encourages the modification of the existing centralized energy systems and their integration with the distributed generation systems. This is based on a considerable approach of energy generation sources to consumers which in turn causes a change in the topology of the distribution networks that have a multi-loop structure but are operated according to the open circuit principle; an expanded use of cogeneration, in particular on the basis of electric boiler plants with the use of heat storage devices; and a considerable increase in the number of devices for metering and processing the data on the conditions of generation, network and consumption facilities.

One of the options of describing the integrated energy system with distributed generation is its representation as a set of autonomous or interacting subsystems (microgrids). The boundary of each subsystem is known and it is invariable. The determination of this boundary provides the possibility of maintaining the energy balances as well as meeting the requirements for the energy supply quality

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and reliability. Each subsystem can interact with the neighboring subsystems in the cases when contingencies occur in the subsystem and when energy supply conditions are optimized.

It is also important to solve the problem of planning the operating condition which optimizes the implementation of balance relationships and requirements for quality and reliability during the control cycle.

A specific character of planning under the presence of distributed energy generation is determined by the online control of the operation. The question about the length of time intervals for both monitoring and measurement of different parameters as well as generation of control actions is important. This is related to the fact that the time characteristics differ for electric and heat processes.

## II. Concept of intelligent integrated energy systems

Intelligent integrated energy systems have a multi-dimensional structure of functional characteristics and expansion properties. They combine a great number of components, intelligence, efficiency, reliability, controllability, flexible use of technologies for energy conversion, transportation, storage, and the load-controlled consumer [1,2]. Conceptually, the integration is carried out in three aspects:

- A system aspect which represents the integration of systems by their type (electricity, heat/cooling and gas systems);
- A scale aspect which reflects the size of the systems with their differentiation into super-, mini- and microsystems;
- A functional aspect which determines the functions of the system (its purpose), including energy (technological); communication, control and decision making.

In terms of the system aspect, the intelligent integrated energy system is represented by the key infrastructural energy systems that can be highly integrated with respect to the functional tasks, mutual redundancy, technological interrelations at various hierarchical levels, etc.

In terms of the scale aspect, we distinguish the following interrelated systems:

- super-systems, i.e. traditional centralized energy systems that consist of large-scale electricity and heat sources, gas fields, underground gas storages, electrical, gas and heat networks;
- mini-systems, i.e. decentralized (distributed) systems including mini electricity and heat sources (including those nonconventional and renewable), which are connected to the distribution electrical, heat and gas networks, and these networks themselves;
- micro-systems, i.e. individual systems with nonconventional and renewable electricity and heat sources as well as house electrical, heat and gas networks.

Functional aspects of the intelligent integrated energy system include the following constituent functions:

- the energy functions that represent production, transportation, distribution and consumption of electricity, heat/cooling, gas at all levels and scales;
- the communication and control functions that represent measurement, processing, transfer, exchange, and visualization of information, control of operating conditions and expansion of the metasystem;
- the decision-making functions, i.e. the metasystem intelligence which includes models and methods for planning the expansion of the integrated energy systems as well as settings for their control.

All the functional properties of the intelligent integrated energy system have strong interrelations with one another in terms of input and output state variables, the structure of forecasts both at the level of operation and at the level of expansion. They form a totally new technological architecture which defines the organization of the metasystem implementing the design solutions of its components, their interactions with one another and with the external environment, as well as the principles of the evolutionary development of such a multi-component structure.

## III. Literature review

Various energy systems, such as electric, gas, heating and other systems were normally designed and operated independently of one another. The advances in technologies and equipment, the emergence of new conditions and opportunities, however, make the interaction between different types of energy systems much stronger, which leads to a considerably increasing interest in the research on joint operation of these systems. A widely applied approach to study the integrated systems is based on consideration of such systems in the form of an energy hub. For example, in [3] the authors suggest a method for optimal energy generation and conversion in the integrated energy system with different energy carriers, which involves the energy hub conception. This method is widely applied in the studies related to optimal operation and design of integrated energy systems [4-7].

