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Assessment of energy conversion for the needs of hydrogen production and storage in terms of environmental impact

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Abstract. Generating clean energy is necessary due to the increasing demand resulting from the development of human civilization and the global economy. The generation of clean energy is justified by the need to reduce the negative impact on the natural environment. Every action aimed at converting one form of energy into another carries consequences related to the efficiency of the transformation process and the physicochemical properties characterizing the systems of its utilization. Special attention should be paid to hydrogen, which is a fuel with high activity in terms of penetration through the structures of conventional construction materials, and there is a high probability of significant emissions of this fuel from its storage and transportation processes. This situation worsens the overall efficiency of the hydrogen utilization process but also necessitates the identification of the consequences of hydrogen emissions into the atmosphere. Therefore, a comprehensive assessment of energy conversion for the purposes of hydrogen production and storage in terms of environmental impact is necessary. The conducted analyses are presented in this article.

1 Introduction

The issue of decarbonizing economic processes is aimed at utilizing carbon-free fuels such as ammonia or hydrogen. The pursuit of energy transformation in the economy at any cost,

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without a comprehensive analysis of the consequences, may have certain negative implications. The low technological efficiency of energy processing systems to obtain ammonia or hydrogen can lead to excessive energy expenditure in the realization of fuel acquisition processes compared to their subsequent utilization. Such a situation promotes excessive greenhouse gas emissions and process heat. This problem is further intensified by difficulties associated with storage and distribution, especially with the leakage of installations. A particular concern in this regard applies to hydrogen, which is a fuel with high diffusivity towards metal structures [1-5]. This results in uncontrolled hydrogen emissions into the environment, worsening the efficiency of hydrogen utilization in energy processes and negatively impacting the atmospheric structure regarding ozone layer degradation.

In the stratosphere, the ozone layer is necessary for absorbing ultraviolet radiation energy, which is sufficient to initiate the dissociation reaction of ozone into oxygen molecules and oxygen atoms. The resulting oxygen molecule reacts with an oxygen atom to reform an ozone molecule. These reactions occur primarily and with greater activity than the reaction of hydrogen and oxygen molecules forming water (H_2O). Despite this, hydrogen-oxygen reactions can occur in the stratosphere, but they are associated with other atmospheric phenomena and chemical conditions. Therefore, it is necessary to limit hydrogen emissions into the atmosphere [3, 4, 6, 7]. The direct correlation here lies in ensuring the tightness of hydrogen storage and distribution installations, which translates into the overall efficiency of energy processing systems using hydrogen.

2 Evaluation of Energy Conversion Utilizing Hydrogen

It is widely accepted that hydrogen should be produced from renewable energy sources such as solar and wind energy. This situation arises due to the variability issue of these types of energy sources, which poses a problem in stabilizing the power grid system. There is a need to store excess electrical energy for later use. One way to do this is by using electrical energy to produce hydrogen through the process of water electrolysis. Producing 1 m^3 of hydrogen through water electrolysis requires about 50 kWh of electrical energy. However, from 1 m^3 of hydrogen in a fuel cell, approximately 35 kWh of electrical energy can be produced. Therefore, in the conversion of electrical energy using an electrolyzer to produce 1 m^3 of hydrogen, and then using a fuel cell to convert 1 m^3 of hydrogen back into electrical energy, we lose 15 kWh of electrical energy. This accounts for 30% of the energy. This portion of energy mostly constitutes thermal energy, which can be utilized for various purposes but ultimately dissipates into the surroundings.

Considering electrical energy, primarily because of its storage potential, the efficiency of the process is around 0.7. Currently, it is estimated that energy losses resulting from hydrogen storage, associated with uncontrolled hydrogen emissions into the environment, energy expenditure on compression processes, and energy expenditure on maintaining installation parameters, may amount to an additional 15% of electrical energy. This translates to a conversion efficiency of around 0.55. In this conversion system, 45% of electrical energy is dissipated into the environment in the form of heat and pure hydrogen. Hydrogen emitted into the environment in its pure form may contribute to negative effects on atmospheric components.

