AN INNOVATIVE ENERGY MANAGEMENT SYSTEM FOR THE INTEGRATION OF VOLATILE ENERGY INTO INDUSTRIAL PROCESSES

A. PELZER, P. LOMBARDI, B. ARENDARSKI & P. KOMARNICKI
Fraunhofer Institute for Factory Operation and Automation Magdeburg.

ABSTRACT

The generation of electricity by volatile renewable energy sources, such as wind and sun, has increased significantly in many European countries in the last decade. Such a success is mostly due to the economic incentives given to the power producers by renewable energy sources. It has encouraged many small- and medium-sized enterprises to generate a part of their electricity consumption locally. Such a modern business model has created a new actor within the electric power system: the prosumer. The electricity generated by decentralized power plants in many small- and medium-sized enterprises to date is not integrated into the industrial processes, but it is, firstly, fed into the electric grid and is, successively, withdrawn from the grid. A direct integration of the electric power generated into industrial processes is preferable both from the energetic as well as from the environmental point of view. In order to do this, it is necessary to use Energy Management Systems (EMSs), which control the consumption and/or the energy storage systems optimally according the power produced by the volatile renewable energy sources. Such EMSs will allow the enterprises to develop Industry 4.0 solutions and, therefore, cut the energy costs for manufacturing. This study aims to describe the information and communication architecture as well as the modus operandi of a developed intelligent EMS for the integration of the volatile electricity into an industrial process.

Keywords: energy storage systems, energy management system, industry 4.0, Internet of Things, production management system, prosumer, renewable energy sources.

1 INTRODUCTION

The installation of power plants based on Renewable Energy Sources (RES) has been intensively supported in many European countries during the last decade. In 2014, about 400 GW produced by power plants based on RES were in operation, which accounted for 28% of the total gross electricity consumption [1]. Two decisions have mainly contributed to such results:

- The economic incentives ensured to the investors of the RES-based power plants, and
- The possibility given to the RES-based operators to feed the grid, at first, without considering who will consume their electricity.

As a consequence of such decisions, an increasing amount of RES generation is curtailed. The latter depends mostly on the grid congestion problems which appear predominantly in the distribution network system [2, 3]. Secondly, a part of the power fed into the system is not even integrated optimally. This is principally true for the prosumers. Indeed, the electricity generated by RES locally in many small- and medium-sized enterprises is not directly integrated into the industrial processes, but is, firstly, fed into the electric grid and, successively, withdrawn from the grid. A direct integration of the electric power generated into the industrial processes is preferable both from the energetic as well as from the environmental point of view. Indeed, in this way, a high amount of network losses of

ISSN: 2056-3272 (paper format), ISSN: 2056-3280 (online), http://www.witpress.com/journals
DOI: 10.2495/EQ-V1-N4-339-348

green energy could be reduced. However, it is very complex to align the production processes to the volatility of the power generation from RES. For this reason, it is necessary to develop innovative and efficient solutions, such as intelligent Energy Management Systems (EMSs), which allow the flexibility of the industrial processes to increase and the volatile power generation by RES to better align to the production processes [4, 5]. In addition, the use of such EMSs will contribute to the development of new solutions based on the concept of Industry 4.0 and, therefore, cut the energy costs, allowing the enterprises to be more competitive in the market.

In this study, the main functions of an innovative EMS for the integration of the volatile RES energy into the industrial processes are described. The paper is structured as follows: Firstly, an overview of the application of EMSs in the industrial sectors is given. In the second part, the EMS developed is described both from an energy and a technical point of view. The preliminary results of the application of the EMS developed to a complex building are pointed out in the final part of the paper.