The problem of an optimal load of generating equipment lies in obtaining an optimal schedule of generating equipment startup and shutdown to meet the expected demand, given costs and constraints of a system. In the context of the integrated energy systems, this refers to the optimal startup and shutdown of each generating unit to meet the demand for several types of energy. The authors of [8] propose a solution to the problem of optimal loading of generating equipment based on the energy hub concept. For solving this problem, it is very important to consider the energy storage possibility. The authors in [9] consider the planning of electricity and heat storage as part of the problem of optimal loading of generating equipment. The authors of [10] present a comparison of energy approach and exergy-based approach to solving the problem of optimal use of generating equipment.

The problem of the integrated energy system control can also be solved by determining optimal power flow. The determination of optimal power flow is reduced to the load distribution among energy sources, which meets the constraints of the energy transmission system in terms of cost minimization. Solving the problem of optimal power flow in the integrated energy system should allow for several energy types. Consequently, several energy sources and devices for energy conversion are required. The optimal power flow in an integrated electric and gas system was investigated in [11]. To this end, the authors developed a mathematical model in which the objective function is determined by a set of points for various components that are characterized by the minimum operation cost of the electric and gas systems and do not violate the constraints of the electric and gas transportation system. A method for calculation of optimal power flow for the integrated electricity, gas and heating system is presented in [12]. The method is focused on the power flow and optimality condition of Kuhn-Tucker for the case with several energy resources.

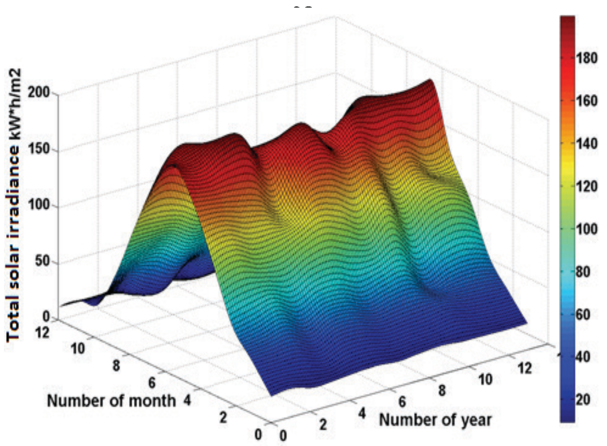
The problem of the optimal power flow calculation for several periods of time is related to the planning of the energy system operation for a set time horizon. In [13], the authors present modeling of an optimal power flow coordinated in time for electric and gas system for the case of distributed energy resources. Due to relatively slow flow speeds and specific features of storage in the gas and heating systems, it is important to take into account the dynamic behavior of these energy systems during several periods of time to solve the problems of control and scheduling of the systems. The authors of [14] study a method for calculation of optimal power flow and scheduling for integrated electric and gas systems with a transient model for the natural gas flow. The calculations were performed to compare the solutions obtained with stationary and transient models of natural gas transmission systems. A model of optimal power flow for several time periods was developed to study combined electricity and gas networks in Great Britain [15, 16].

Some of the studies aim to investigate the control of integrated systems with a focus on centralized and decentralized control. In [17], the authors present the findings of the research into centralized control, which involves an approach to the control with projection models for integrated energy systems. The central controller determines the actions for each energy hub to ensure better efficiency in terms of stability of the transportation system, use of storage devices and forecasts of loads and prices. In [18], the authors propose a hierarchical centralized control of an integrated microgrid. The controller receives the data on transient characteristics of the natural gas flow and operation of energy converters. To take into consideration the dynamic characteristics of different systems, the controller was divided into three layers: slow, medium-speed and fast. The study is focused on the control of executive mechanisms when the renewable generation fluctuates, the start of a conditioner, start of a microturbine, demand response and filling of energy storage. Further, the results of this research were extended to the control of an integrated energy system [19]. A strategy of real-time control of the integrated electric and heating system was proposed in [20]. The strategy of control has a hierarchical centralized architecture and is designed to maintain the frequency of a power supply system at a level of 50 Hz and a temperature of district heating water equal to 1000C. An approach to solving the scheduling problem is presented in [21], where optimization is performed for a time period of 24 hours, and a strategy of real-time control compensates for a gap between a scheduled load and a real load by control actions.

