Design of a smart-grid energy system at VŠB- Technical University of Ostrava

Jan Najser[1], Jaroslav Frantík[1], Marcel Mikeska[1] and Libor Hrdina[1]

[1] ENET Centre, VŠB -Technical University of Ostrava, 17. listopadu 15, Ostrava-Poruba CZ-708 00, Czech Republic

Abstract

Smart grid energy systems and off-grid systems, which involve renewable energy, have become of a great interest worldwide. These eco-friendly technologies lead to reductions in waste production, which are the on-going priorities of the European Union. In this study, a smart energy system installed in the Technology Centre Ostrava (TCO) at VŠB- Technical University of Ostrava is described. On the grounds of our previous research, a prediction model of operation of a smart grid system is presented. The smart grid combines a solar photovoltaic system, fuel cell technology, pyrolysis unit, cogeneration unit, power converters, and battery packs. These subsystems can operate separately but the goal of this study is to demonstrate their cooperation for the purpose of energy production.

Keywords: Renewable energy, solar system, smart grid, energy storage

1. Introduction

In smart energy systems, various energy sources and energy storing devices are interconnected to supply electric energy to existing facilities or to the electric grid (Singh and Baredar, 2016). Energy storage is an important part of such systems because solar energy is an intermittent source of energy. It supplies energy only during the day and the energy supplied varies with changes in weather conditions (Hegedus and Luque, 2011; Perna et al., 2018). Rechargeable batteries with high energy density are widely used in many fields such as electronic equipment, electrical vehicles, aerospace, etc. (Li et al., 2017).

2. Smart-grid system components

The Technology Centre Ostrava (TCO) in the Czech Republic was established within the project ENET - Energy units for the exploitation of unconventional energy sources in 2010 (Vaculik et al., 2016). The smart energy system at TCO consists of a solar photovoltaic system, fuel cell technology, pyrolysis unit, cogeneration unit, and battery packs that are all parts of the Research and Technology Centre Ostrava (Fig. 1).

doi:10.18086/swc.2019.19.07 Available at http://proceedings.ises.org

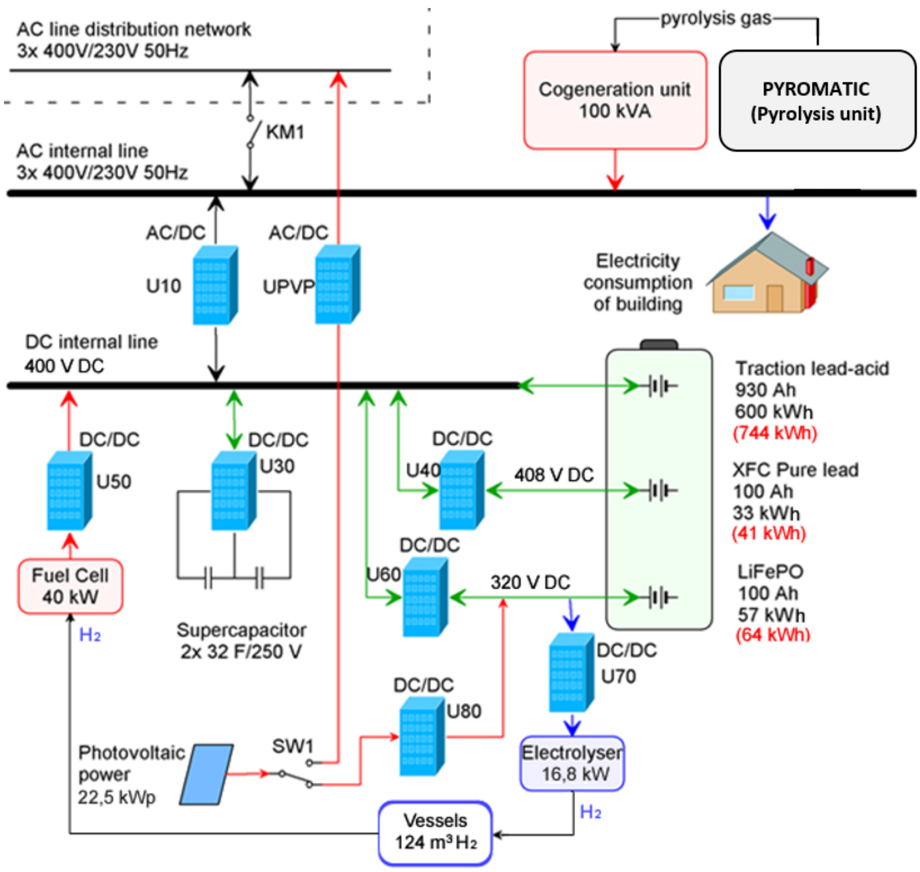

Fig. 1: Smart energy system placed in TCO at VŠB- Technical University of Ostrava

2.1. Solar photovoltaic system

The solar photovoltaic system consists of three types of photovoltaic panels (Fig. 2). The installed total power output is 22.5 kWp.