2 ENERGY MANAGEMENT SYSTEMS APPLIED TO THE INDUSTRIAL SECTOR

The development of new functionality for the EMSs is involving increasing attention in the research area [6, 7]. Many studies have been dedicated to find new solutions to improve the energy efficiency within industrial processes. How the adoption of EMS by energy-intensive industries, such as pulp and paper production, may improve the energy efficiency of the whole production process was pointed out in [8–10]. This was investigated similarly in [11, 12], in which the iron, steel, ceramic and cement industrial sectors were considered. The necessity of developing interdisciplinary energy managers in order to better understand the complexity of the EMS applied to high-tech industrial sectors was pointed out in [13]. New energy management approaches for energy benchmarking which could be implemented within the EN 16001, ISO 50001 and ISO 14044 standards for intensive energy processes (glass and class iron melting) were proposed in [14].

The practical application of almost all this research focuses on the feedback from the energy manager regarding the energy-saving potential (if any) within the industrial applications. Indeed, the monitoring of the energy consumption and its analysis are the most developed functionality. Very rudimentary control strategies have been developed [15]. Most of them do not consider the production process, but are limited to switching off some secondary loads (in case of necessity), such as lights or offices' cooling-systems [16]. Multi-criteria control strategies for complex buildings (mostly tertiary sector) were proposed in [17, 18]. These strategies aim to integrate the electricity generated by RES optimally by the use of stationary and mobile energy storage systems (electric vehicles).

To the best of the authors' knowledge, there are few EMSs to date which face the problem of how to optimally integrate the intermittent energy generated by the RES into the industrial processes. The direct integration of the electricity generated has the advantage of reducing the losses accounted when the electricity is initially fed into the grid and successively withdrawn from the grid. However, in order to align the intermittent generation of RES with the variable consumption of the load, it is necessary to monitor the generation and consumption, to forecast the power generation and consumption, and to develop new solutions which make the control of the power generation, consumption and storage more flexible.

3 INFORMATION AND COMMUNICATION ARCHITECTURE OF THE EMS DEVELOPED

The main idea of the EMS developed is based on the dynamic control of the power consumption and power storage according to the power generated by the RES. In comparison to the classic EMS, there is a paradigm change regarding the newly developed EMS. The classic EMSs normally supply information (feedback) to the energy manager and do not control the industrial processes dynamically. In order to realize such a dynamic EMS, technologies and solutions from the field of the ‘Internet of Things’ and Industry 4.0 [19] may be used. New solutions, therefore, may be developed which can be activated and implemented automatically as micro services [20, 21].

The design of a dynamic EMS is based on the definition of the corporate objectives. At first, the goals which should be covered by the EMS have to be defined. Additionally, the boundary of the system, which may be related to the management processes, the energy usage and the energy sources need to be defined. At the same time, the interfaces, mostly for the data exchanges with other systems, have to be implemented. Figure 1 depicts the main objectives considered for the design of the EMS

Another requirement is that all energy resources and flows must be monitored. Therefore, the existing information and communication technology (ICT) infrastructure and devices, such as measuring tools, have to be integrated within the EMS. The information collected must be analyzed in order to perform key indicators. The implication is that the measuring devices must be able to analyze and process a lot of information in real time. Stream processing frameworks can be used effectively for this challenge. The Apache Spark has been used as a processing framework within the newly developed EMS.

Furthermore, it is necessary to develop a domain model of all the energy sources. This model defines all entities and their properties and can be used by the energy services to communicate with each other and store all information in a database system. A ‘cross energy data model’ has been developed within the newly developed EMS. It considers not only the electrical form of the energy, but also the thermal and mechanical forms. Objects are collected in classes regarding the properties of each power plant, power storage and energy converter, the manufacturing processes, their scheduling, the transport medium, the equipment, the energy