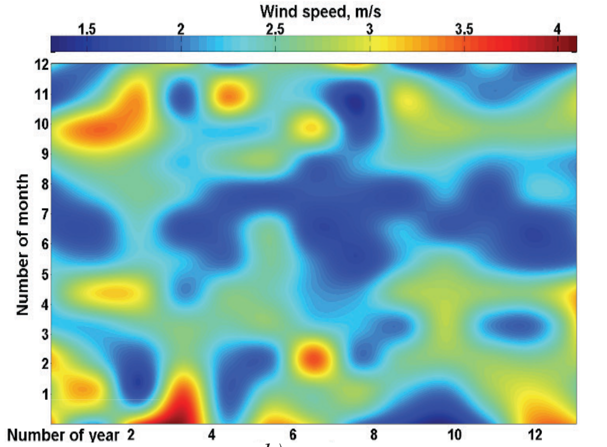
Although the centralized architecture of control can provide the best total energy system performance, its complexity limits its wide practical application. The distributed control architecture divides the common optimization and control problem into subproblems that are solved with individual models. The local control action to be performed, however, depends on the actions of neighboring controllers and should be coordinated. In [22], the authors propose a distributed control system for combined electricity and natural gas systems. The system consisting of several interrelated energy hubs was controlled by corresponding control agents. In [23], these results were extended to the studies of distributed control based on projection models and the use of storage devices in gas systems.

The integration of electric and heating systems is most pronounced in cities and populated areas, and manifests itself: in combined electricity and heat generation; the use of energy storage systems to ensure flexibility of cogeneration operation; and the use of electric equipment for heat production, transport and distribution. The joint operation and scheduling of electric and heating systems based on cogeneration are discussed in [24]. The interaction between electric and heating systems in the view of the need to ensure the required demand response was considered in [25]. Various electricity and heat supply options were compared when solving the problems of operation and scheduling in terms of techno-economic and environmental indices in [26, 27].

The sources of combined electricity and heat generation interconnect electric, heating and gas systems. In [28], the authors applied Sankey diagrams to illustrate energy flows through the electricity-heat-gas networks when considering several scenarios for the involvement of a cogeneration power plant and heat pumps. The research was also focused on the impact of different technologies




a)




b)

*Fig. 1. – a) total solar irradiance; b) – wind speed (10 m).*

Figure 1 shows the total solar irradiance and wind speed.

Figure 2 shows the relationship between climate data and energy systems modeling.

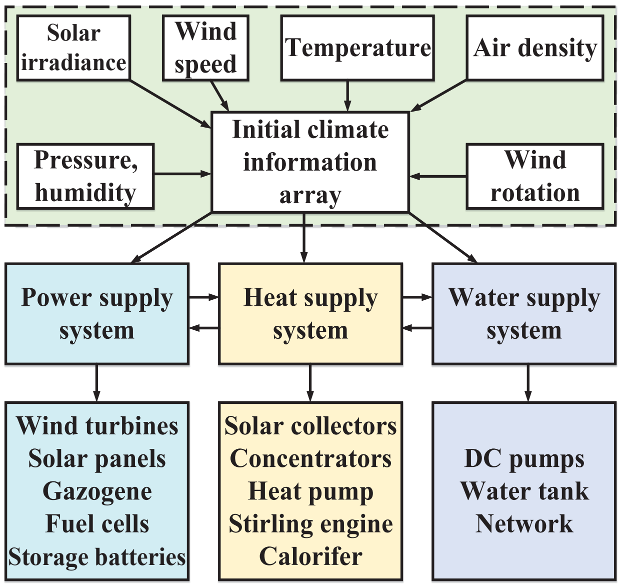



*Fig. 2. Relationship between climate data and energy systems modeling.*

on the operation of each network. The implications of switching from hydrocarbon fuel to renewables in the electric system for the district heating systems and gas network were studied in [29, 30].

## IV. Climate indicators and their role in research

Integrated microsystems often comprise different types of power generation equipment using renewable energy sources. Solar panels, wind turbines, gas generators, battery units, and fuel cells can be used for electrical supply. Solar collectors, concentrators, heat pumps and thermal storage units can be used for heat supply. An integrated power system can consist of different combinations of the above-mentioned equipment.

The common feature for all of these installations is the use of renewable energy sources such as solar and wind power, low-potential heat, waste substances and so on.

Consequently, detailed information on the following natural and climatic factors is required when examining energy systems involving renewable energy sources: solar irradiance, wind speed and direction, temperature, humidity, pressure, and air density.