- Section 1: 60 pcs of polycrystalic photovoltaic panels Trina Solar TSM PC05 210Wp (static panels installed on a sloping roof)
- Section 2: 18 pcs polycrystalic photovoltaic panels EcoDuoAUO PM220P00, 230 Wp (panels installed on electrically driven trackers)
- Section 3: 10 pcs amorphous photovoltaic cells Fatrasol Model 576 (8 x 68 W), 576 Wp (cells sheets installed on a flat roof of the hall)

Each section has its own DC/AC On Grid inverter for supply to the power grid and a DC/DC inverter to charge the batteries. This solution enables improved charging efficiency, since dual DC/AC and AC/DC conversion is not required.

Fig. 2: Three types of photovoltaic panel on the roof of TCO - static panel, tracker and amorphous cells

2.2. Fuel cell system

Fuel cell system consists of a station of technical gases (outside installation), electrolyzers and fuel cells (Fig. 3). Station of technical gasses is formed with 30 pcs of gas cylinders (124 m^3 of hydrogen, water volume 4440 dm^3, and working pressure 2800 kPa). As electrolyzers 4 pcs of type AEM (Alkaline Exchange Membrane) electrolyzers are used (maximum hydrogen production 1009 NL h^{-1}, input power 4200 W). Total hydrogen production is 4000 dm^3 h^{-1} and total input power is 16.8 kW. Used fuel cells are type PEM (Proton Exchange Membrane) NEDSTACK FCS 8-XXL, output power 8 kWe (230 A), max. hydrogen consumption 102 dm^3 min^{-1}, total power output 40 kW.

Fig. 3: Fuel cell system (left- electrolyzers, right- fuel cells)

2.3. Pyrolysis unit

Pyrolysis unit PYROMATIC 250 (Fig. 4) allows for thermochemical conversion of biomass, processed waste and other materials. The device has a continuous reactor which can reach temperatures up to 700 °C and processing speed from 30 to 250 kg h^{-1}. The unit is equipped with thermal, pressure and flow sensors which enables controlled operation. It also allows sampling of pyrolysis gases, liquid and solid products. The reactor is heated by natural gas combustion. Pyrolysis unit has the following main parameters: 600 kW power of main burner type Eclipse, dimension 4400 x 14800 x 4950 mm and weight 5800 kg [6].

Fig. 4: Pyrolysis unit PYROMATIC 250

2.4. Cogeneration unit

Cogeneration unit uses the pyrolysis gases to generate electric energy and heat. It consists of two main parts, the combustion engine (Fig. 5), and electricity generator. The heat from the cogeneration unit is distributed by water circuit and can be used as a heat source in an island mode/off-grid operation. Similarly, the electricity can be used in an island /off-grid mode, but it can also be distributed to the power grid with financial profits.

Fig. 5: Combustion engine of the cogeneration unit

2.5. Battery system

Battery system consists of three types of accumulators. The batteries are LiFePo4, Lead Acid Traction accumulators (Fig. 6), and Valve Regulated Lead Acid accumulators. The lithium batteries were chosen considering the frequent cycling, and lead acid batteries with regard to the accumulation of a higher amount of energy.

Accumulators LiFePo4:	- two sections with nominal voltage 320V, capacity 100Ah
	- total storage capacity 64 kWh (usable 57 kWh).
Lead acid traction accumulators:	- two sections with nominal voltage 400 V, capacity 930 Ah
	- total storage capacity 744 kWh (usable 600 kWh).
Valve Regulated Lead Acid accumulators:	- nominal voltage 408 V, capacity 100 Ah
	- total storage capacity 41 kWh (usable 33 kWh).