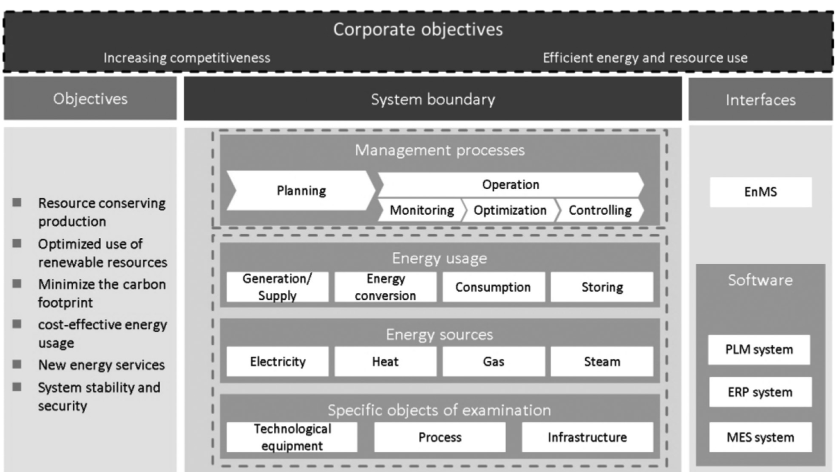

Figure 1: Main objectives for the design of the EMS.

and material mediums, and user-defined classes. A scheme of the classes designed and their relationships is depicted in Fig. 2.

There are functions in the operation mode to monitor, forecast and control the energy sources (for generation, storage and consumption). Here, the functions must meet certain requirements or possess certain characteristics. The monitoring of the system state must be performed at a sufficient accuracy and sample rate. These parameters are dependent on the power fluctuations of the respective components. When optimizing the energy use, differential equations are used to describe the physical properties of the individual system components and their restrictions. Considering the restrictions, operational constraints that are defined by technical staff are also taken into account. The most diverse data retention technologies

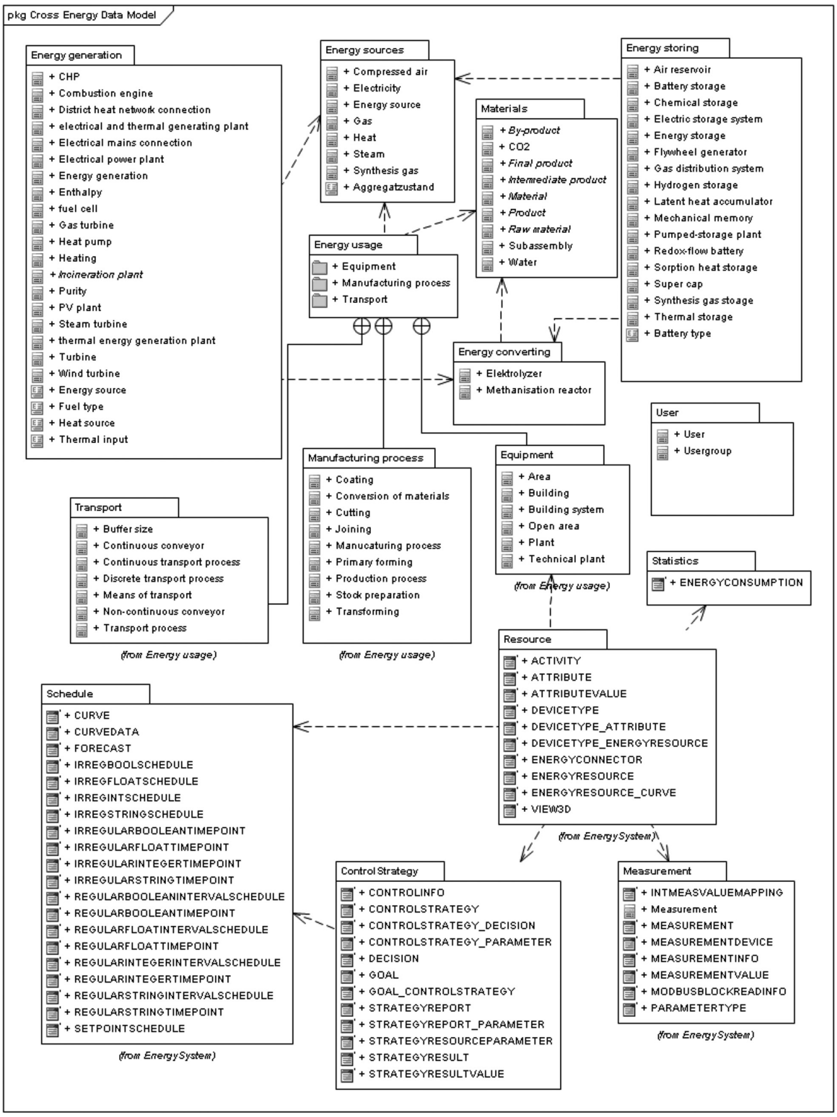

Figure 2: Designed cross energy data model architecture.