To increase the accuracy of research findings, climate indices have to approximate real values as much as

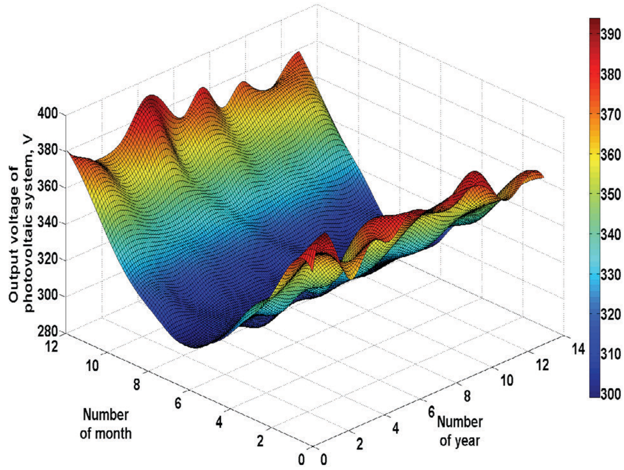



*Fig. 3. The output voltage of the photovoltaic system.*

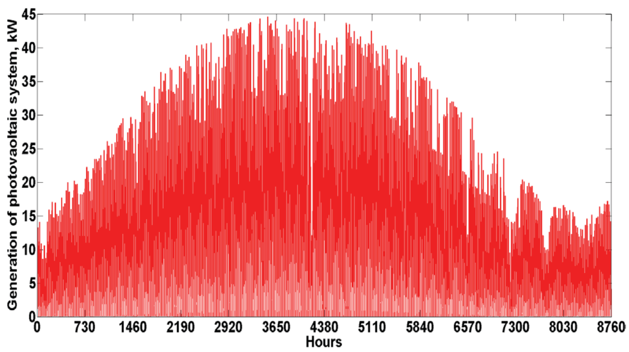



*Fig. 4. Power output of the photovoltaic system (50 kW) during the year.*

possible. To this end, the study follows the method of reproducing natural and climate indices by using the year-long meteorological series, available in the public domain.

These meteorological series record, line by line, the major climate indices such as wind speed and direction, air temperature, pressure, humidity and assessment of total cloud cover.

A combination of Iqbal and Kasten-Czeplak mathematical models is used to calculate the total solar irradiance. In the calculation of the total solar irradiance for each day, sunrise, zenith and sunset times are determined based on geographic coordinates and time zones. In the first stage, solar irradiance is determined under clear sky conditions. In the second stage, the solar irradiance attenuation quotient is determined based on cloud cover, cloud composition, the percentage of bad weather clouds and so on.

These data can be directly used for modeling solar panels, collectors, concentrators and wind generators.

## V. Modeling the integrated energy systems with renewable energy sources

What is special about the integrated microsystem is its direct relationship with the centralized energy system. Besides, various heat and electric power generation techniques should be taken into consideration as modeling these systems is a challenging task.

The chronological calculation method is used to model the integrated systems. This method involves the determination of the system's basic operating parameters with regard to every discrete step of the considered period. Importantly, this calculation method is fully consistent with the year-long meteorological series which, by their very nature, respect the continuity of changes in meteorological indices. Of special importance is the fact that the data collected directly from weather stations are used to reproduce natural and climate conditions. All of the above makes it possible to accurately model the operating conditions of the integrated systems using renewable energy sources.

Figure 3 shows the output voltage of the photovoltaic system.

Modeling is performed for a period of up to 20 years according to real climate data. These climate data are a chronological sequence of events. Moreover, these data can be applied to various components of the integrated system.

## VI. Conclusions

The organization of the coordinated process of energy system operation and consideration of different energy system types as a single integrated energy system will allow us to considerably increase their security, reliability, cost-effectiveness and environmental friendliness. An inevitable expansion of the distributed generation on the basis of unconventional and renewable energy sources both at the level of energy systems and directly at consumers', as well as their integration in the centralized systems require the implementation of new principles for the construction of these systems and establishment of intelligent systems to control them on the basis of developed information-communication support. The potential advantages of the decentralized integrated energy system with renewable energy sources can be easily implemented through the correctly selected integration mechanisms. Such advantages can include:

- Energy saving and reduction in the emission of harmful substances.
- The decrease in energy transmission and distribution losses.
- Stabilizing the stochastically varying power output.
- Increasing flexibility of energy supply.
- Participation of end users in both electricity market transactions and energy system control.
- Transition to the intelligent energy system concept.

