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Editorial

Recent Advances in Green Hydrogen Technology

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1. Background

During the 20th century, the global energy system was mainly based on the use of fossil fuels, such as oil, natural gas, and coal. However, this intensive use of such fuels determined severe issues in terms of availability and effects on the environment. Such an energy paradigm was definitively not sustainable due to the mass utilization of fossil fuels, along with growing energy demands by both industrialized and developing countries. At the same time, such an intensive use of fossil fuels induced a significant increase in the CO_2 emissions, which are responsible for the greenhouse effect. In this framework, most governments worldwide realized that this energy paradigm was no longer sustainable and that a new energy system based on carbon-free fuels should be developed. Here, the role of renewable energy sources is crucial because they enable the production of electricity, for heating and cooling, avoiding CO_2 emissions and fossil fuel consumption. A similar result can be achieved by nuclear power plants, which produce huge amounts of electricity without CO_2 emissions. However, nuclear power plants are affected by issues related to the safety of operation and to the disposal of nuclear waste. In several cases, a combination of the use of renewables and nuclear power plants is considered to be the most attractive strategy for achieving the transition from the current to a fully decarbonized energy system. According to the International Energy Agency (IEA) [1], huge investments are expected in this field in the next few years, especially for the development of renewable energy technologies. However, the IEA also estimates that the global CO_2 emissions are expected to grow in the next few years. Hence, the development and application of novel technologies, along with suitable energy policies and regulations [2], are crucial to limit the greenhouse effect [3]. In this framework, the European Union (EU) plans to cut emissions at least by 40% before 2030, in comparison to its 1990s level [4] and to increase the share of renewable energy production to at least 32%, and to improve energy efficiency by at least by 32.5%. The final goal is a fully decarbonized energy system by 2050 [5]. In this scenario, the use of hydrogen is particularly attractive because its energy utilization does not determine any CO_2 emissions. Unfortunately, hydrogen as a fuel is negligibly available on the Earth and it must be produced by different techniques. The most common is the steam reforming process, which converts hydrocarbons into carbon dioxide and hydrogen. This technique suffers from indirect CO_2 production. However, hydrogen may be also produced by water electrolysis, driven by electricity. In this case, no CO_2 production is achieved when the electricity is provided by renewables. For this reason, the hydrogen produced by electrolysis driven by renewables is also called "green hydrogen", which represents a very attractive solution both as a fuel and as energy storage system, as discussed in the next section.

2. Overview of the Recent Advances in Green Energy Technologies

In the past few years, several papers have been published proposing novel technologies for the production of green hydrogen by renewables and/or to integrate hydrogen into existing energy systems. In this framework, one of the most promising solutions is represented by the possibility of using hydrogen as an electrical storage system. In fact, it is well known that renewables suffer from the unpredictability of production. This circumstance determines a significant mismatching between energy production and demand. Therefore, a suitable energy storage system is crucial to maximize the utilization of renewable resources. Unfortunately, conventional electrochemical batteries suffer from limited capacities, high capital costs, low power densities, and disposal issues. Therefore, in the past few years, a novel approach has been presented, based on the use of hydrogen. Here, the hydrogen can be produced by electrolysis, using only the renewable electricity produced which exceeds the user demand. Therefore, the excess electricity is converted into hydrogen. Then, when the user demand is higher than the renewable production, the previously produced hydrogen can be converted into electricity by a fuel cell, matching the user electricity demand. This novel system promises a significantly higher storage capacity with respect to conventional electrochemical batteries.

This topic was investigated by Arsalis et al. [6] in a recent review paper. Here, the authors focused on regenerative fuel cells coupled with PV fields. Regenerative fuel cells feature the possibility of operating both in electrolyzer and fuel cell modes, integrating both components in a single device. The authors presented a detailed description of the components usually included in such systems, namely, electrolyzers, fuel cells, energy storage units, batteries, hydrogen storage, power electronics, and controllers. Then, detailed descriptions of the most common simulation tools are provided. The authors also reviewed the papers available in the literature, focusing on the application of such novel systems in microgrids, presenting the architecture of these systems and the results of the research. The authors concluded that the proposed system is extremely promising from the energy point of view. However, the long-term economic profitability is still limited by the poor lifetime and by the high capital cost of electrolyzers and fuel cells. Therefore, it is necessary to develop novel and optimized design configurations for the components of the system in order to achieve reasonable economic profitability and to reduce the capital costs for the most expensive components.