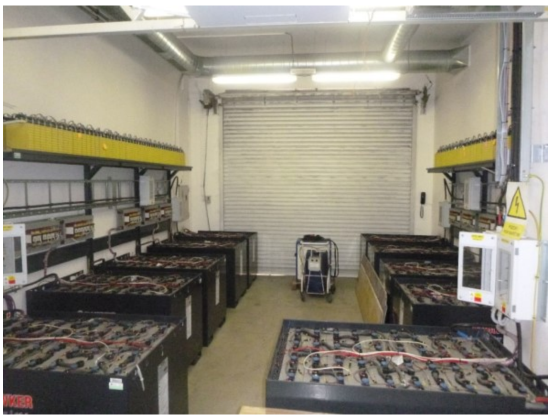

Fig. 6: Accumulators

2.6. Underground gas storage tanks

There are two underground gas storage tanks located at the Technology Centre Ostrava. The first has a volume of 15 m^3 and working pressure 60 kPa, while the second has a volume of 15 m3 and working pressure 700 kPa. Under such conditions, they can store up to 142.48 m^3 of produced gas to be used as required.

2.7. Description of the Control System

The TCO control system has a distributed hierarchical structure, that is, the whole center control is divided among multiple programmable logic controllers (PLCs) that are connected to the parent PLC by an Ethernet network. It is connected to a server running OPC (Open Process Control) server, to which the visualization system is connected.

The PLCs of the individual technologies are located in the control room in the distribution boxes, where a switch and a disk-based server are also located. Together with these main devices, two Transmitters from the Profibus interface to the RS485 interface are also found in the distribution boxes. The designation of each PLC is consistent with the names stored in the control program.

The communication between individual PLCs, provided by block-oriented S7 (Siemens), is carried out by sending datablocks using the BSEND and BRCV functions, using the S7-300 and S7-400 central processing units. These blocks are used for PLC communication of individual technologies with the superior PLC. PLCs with the Pyrolysis System, Operating Technology, Synthetic Gas Converter, Photovoltaic, Fuel Cells, Heat Processes and Accumulation are linked to the PLC Accumulation and Power Generation PLC and are subsequently connected to the OPC server. It "runs" on the physical TCO server.

The communication protocol of the OPC server creates a common communication interface between HW and SW resources. The OPC server is not a physical server but a software program installed on a physical TCO server. This program provides communication with a superior control and visualization system, ie it reads data from a PLC that subsequently mediates visualization in the OPC format.

The visualization system consists of two basic parts - server and client visualization. This is a server-client network architecture. Both parts communicate through the computer network. The server part mediates communication between the OPC server and the client part of the visualization that "runs" on multiple TCO computers while also communicating with power semiconductor converters using the MODBUS and PROFIBUS communication protocol drivers.

3. Experimental

In the experimental part of this paper, a model situation of continuous cooperation is described. The goal is to evaluate possibility of electricity production. Produced electricity should cover the energy demands for system operation plus energy, which can be supplied to a power grid with financial benefits.

3.1. Solar photovoltaic and fuel cell system operation

For the purpose of this research, a 24-hour operation mode of photovoltaic system was recorded in summer day (Fig. 7). It was recorded that in summer day the produced energy was 342 MJ (95 kWh).

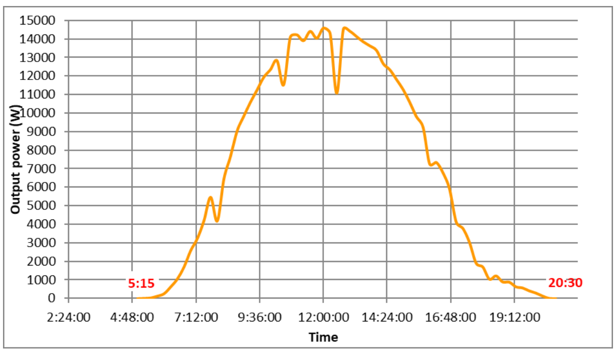

Figure 7: Summer day power production of photovoltaic system

The estimated total accumulation efficiency, which includes the phase of charging and discharging electrochemical accumulators, is 69 %. The efficiency of the electrolyzers is 85 % and the efficiency of the fuel cells is 45 %. Considering the entire accumulation cycle, including the efficiency of the necessary semiconductor converters, the overall efficiency of the hydrogen system accumulation is 29.2 %. During operation, part of the energy is accumulated with hydrogen and a part with batteries, so simplification has been introduced, where the charging takes place with an efficiency of 80 % and discharge with efficiency of 65 %.