Further research will focus on the development of the concept of integrated energy systems with renewable energy sources.

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## References

[1] N. I. Voropai and V. A. Stennikov, "Intelligent integrated energy systems," *Izvestiya Rossiiskoi akademii nauk. Energetika*, no. 1, pp. 64-73, 2014. [in Russian].

[2] N. I. Voropai, V. A. Stennikov and E. A. Barakhtenko, "Integrated Energy Systems: Challenges, Trends, Philosophy," *Studies on Russian Economic Development*, vol. 28, no. 5, pp. 492–499, 2017.

[3] M. Geidl and G. Andersson. (2008, Jul). Optimal power dispatch and conversion in systems with multiple energy carriers. Presented at 16th PSCC. [Online]. Available: http://www.eeh.ee.ethz.ch/uploads/tx_ethpublications/pscc_2005_geidl.pdf

[4] M. Geidl and G. Andersson, "Operational and structural optimization of multi-carrier energy systems," *Euro. Trans. Electr. Power*, vol. 16, no. 5, pp. 463–477, 2006. DOI:10.1002/etep.112.

[5] X. Xu, X. Jin, H. Jia, X. Yu and K. Li, "Hierarchical management for integrated community energy systems," *Applied Energy*, vol. 160, pp. 231-243, Dec. 2015. DOI: 10.1016/j.apenergy.2015.08.134.

[6] B. Zhou, D. Xu, C. Li, C. Y. Chung, Y. Cao, K. W. Chan and Q. Wu, "Optimal Scheduling of Biogas–

Solar–Wind Renewable Portfolio for Multicarrier Energy Supplies," *IEEE Transactions on Power Systems*, vol. 33, no. 6, p. 6229-6239, 2018. DOI: 10.1109/TPWRS.2018.2833496.

[7] D. Xu, B. Zhou, K. W. Chan, C. Li, Q. Wu, B. Chen and S. Xia, "Distributed Multi-Energy Coordination of Multi-Microgrids with Biogas-Solar-Wind Renewables," *IEEE Transactions on Industrial Informatics*. DOI: 10.1109/TII.2018.2877143.

[8] L. M. Ramirez-Elizondo and G. C. Paap, "Unit commitment in multiple energy carrier systems," 41st North American Power Symposium, Starkville, MS, USA, 2009, pp. 1-6. DOI: 10.1109/NAPS.2009.5484065

[9] L. Ramirez-Elizondo, V. Velez and G. C. Paap, "A technique for unit commitment in multiple energy carrier systems with storage," 2010 9th International Conference on Environment and Electrical Engineering, Prague, Czech Republic, 2010, pp. 106-109. DOI: 10.1109/EEEIC.2010.5489999

[10] L. M. Ramirez-Elizondo, G. C.Paap, R.Ammerlaan, R. R. Negenborn and R. Toonssen, "On the energy, exergy and cost optimization of multi-energy-carrier power systems" *International Journal of Exergy*, vol. 13, no.3, pp. 364-386, 2013. DOI: 10.1504/IJEX.2013.057356.

[11] Seungwon An, Qing Li and T. W. Gedra, "Natural gas and electricity optimal power flow," 2003 IEEE PES Transmission and Distribution Conference and Exposition (IEEE Cat. No.03CH37495), 2003, pp. 138-143 Vol.1. DOI: 10.1109/TDC.2003.1335171.

[12] M. Geidl and G. Andersson, "Optimal Power Flow of Multiple Energy Carriers," *IEEE Transactions on Power Systems*, vol. 22, no. 1, pp. 145-155, Feb. 2007. DOI: 10.1109/TPWRS.2006.888988.

[13] S. Acha, "Modelling Distributed Energy Resources in Energy Service Networks", *The Institution of Engineering and Technology*, UK, 2013.

[14] C. Liu, M. Shahidehpour and J. Wang, "Coordinated scheduling of electricity and natural gas infrastructures with a transient model for natural gas flow," *Chaos*, vol. 21, no. 2, 2011. DOI: 10.1063/1.3600761.

[15] M. Chaudry, N. Jenkins and G. Strbac, "Multi-time period combined gas and electricity network optimization," *Electric Power Systems Research*, vol. 78, no. 7, pp. 1265-1279, Jul. 2008. DOI: 10.1016/j.epsr.2007.11.002.