Therefore, it is necessary to analyze other options for its storage and conversion. One such method is binding hydrogen in the form of chemical compounds that maintain high stability under ambient conditions. One of these compounds is methanol (CH_3OH). It can be produced in biomass gasification processes, where at high temperatures, carbon monoxide combines with hydrogen in the presence of water vapor and an appropriate catalyst to form methanol. It can be used as fuel to power fuel cells directly and can also undergo preliminary steam reforming processes, whereby hydrogen is obtained again as fuel for fuel cells along with carbon dioxide. The conversion efficiency in such a system has been subject to research verification.

3 Research on Energy Conversion from Methanol

3.1 Research Setup

Laboratory research was conducted on a research setup consisting of basic functional modules (fig. 1). The main component is a PEMFC fuel cell with a maximum power of 5 kW (fig. 2) fueled by hydrogen generated for the cell's operation in the reformer. The reformer receives fuel in the form of a mixture of methanol and water with a percentage composition of 60/40, respectively. The hydrogen produced in the reformer is separated from the remaining gases and directed to the fuel cell.

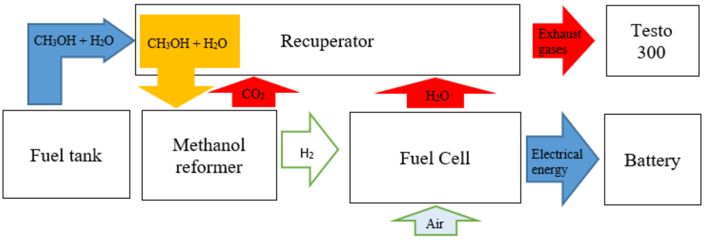

Fig. 1. The schematic diagram of the setup for converting energy from methanol to electrical energy using a fuel cell.

The remaining gases flow through a recuperator, preheating the fuel, and then are directed to the gas outlet, where they combine with the exhaust gases from the fuel cell and are jointly emitted into the atmosphere. The electrical energy generated by the fuel cell is supplied to the battery, the basic parameters of which are listed in Table 1.

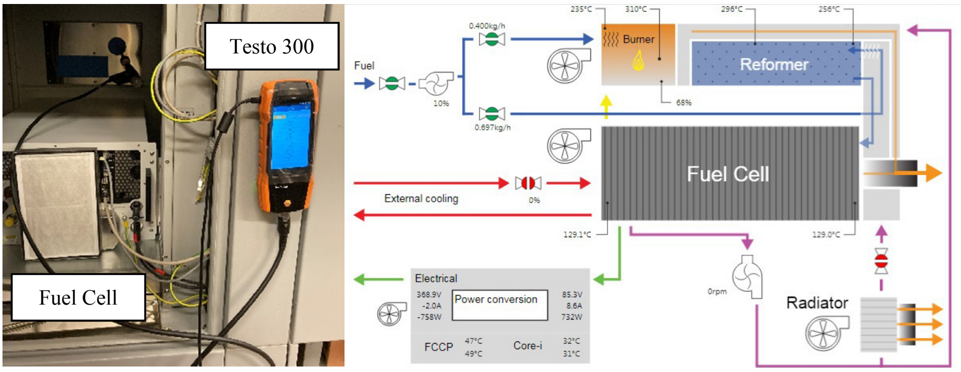

Fig. 2. H5-5000 V3 – 48VDC Senenergy during the examination of operational parameters and the control panel view.

The entire process is managed by the control system in accordance with the specified current intensity parameters, taking into account the current voltage resulting from the battery charge level. The control system of the system is equipped with fuel flow measurement systems, air flow measurement, and temperature measurement at key points for identifying the state of the energy conversion process (fig. 2). Additionally, the concentration of harmful compounds in the exhaust gases was measured using a Testo 300 flue gas analyzer. The analyzer allows for the measurement of carbon dioxide concentration with an accuracy of +/- 0.2% vol., carbon monoxide concentration +/- 20 ppm, and nitrogen oxide concentration +/- 5 ppm. Measurements were taken for several fuel cell load settings controlled by electric current intensity.

Table 1. Battery technical parameters.

Parameter	Value
Total energy capacity [kWh]	15
Operational energy capacity [kWh]	12
Number of cells	1600
Nominal voltage of a single cell [V]	3.75
Nominal capacity of a single cell [Ah]	36
Nominal voltage [V]	395
Total weight [kg]	86

3.2 Research Results

The aim of the research was to verify the parameters of energy conversion from methanol to electrical energy using the energy generation system in the methanol-reformer-fuel cell-battery setup. The system's operational parameters were evaluated based on measurements of basic operational parameters and ecological parameters. Based on the obtained results, an operational characteristic of the system (fig. 3) and a characteristic of ecological parameters in the form of the concentration values of harmful compounds contained in the exhaust gases from the energy generator system (fig. 4) were prepared.

