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Analysis of component operation in power-to-gas-to-power installations

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HIGHLIGHTS

- The efficiency characteristics of AEM electrolyzers and PEM fuel cell are shown.
- Characteristics of hydrogen generator and auxiliary power index are assessed.
- The economic analysis for P2G2P system is determined.
- Advantages and disadvantages of P2G2P installations are shown.

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ABSTRACT

This article presents results of research into hydrogen generators and fuel cells (basic elements in Power-to-Gas-to-Power systems) together with an economic analysis of this installation type. A hydrogen generator containing two AEM (Anion Exchange Membrane) alkaline electrolyzers with a performance of 0.5 Nm^3 H_2/h and a PEM fuel cell with an electrical power of 0.72 kW were tested. A methodology is presented for determining gross and net efficiency characteristics of the tested devices using measurement results. These operations allowed assessment of the efficiency characteristics as a function of electrical power and identification of the power needs of a hydrogen generator and a fuel cell system. This is important because in P2G2P installations integrated with renewable energy sources these devices operate with variable loads. For a nominal power value, the efficiency of the hydrogen generator was 63% and the efficiency of the fuel cell system was about 40%. For an energy storage system in hydrogen form, a simplified methodology for determining the price ratio of the electric energy sales to the purchase price of the electricity was determined, in order to discover whether the system could be economically efficient. This allowed the determination of the components of this relationship related to the efficiency of the installation and the investment costs of each element. Economic analyses assumed the installation operated with nominal power for a certain period of time throughout the day, strictly connected to the valley and peak of electricity demand. Analysis results are presented as a function of P2G2P system efficiency and working time of hydrogen generators and fuel cells during twenty-four hours. Studies and analyses were performed for P2G2P installations with the most commonly considered elements in energy storage systems. These are considered a very promising solution to the energy balance process, for connecting a high amount of power from renewable energy sources to the power grid.

1. Introduction

In highly developed countries due to the need to reduce greenhouse gas emissions and air pollution, renewable energy sources and new energy solutions are playing an increasingly important role in national power systems [1–5]. Increasing the potential of renewable energy sources and integration of individual photovoltaic installations or wind farms with energy systems requires increasing the flexibility of such energy systems. This is related to possible fluctuations in the amount of energy produced by such installations resulting from a change in meteorological conditions. Increases in the flexibility of power systems can be achieved by using additional installations enabling the storage of surpluses of generated electricity [6]. There are many technological solutions that enable energy storage, many of which also use hydrogen as an energy carrier.

Currently the common use of hydrogen for energy purposes is still not a reality, largely due to the enormous cost of such an installation, the high cost of hydrogen (H_2) production and problems with the operation of high power installations. In addition, H_2 is also considered a dangerous gas. This results in large social resistance associated with the

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use of hydrogen as a fuel. There are still many problems associated with the production, storage, transport and use of pure hydrogen which have to be solved [7–9]. Research on individual devices included in installations using hydrogen as an energy carrier may contribute to solving many problems and to setting out new routes allowing for high-efficiency storage of large amounts of energy. The growing interest in both academia and industry, including the implementation of numerous projects, may also result in a more effective reduction of social resistance associated with the use of such kinds of installations.

Hydrogen as energy carrier can be primarily used in energy storage systems. One of these technology is known as a Power-to-Gas-to-Power power plant (P2G2P) and this uses electrolyzers and fuel cells as the primary energy conversion components, which simultaneously provide fast power balancing. P2G2P installations are considered a potential way to store energy; therefore, at the present a lot of studies are devoted to this technology. These studies include e.g. thermodynamic analysis, economic calculations or modeling simulations. This paper fills the gap between measurements, thermodynamic and economic, by employing a complex analysis of basic elements in P2G2P systems based on measurement results and economic analysis of the entire P2G2P power plant. The main characteristics of the tested devices were determined and are presented in the article together with a simplified methodology for determining the price ratio for the electrical energy sales to the purchase price of the electricity in Power-to-Gas-to-Power installations. The motivation for undertaking the research was the need to integrate key elements of an energy storage installation (P2G2P), e.g. the hydrogen generator and fuel cell, in order to check the correctness of the thesis about the possibility of using H_2 as an energy carrier connected with the economic basis for these investments. The paper describes a hydrogen generator and fuel cell system, taking into account their auxiliary power, which affects to the values and shape of the efficiency characteristics of these devices. The analysis of Power-to-Gas-to-Power systems, taking into account the characteristics presented in the study, allows a demonstration of the real operating conditions of such systems under variable load. The results of this study can be used in the future in the basic design of P2G2P energy systems, which can be used to store large amounts of energy, or they can be the basis for validation of mathematical models used to determine the characteristics of AEM electrolyzers or PEM fuel cells.