[16] S. Clegg and P. Mancarella, "Integrated electrical and gas network modeling for assessment of different power-and-heat options," *2014 Power Systems Computation Conference*, Wroclaw, 2014, pp. 1-7. DOI: 10.1109/PSCC.2014.7038405.

[17] M. Arnold, R. R. Negenborn, G. Andersson and B. De Schutter, "Model-based predictive control applied to multi-carrier energy systems," 2009 *IEEE Power & Energy Society General Meeting*, Calgary, AB, 2009, pp. 1-8. DOI: 10.1109/PES.2009.5275230.

[18] X. Xu, H. Jia, D. Wang, D. C. Yu and H.-D. Chiang, "Hierarchical energy management system for multi-source multi-product microgrids," *Renewable Energy*, vol. 78, pp. 621-630, 2015.

[19] X. Xu, X. Jin, H. Jia, X. Yu and K. Li, "Hierarchical management for integrated community energy systems," *Applied Energy*, vol. 160, pp. 231-243, 2015.

[20] V. Vélez, L. Ramirez-Elizondo and G. C. Paap, "Control strategy for an autonomous energy system with electricity and heat flows," *2011 16th International Conference on Intelligent System Applications to Power Systems, Hersonissos*, 2011, pp. 1-6. DOI: 10.1109/ISAP.2011.6082245.

[21] L. M. Ramírez-Elizondo and G. C. Paap, "Scheduling and control framework for distribution level systems containing multiple energy carrier systems: Theoretical approach and illustrative example," *International Journal of Electrical Power & Energy Systems*, vol. 66, pp. 194-215, 2015.

[22] M. Arnold, R. R. Negenborn, G. Andersson and B. De Schutter, "Distributed control applied to combined electricity and natural gas infrastructures," 2*008 First International Conference on Infrastructure Systems and Services: Building Networks for a Brighter Future (INFRA), Rotterdam*, 2008, pp. 1-6. DOI: 10.1109/INFRA.2008.5439653.

[23] M. Arnold, R. R.Negenborn, G. Andersson, B. De Schutter, "Distributed Predictive Control for Energy Hub Coordination in Coupled Electricity and Gas Networks," *Intelligent Infrastructures. Intelligent Systems, Control and Automation: Science and Engineering*, vol. 42, *Netherlands: Springer*, 2010, pp. 235-273.

[24] F. Salgado and P. Pedrero, "Short-term operation planning on cogeneration systems: A survey," *Electric Power Systems Research*, vol. 78, no. 5, pp. 835-848, 2008. DOI: 10.1016/j.epsr.2007.06.001.

[25] M. Houwing, R. R. Negenborn and B. De Schutter, "Demand Response With Micro-CHP Systems," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 200-213, Jan. 2011. DOI: 10.1109/JPROC.2010.2053831.

[26] T. Capuder and P. Mancarella, "Modelling and assessment of the techno-economic and environmental performance of flexible Multi-Generation systems," *2014 Power Systems Computation Conference,* Wroclaw, 2014, pp. 1-7. DOI: 10.1109/PSCC.2014.7038404.

[27] T. Capuder and P. Mancarella, "Techno-economic and environmental modeling and optimization

of flexible distributed multi-generation options," *Energy*, vol. 71, pp. 516-533, 2014.

[28] X. Liu and P. Mancarella, "Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems," *Applied Energy*, vol. 167, pp. 336-352, Apr. 2016. DOI: 10.1016/j.apenergy.2015.08.089.

[29] W. Kusch, T.Schmidla and I. Stadler, "Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewables," *Energy*, vol. 48, pp. 153-159, 2012.

[30] J. Vandewalle, N. Keyaerts and W. D'haeseleer, "The role of thermal storage and natural gas in a smart energy system," *2012 9th International Conference on the European Energy Market, Florence,* 2012, pp. 1-9. DOI: 10.1109/EEM.2012.6254803.

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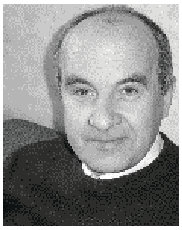

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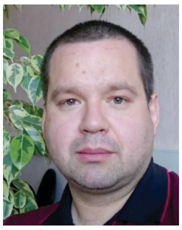

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