3.2. Pyrolysis unit operation

For evaluation of electricity production, the data from our previous research has been used. Ground tires were pyrolyzed in temperature 600 °C. Since our research centre can process only pyrolytic gas, characterization of pyrolytic liquid and coke is not described. Average pyrolytic gas composition is listed in Tab. 1. Pyrolytic gas was characterized by continuous type of devices. In CALOMAT 6 analyzer we determined the hydrogen content, and for methane an ULTRAMAT 6 analyzer was used for the carbon monoxide and carbon dioxide content. FIDAMAT 6 analyzer was used to measure the TOC (total organic carbon) but the result was reduced by methane content so it represents only the sum of high hydrocarbons.

Operating conditions of the test are:

- Feeding speed: 45 kg h^{-1}
- Average electricity consumption: 1.08 kW
- Average pyrolytic gas production: 18.915 m^3 h^{-1}
- Average natural gas consumption: 14.65 m^3 h^{-1}

Tab. 1: Pyrolytic gas composition

Compound	H_2	CH_4	CO_2	CO	TOC	Sum
Volume (%)	11.1	45.4	8.2	4.5	29.3	98.54

The net calorific value of the pyrolytic gas was calculated on the basis of chemical composition to be 36.16 MJ m^{-3}. This net calorific value is consistent with other research (Czajczyńska et al., 2017; González et al., 2001; Leung et al., 2002; Martínez et al., 2013). In hour operation the pyrolysis unit will produce gas containing 684 MJ of chemical energy.

3.3. Cogeneration unit operation

Efficiency of the cogeneration unit was calculated on the basis of data from the manufacturer and net calorific value of the pyrolysis gas. In the case of ground tires, the pyrolysis gas has the net calorific value 36.16 MJ m^{-3} and with the chemical hourly energy input from pyrolytic gas 684 MJ we can get an hourly output 252 MJ of electricity and 361.4 MJ of heat energy. The pyrolysis unit and cogeneration unit are connected by underground gas tanks, which serves as buffer. However, cogeneration unit can combust up to 45.7 m^3 h^{-1} of pyrolytic gas.

3.4. Prediction of smart system performance in continuous mode operation

Based on the results from the pyrolysis of grounnd tires, the production of pyrolytic gas is 18.91 m^3 h^{-1}, which contains 684 MJ of chemical energy. In 24-hour-operation 454 m^3 of pyrolytic gas would be produced, thus corresponding to 16416.64 MJ. The subject of interest is the electricity production, which would be 5976 MJ. Efficiency of the cogeneration unit for electricity production is therefore 36.4 %.

From the amount of natural gas (351,5 m^3) needed for heating the reactor of pyrolysis unit and its calorific value (33.48 MJ m^{-3}) has been calculated that in 24 hours operation mode the energy used for heating was 11768.22 MJ.

Electricity consumption was 93.3 MJ and chemical energy of the fuel was 38804.4 MJ. Total energy inputs of the pyrolysis unit were 50665.92 MJ. Energy outputs were calculated as sum of chemical energy from pyrolytic gas, liquid and coke to be 35101.48 MJ.

From the results of energy inputs and outputs it's clear that the energy efficiency of pyrolysis unit in continuous 24 hours operation mode is 69.2 %. This low value of efficiency is mostly caused by wasting the energy in form of flue gas from natural gas combustion in reactor heating process.

It was recorded that photovoltaic system produces 342 MJ of electricity in summer day. This energy can be stored in battery packs and directly used for pyrolysis unit operation, control room operation or it can be supplied to the power grid if there is demand.

In total, the electric energy outputs from the smart grid system in summer day with continuous operation of pyrolysis unit could be 6318 MJ per day. This corresponds to a daily electricity production. The electricity demand for pyrolysis unit operation is 93.3 MJ per day and for control room about 216 MJ per day. If we consider all energy inputs into the smart grid system (51223.92 MJ) and only electric energy supplied to the power grid (6318 MJ), the efficiency would be 12.3 %. This low value is caused by losses in form of flue gas but mostly because it does not include heat energy from cogeneration unit operation and chemical energy of pyrolytic liquid and coke.

That gives us a considerable amount of daily energy, which can be stored in battery packs or used in electrolyzers, then stored in the form of hydrogen and transferred to electricity in fuel cells if needed. In addition, pyrolysis gas can be stored in underground tanks and used according to demand. This composition of smart grid system offers many possibilities in energy management. It can operate as an off-grid system or react on power grid fluctuations and supply electricity in peak hours when the demand is growing.