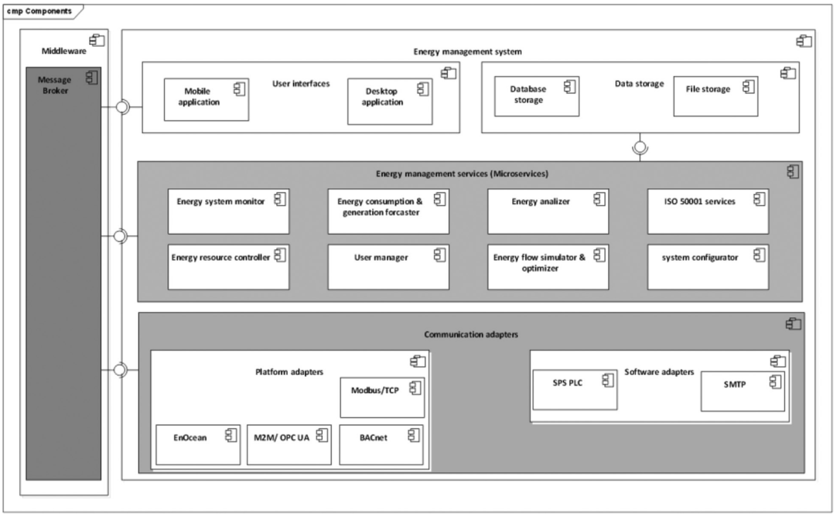

Figure 3: Architecture of the functionalities and communications developed.

can be used for storage. These technologies need to be able to analyze large amounts of data in real time (BigData technologies for Industry 4.0). Dependencies within the process chain may be analyzed using the energy analysis service, allowing new potential for increased flexibility to be revealed as well as modeling new technical equipment operation modes that have a positive impact on energy consumption. Figure 3 shows the architecture of the newly developed EMS's functionalities and communications.

4 THE EMS FUNCTIONALITIES DEVELOPED WITHIN THE INDUSTRY 4.0 CONCEPT

The main aim of the newly developed EMS is the optimal integration of the electric power generated by volatile RES into the industrial processes. In order to do this, it is necessary to monitor and control both the industrial production processes and the power generation and storage processes. A system with such characteristics will allow the industrial systems to develop to the so-called 'Industry 4.0' standard. Indeed, within the Industry 4.0 concept, the production machinery will be able to communicate with an intelligent Production Management System (PMS) which will control the machinery optimally according to its objective function. The PMS sends and receives information to and from the EMS, which monitors the electric power generators and monitors and controls the energy storage system (see Fig. 4).

The EMS operability has been tested at the Fraunhofer Institute IFF Magdeburg in the building VDTC. A photovoltaic plant with an installed power of 10 kW is installed on the roof of this building. A lithium-ion battery is also connected to the building's electric grid. The battery has an energy storage capacity of 20 kWh and is able to charge and discharge up to 10 kW of electric power. A laboratory for testing some of the industrial processes is also situated within the building. The laboratory is composed of a robot which reproduces the mechanical assembly of an industrial process. Its industrial process is composed of three phases: drying, mechanical assembly and storage of the finished product. The assembly process consumes a maximal electric power of 3 kW. Table 1 summarizes the main characteristics of the EMS facility test.