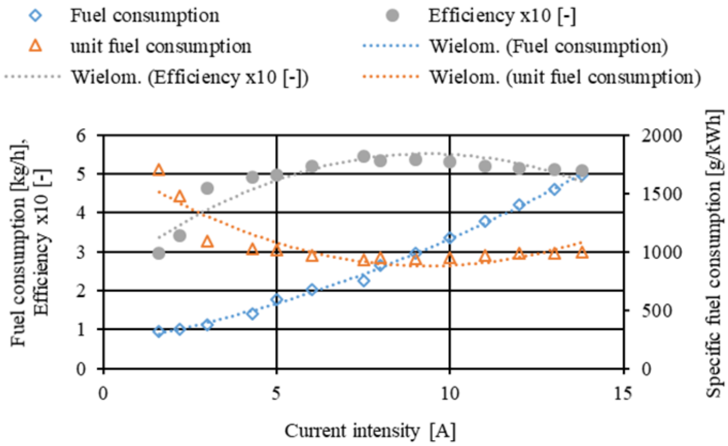

Fig. 3. Characterization of hourly and unit fuel consumption as a function of current intensity at the output of the energy generation system converter.

The hourly fuel consumption characteristic was determined, and based on it, the values of unit fuel consumption were calculated. The presented dependencies indicate the lowest value of unit fuel consumption at a system load level of approximately 55%, corresponding to a current intensity of 7.5 A. At this operating point, the energy generation system achieves the highest efficiency of around 0.55.

During the conducted work, measurements of harmful compound emissions in the exhaust gases were carried out using a TESTO 300 flue gas analyzer. The measurement results of the concentration of harmful compounds in the exhaust gases of the energy generator indicate negligible amounts of these compounds, and the measured values of CO and NO are so small that they represent about 0.2 of the measurement error range. Therefore, it can be assumed with a high degree of certainty that the exhaust gases obtained are free from harmful compounds such as CO and NO, and the concentration of CO_2 is closely related to the generated energy value.

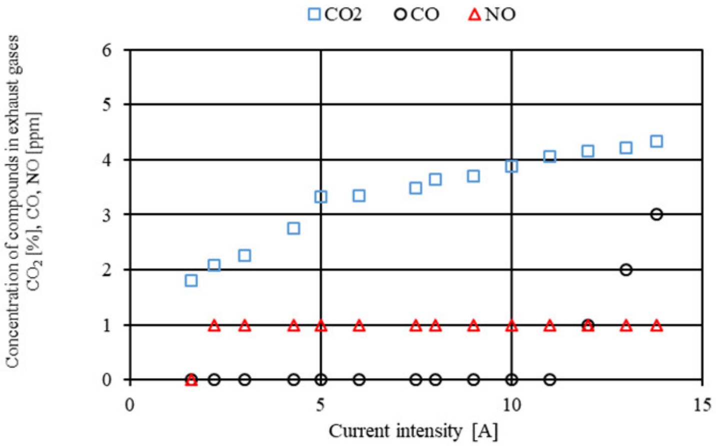

Fig. 4. Measurement results of the exhaust gas composition from the energy generation system using the Testo 300 analyzer as a function of current intensity at the output of the energy generation system converter.

4 Conclusion

The analysis of the energy conversion process using hydrogen in the form of stable chemical compounds under normal conditions such as water and methanol indicates similar process efficiencies of around 0.55. When assessing these energy conversion processes, it is crucial to consider the environmental impact aspect. In energy conversion processes where hydrogen is obtained from the electrolysis of water, the chemical transformations involving hydrogen occurring in the stratosphere are significant and still subject to research and analysis. In the case of energy conversion through hydrogen obtained from methanol, the emission of carbon dioxide as a greenhouse gas is of importance. However, in this case, it can be utilized for methanol production, which positively contributes to its integration into the energy cycle as a hydrogen carrier. Further considerations in this direction should also encompass safety aspects in the energy conversion process. A comprehensive examination of many comparative aspects will be the subject of further analyses, leveraging the dependencies obtained from conducted research.

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