4. Conclusions

In this study, the smart grid system installed in Technology Centre Ostrava (TCO) at VŠB- Technical University of Ostrava was presented. From our previous research, the model situation of summer day continuous operation was described. It has been calculated that the produced electricity considerably exceeds demand for operation. This system offers many possibilities to deal with excess energy. It can work as an off-grid system or react on energy demand and supply it to the power grid with financials benefits. In addition, a large part of the energy outputs would be heat from cogeneration which has not been considered in this research. This heat could be used for building heating or drying of biomass fuels and other applications. If we consider all energy inputs into the smart grid system in 24-hour operation mode (51223.92 MJ) and only electric energy supplied to the power grid (6318 MJ), the efficiency was calculated to be 12.3 %. The most important aspect is that in daily operation of this system, 1080 kg of ground tires would be processed with energy gains. This bring the environmental view since normally waste tires would end in a landfill. Naturally, the other pyrolysis products (liquid and solid residue) would have to be processed environmentally as well. The amount of natural gas for pyrolysis unit heating is considerable and energy consumed would significantly shift the balance. Additional research on the subject is needed and real continuous 24 hour operation testing with recording of energy flow into every part of smart grid system will be conducted in the next study. It will include the total calculation of energy inputs (fuel, solar and natural gas energy) and outputs (pyrolysis gas, liquid and solid) with energy conversion and energy losses.

5. Acknowledgments

This paper was created in the Project LTI17023 "Energy Research and Development Information Centre of the Czech Republic" funded by Ministry of Education, Youth and Sports of the Czech Republic, program INTER-EXCELLENCE, subprogram INTER-INFORM, project LO1404: Sustainable Development of Centre ENET and specific research SP 2019/160.

6. References

Czajczyńska, D., Krzyżyńska, R., Jouhara, H., Spencer, N., 2017. Use of pyrolytic gas from waste tire as a fuel: A review. Energy 134, 1121–1131. https://doi.org/https://doi.org/10.1016/j.energy.2017.05.042

González, J.F., Encinar, J.M., Canito, J.L., Rodríguez, J.J., 2001. Pyrolysis of automobile tyre waste. Influence of operating variables and kinetics study. J. Anal. Appl. Pyrolysis 58–59, 667–683. https://doi.org/https://doi.org/10.1016/S0165-2370(00)00201-1

Hegedus, S., Luque, A., 2011. Achievements and Challenges of Solar Electricity from Photovoltaics, in: Handbook of Photovoltaic Science and Engineering. Wiley-Blackwell, pp. 1–38. https://doi.org/10.1002/9780470974704.ch1

Leung, D.Y.C., Yin, X.L., Zhao, Z.L., Xu, B.Y., Chen, Y., 2002. Pyrolysis of tire powder: influence of operation variables on the composition and yields of gaseous product. Fuel Process. Technol. 79, 141–155. https://doi.org/https://doi.org/10.1016/S0378-3820(02)00109-1

Li, Q., Liu, Y., Guo, S., Zhou, H., 2017. Solar energy storage in the rechargeable batteries. Nano Today 16, 46–60. https://doi.org/https://doi.org/10.1016/j.nantod.2017.08.007

Martínez, J.D., Murillo, R., García, T., Veses, A., 2013. Demonstration of the waste tire pyrolysis process on pilot scale in a continuous auger reactor. J. Hazard. Mater. 261, 637–645. https://doi.org/https://doi.org/10.1016/j.jhazmat.2013.07.077

Perna, A., Minutillo, M., Lavadera, A.L., Jannelli, E., 2018. Combining plasma gasification and solid oxide cell technologies in advanced power plants for waste to energy and electric energy storage applications. Waste Manag. 73, 424–438. https://doi.org/https://doi.org/10.1016/j.wasman.2017.09.022

Singh, A., Baredar, P., 2016. Techno-economic assessment of a solar PV, fuel cell, and biomass gasifier hybrid energy system. Energy Reports 2, 254–260. https://doi.org/https://doi.org/10.1016/j.egyr.2016.10.001

Vaculik, P., Kubalik, P., Honus, S., Frantik, J., 2016. The control concept of multisource off-grid system, in: EEEIC 2016 - International Conference on Environment and Electrical Engineering. https://doi.org/10.1109/EEEIC.2016.7555441