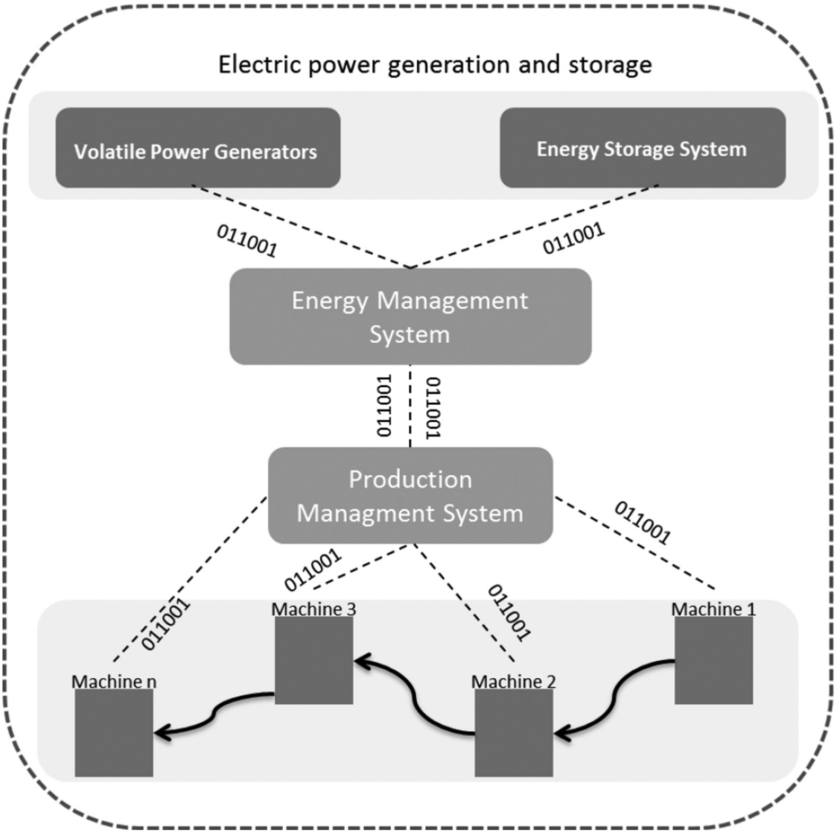

Figure 4: EMS and PMS architecture scheme concept.

Table 1 Energy Management System facility test.

	Max power generated/ discharged [kW]	Max power consumed/charged [kW]	Storage capacity [kWh]
Photovoltaic	10		
Industrial process		3	
Energy storage system	10	10	20

As mentioned previously, in order to fulfill the aim of integrating the volatile power generation by the photovoltaic plant into the industrial process, the EMS uses three functions which have been developed and tested:

- Monitoring
- Forecasting and
- Controlling.

The monitoring function allows the EMS to monitor the electric power generated, stored and consumed within the VDTC building. In order to do this, different meters have been installed.

A central meter, which is connected to the building's transformer, measures the power taken from the electric grid. Other meters measure the power consumed in the laboratories and on the different floors of the building. The electric power used in the industrial process laboratory is also measured with a dedicated meter. The PMS communicates with the EMS, sending it the information for the monitoring of the process.

In addition to the power consumption, the power generated and stored is also monitored. A meter is connected to the photovoltaic plant's inverter and a second meter measures the charged and discharged power of the battery and its state of charge. The data collected by all the meters are sent to a central data storage by the Modbus protocol. The meters at the photovoltaic plant, the battery and the industrial process transmit their data by the Ethernet TPC/IP protocol. The data storage sends its data to the EMS according to the SQL protocol. A draft of the communication scheme is shown in Fig. 5.

The electricity consumed, generated and stored is visualized through digital meters with needle and bar diagrams. The meters with needles measure the power consumed and generated, while the bar diagrams the hourly and daily forecast of the electricity consumed and generated (see Fig. 6).