2. Review of the technological concept for hydrogen use in power industry systems

Currently, hydrogen is commonly used for ammonia synthesis, petroleum desulfurization, nitrogen fertilizers, methanol, synthetic rubber and lubricant production processes. Although in comparison to other fuels hydrogen has a number of important features for the global economy, hydrogen use for energy purposes is small and usually found in research facilities. Among these features the following can be distinguished:

- the highest *HHV* (higher heating value) per mass unit
- low ignition initiation energy (more efficient combustion process)
- a wide range of flammability (4–70% in mixture with air)
- the capacity for direct use in fuel cells
- hydrogen oxidation product is pure water (significantly less polluting for the environment)
- practically inexhaustible stocks (in water form)

Many concepts for such installations have been developed for hydrogen use for energy purposes. In this case, the installations are considered Power-to-Fuel (P2F), including Power-to-Gas (P2G) or Power-to-Liquid (P2L) and Power-to-Gas-to-Power systems (P2G2P). The individual concepts of these installation are described in [10–14]. The possibilities of using hydrogen in various types of installations are presented in Fig. 1.

Currently in the energetic sector, hydrogen as a fuel is primarily used in PEM fuel cells. There are still no large power fuel cell units based on hydrogen; the largest devices have a power of about 1 MW. These are perfect for use in industrial installations, households and transport. The main advantage of this technology is the low operating temperature, quick start and high flexibility of the system. The main problems for PEM fuel cells are the use of very expensive electrode material (platinum) and purity requirements for the fuel. Stored hydrogen can also be used in gas turbines. It is supplied to the turbine, together with other flammable gases, and can be transported by existing infrastructure for natural gas transmission. In the case of hydrogen used in transport some concepts are described in [15].

3. Concept of power-to-gas-to-power installations

Energy storage technologies are a crucial component in the power grid, indispensable for the effective use of renewable energy sources such as photovoltaic installations or wind farms. Among the energy storage technologies, Pumped Hydro Storage (PHS) systems are the most widely used, especially in large-scale applications. PHS power plants convert electricity to potential energy of the water. In this form, energy can be stored and converted again to electricity when is needed in the power grid. PHS installations are characterized by an efficiency of 70–85% and lifetime of about 40 years [16–18]. Another option for large-scale energy storage technologies is Compressed Air Energy Storage (CAES). In this installation type, energy is stored in the form of high pressure gas (air) and underground caverns can be used as compressed air storage. The efficiency of a working CAES power plant is about 42–54% [18].

There are also many concepts for using hydrogen as an energy carrier in a P2G or G2P installation. Most of these include conversion of hydrogen back to electricity (P2G2P) [19,20]. Hydrogen can be converted in other types of fuel such as methane, methanol or even ammonia [21]. H_2 can also be injected into existing gas network pipelines. However, due to the fact that the re-conversion of hydrogen to electrical energy is the most commonly considered solution, in the further part of the paper, an analysis of the P2G2P installation is proposed.

In Power-to-Gas-to-Power installations, electrical energy is converted into a gaseous fuel, which is stored or transported and then can be used for electricity production. This technology is used for energy surplus storage in hydrogen form and reused in periods of high electricity demand in the electricity grid. Energy surpluses are mainly generated in power plants based on renewable energy sources such as wind farms or photovoltaic plants. These installations can be connected to the main power grid or work on a separate network system (locally). The main elements of the installation are: electrolyzers, which produce hydrogen and oxygen in water electrolysis processes; gas storage facilities; and power generators (Fig. 2). Polymeric membrane (PEM) or alkaline electrolyzers are most commonly used in Power-to-Gas-to-Power installations. As gas storage technologies, pressure vessels, and low-pressure tanks with metal hydrides or cryogenic vessels are mainly used. The role of electric generators is in most cases performed by PEM fuel cells. The use of gas turbines for this purpose is limited, because they cannot be powered by pure hydrogen as a fuel [19].

At present, there is great interest in the use of hydrogen to energy storage [22]. This is connected with the very rapid increase in installed capacity in power plants characterized by unstable electricity production, which depend largely on weather conditions. The share of wind and solar power plants, which use photovoltaic cells, in global electricity production is about 5%, but recently growth of the installed power capacity of these units has been about 15–30% for every year [23].

A number of projects for energy storage in hydrogen form are being realized all over the world [22]. Mostly, low power installations are being constructed. The electrical power from using electrolyzers is usually lower than 1 MW and the power of fuel cells reaches 100 kW.

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