The forecast is the second function developed. It allows the prediction of the power consumed and generated. The predicted time horizon varies from 15 min to 24 h. The forecasting of generation and consumption is based on the neuronal artificial network algorithms, which

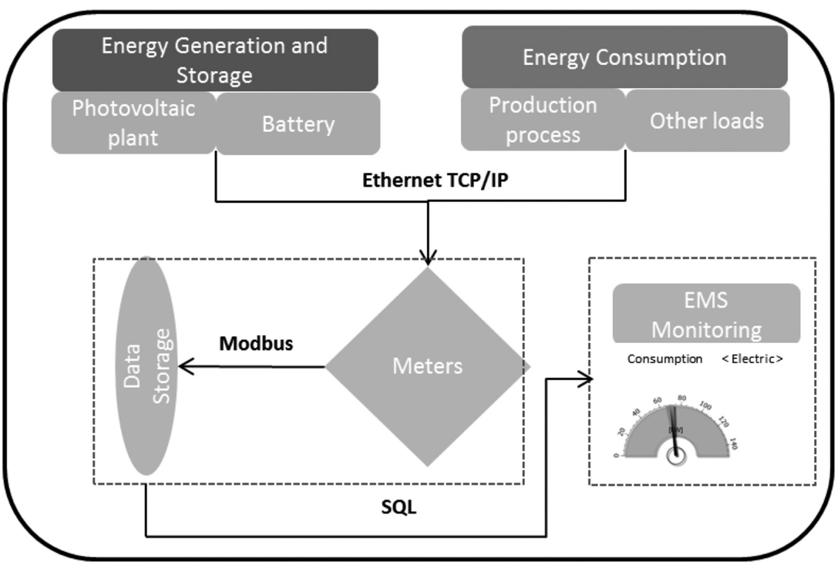

Figure 5: EMS monitoring scheme.

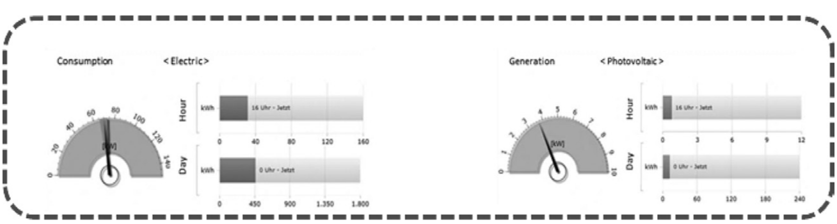

Figure 6: Visualization of the power and energy consumed (left) and generated (right).

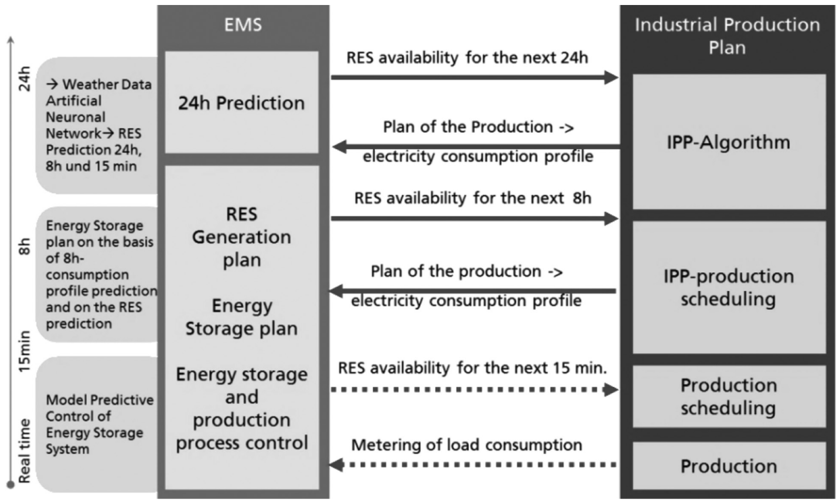

Figure 7: Time schedule and data exchange scheme.

use both the historical data, stored inside a data base, and the information from the weather station to perform the predictions.

The industrial production plant (IPP) for the day ahead is delivered on the basis of the predicted power, which can be generated by the volatile RES. The IPP schedules the industrial production during the next day. It particularly plans the quantity of the production and in which part of the day it should be produced. To achieve this aim, the IPP considers the availability of the RES power generation, the amount of the energy consumed for the assembly process and the space available to store the finished product. As a result of such a process, an electricity consumption profile is emitted and sent to the EMS. In the same way, two new electricity consumption profiles, which are based, respectively, on the 8 h and on 15 min ahead predictions, are reproduced. Among these profiles, those with the shortest time horizon profile will be used successively by the EMS as a reference trajectory for the controlling process.

The controlling process is the last function developed. A controlling strategy based on the model predictive control has been developed for the optimal control of the energy storage system. The strategy takes into account the amount of RES available and the industrial production scheduled. In order to avoid the energy losses of storing electricity inside the battery, the EMS prefers to control the production process by speeding up or slowing down the process carried out by the robot. If it is not possible, the EMS will charge or discharge the battery in order to balance the forecasting errors of the power generation and consumption. The time scheduling scheme and its time data interaction between the EMS and the IPP are depicted in Fig. 7.

5 CONCLUSIONS

More and more enterprises in Europe are generating electric power locally using renewable resources, such as wind and sun. They are, therefore, becoming energy ‘prosumers’. The electric power generated is not fed directly into the industrial processes, but it is initially fed into the electric grid and, successively, withdrawn from it. A direct use of the electric power generated in the industrial processes is preferable both from an energy and an environmental point of view. The design of an intelligent EMS may allow the integration of the volatile power generated by RES directly into the industrial processes. Such EMSs may contribute to speeding up the enterprises' modernization process towards Industry 4.0, which is based on the concept of the Internet of Things.

The ICT architecture of an innovative EMS and its functionalities have been explained in this study. The EMS functionalities have been designed to integrate the volatile electric power generated by a photovoltaic plant into an industrial process. The industrial process is composed of three underprocesses which are realized inside a robot machine. The functionalities developed allow the integration of all the electric power generated by the photovoltaic plant into the industrial process. In order to do this, an energy storage system (battery) is used to compensate for the volatile power generation and the forecasting errors of the electric power which can be generated.

The innovative EMS is currently in a testing phase at the Fraunhofer Institute IFF Magdeburg.

ACKNOWLEDGMENT

This study has been supported by the Fraunhofer internal program "E³- Research Factory" (http://www.e3-fabrik.de/en.html).

REFERENCES

[1] Eurostat Statistics Explained, "Energy from renewable sources" available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_from_renewable_sources.

[2] Klabunde, C., Moskalenko, N., Styczynski, Z., Lombardi, P. & Komarnicki, P., Use of energy storage systems in low voltage networks with high photovoltaic system penetration. PowerTech, 2015 IEEE Eindhoven, 2015.

[3] Bielchev, I., Richter, M., Banka, M., Trojan, P., Styczynski, Z.A., Naumann, A. & Komarnicki, P., Dynamic distribution grid management through the coordination of decentralized power units IEEE Power and Energy Society General Meeting, 2015-September, art. no. 7286124.

[4] Samad, T. & Kiliccote, S., Smart grid technologies and applications for the industrial sector. *Computers & Chemical Engineering*, **47**, pp. 76–84, 2012. http://dx.doi.org/10.1016/j.compchemeng.2012.07.006

[5] Paulus, M. & Borggrefe, F., The potential of demand-side management in energy-intensive industries for electricity markets in Germany. *Applied Energy*, **88**, pp. 432–441, 2011. http://dx.doi.org/10.1016/j.apenergy.2010.03.017

[6] Rasool, G., Ehsan, F. & Shahbaz, M., A systematic literature review on electricity management systems. *Renewable and Sustainable Energy Reviews*, **49**, pp. 975–989, 2015. http://dx.doi.org/10.1016/j.rser.2015.04.054

[7] Schulze, M., Nehler, H., Ottosson, M. & Thollander, P., Energy management in industry – a systematic review of previous findings and an integrative conceptual framework. *Journal of Cleaner Production*, **112**, pp. 3692–3708, 2016. http://dx.doi.org/10.1016/j.jclepro.2015.06.060

[8] Thollander, P. & Ottosson, M., Energy management practices in Swedish energy-intensive industries. *Journal of Cleaner Production*, **12**, pp. 1125–1133, 2010. http://dx.doi.org/10.1016/j.jclepro.2010.04.011

[9] Rudberg, M., Waldemarsson, M. & Lidestam, H., Strategic perspectives on energy management: A case study in the process industry. *Applied Energy*, **104**, pp. 487–496, 2013. http://dx.doi.org/10.1016/j.apenergy.2012.11.027

[10] Sivill, L., Manninnen, J., Hippinen, I. & Ahtila, P., Success factors of energy management in energy-intensive industries: Development priority of energy performance measurement. *International Journal on Energy Research*, **37**, pp. 936–951, 2013. http://dx.doi.org/10.1002/er.2898

[11] Ahmet Ates, S. & Durakbasa, N.M., Evaluation of corporate energy management practices of energy intensive industries in Turkey. *Energy*, **45**, pp. 81–91, 2012. http://dx.doi.org/10.1016/j.energy.2012.03.032

[12] Madloola, N.A., Saidura, R., Hossaina, M.S. & Rahimb, N.A., A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy Reviews*, **15**, pp. 2042–2060, 2011. http://dx.doi.org/10.1016/j.rser.2011.01.005

[13] Gitelman, L., Magaril, E. & Khodorovsky, M., Interdisciplinarity as heuristic resource for energy management. *International Journal of Energy Production and Management*, **1**, pp. 163–171, 2016. http://dx.doi.org/10.2495/EQ-V1-N2-163-171

[14] Giacone, E. & Mancò, S., Energy efficiency measurement in industrial processes. *Energy*, **38**, pp. 331–345, 2012. http://dx.doi.org/10.1016/j.energy.2011.11.054

[15] Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M. & Ernst, F., Integrating energy efficiency performance in production management - Gap analysis between industrial needs and scientific literature. *Journal of Cleaner Production*, **19**, pp. 667–679, 2011. http://dx.doi.org/10.1016/j.jclepro.2010.11.011

[16] Shrouf, F., Ordieres-Meré, J., García-Sánchez, A. & Ortega-Mier, M., Optimizing the production scheduling of a single machine to minimize total energy consumption costs. *Journal of Cleaner Production*, **67**, pp. 197–120, 2014. http://dx.doi.org/10.1016/j.jclepro.2013.12.024

[17] Moskalenko, N., Lombardi, P. & Komarnicki, P., Control strategies and infrastructure for a dynamic energy management system (DEMS). *PowerTech Conference*, IEEE Grenoble, 2013.

[18] Moskalenko, N., Lombardi, P. & Komarnicki, P., Dynamic energy management system based on the multi-criteria control strategy. Cigré SC C6 Colloquium, Yokohama, 2013.

[19] Carlini, E.M., Giannuzzi, G.M., Mercogliano, P., Schiano, P., Vaccaro, A. & Villacci, D., A decentralized and proactive architecture based on the cyber physical system paradigm for smart transmission grids modelling, monitoring and control. *Technology and Economics of Smart Grids and Sustainable Energy*, 2016.

[20] Zhao, B., Xue, M., Zhang, X., Wang, C. & Zhao, J., An MAS based energy management system for a stand-alone microgrid at high altitude. *Applied Energy*, **143**, pp. 251–261, 2015. http://dx.doi.org/10.1016/j.apenergy.2015.01.016

[21] Karavas, C.S., Kyriakarakos, G., Arvanitis, K.G. & Papadaki, G., A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids. *Energy Conversion and Management*, **103**, pp. 166–179, 2015. http://dx.doi.org/10.1016/j.enconman.2015.06.021