In this framework, Al-Badi et al. [7] presented a feasibility analysis for a system including a PV field, wind turbines, electrolyzers, and fuel cells. Here, hydrogen is used as an energy storage system because it is produced when the renewable energy production is higher than the user demand and is consumed when the user demand is higher than the renewable energy production. The system is to be installed in a location in Oman, where electricity is produced by reciprocating engines with a total capacity close to 100 MW. The proposed system includes PV panels, wind turbines, and a storage system (based on an electrolyzer, fuel cells, and hydrogen storage). The system was analyzed from both energy and economic points of view using the well-known tool HOMER Pro. On the basis of the measured data for solar irradiance and wind velocity, the authors calculated both the energy and economic performance of the proposed system. A cost of energy of USD 0.436/kWh was calculated, whereas the levelized cost of energy was USD 0.243/kWh. These results were obtained considering USD 100 per ton of CO_2 saved. From the economic point of view, the authors concluded that hydrogen is more cost-effective than batteries in the long term. The combination of wind energy and green hydrogen was also investigated by Kavadias et al. [8], with special reference to the transport sector. In particular, the authors focused on a 10 MW wind park and assumed that the excess electricity produced by the wind energy could be converted into green hydrogen by electrolysis in order to supply hydrogen refueling stations (HRSs) for vehicles equipped with fuel cells. Detailed calculations were performed to evaluate the dynamic performance of the HRS. The authors also included an economic model for evaluating the profitability of the proposed system. The calculations were performed to determine the optimal capacity of the storage tank. In the best scenario, the payback period was close to 10 years without funding. However, authors concluded that suitable funding policies are crucial to promote this technology.

A significant research effort has also been performed to identify novel devices and/or system arrangements in order to achieve better economic performance. Rosenstiel et al. [9] presented a novel arrangement where the electrolyzer was simultaneously coupled with a photovoltaic field and a concentrating solar power system (CSP), coupled with thermal energy storage (TES) systems. This novel arrangement is expected to improve the number of operating hours of the electrolyzer and to reduce the levelized cost of energy. System performance was calculated with a suitable simulation model, also including detailed techno-economic algorithms. Similarly, suitable control strategies were implemented in order to enhance the number of operating hours of the electrolyzer. The calculations showed that the combination of PV and CSP is much more profitable than a system only including PV panels. Another innovative arrangement was investigated by Calise et al. [10]. Here, the authors analyzed the use of a reversible solid oxide cell, which is a device that can operate both in electrolyzer and fuel cell modes. This innovative device is based on solid oxide fuel cell (SOFC) technology, which is a high-temperature fuel cell, featuring ultra-high efficiency, flexibility in fuel utilization, high operating temperatures (600–1000 °C), and high capital costs. The device was coupled with a hydrogen tank, and it was integrated in a 50 kW PV system serving a building located in southern Italy. A detailed simulation model was developed in MATLAB to evaluate the performance of the SOC. Then, this model was integrated in a dynamic simulation platform in TRNSYS. Special attention was also paid to the simulation of the building and its time-dependent electrical demand. The results are extremely interesting from the energy point of view, with primary energy savings close to 70%. However, the economic profitability is still poor due to the huge capital cost of the SOC, determining a payback period close to 10 years in the best scenario.

Another extremely interesting option related to the use of green hydrogen is the hydrogenation of captured CO_2 [11]. It is well known that the full decarbonization of the energy system is a goal that cannot be achieved in the next few years. A reasonable target is 2050. Therefore, in this transition phase, additional techniques must be implemented in order to limit CO_2 emissions. One of these is represented by CO_2 sequestration. It is relatively easy to separate CO_2 from the flue gases of a conventional power plant powered by fossil fuels. Conversely, it is extremely difficult to store such large amounts of captured CO_2. Thus, a very interesting idea is to combine such captured CO_2 with H_2, produced by renewables, in order to produce hydrocarbons. This system can be considered as a sort of virtual energy storage system, because the excess renewable electricity is used to produce the hydrogen for this process. In addition, CO_2 is valorized for energy purposes rather than performing complex and expensive storage. This topic was extensively analyzed in a review by Varvoutis et al. [11], who presented the different configurations and technologies in the Power-to-X framework.

Awaleh et al. [12] investigated the possibility of producing green hydrogen from renewable electricity produced by a combination of wind energy and geothermal energy for a location in the Republic of Djibouti. Suitable models were implemented in order to calculate the energy production by wind turbines and geothermal power plants. Weather data were provided by local measurement stations. The geothermal power plant was based on a dry steam system and on a single flash power plant. The data of the geothermal reservoir were evaluated using the USGS volumetric method. The calculations were performed considering energy, exergy, and economics of the system. The calculate cost of the produced hydrogen was equal to USD 4.78/kg in the case of single flash geothermal power plants. Conversely, when dry steam geothermal power plants were considered, the cost of the produced hydrogen decreased to USD 3.46/kg.

3. Conclusions

The papers presented in the previous section clearly demonstrate that hydrogen is a great opportunity to promote the decarbonization of the energy sector. Hydrogen is particularly attractive when it is coupled with renewable energy sources. In this case, it can also be used as an electrical energy storage system, and this arrangement may be of pivotal importance to reducing the mismatch between renewable energy production and user demand. Hydrogen can be also used to supply vehicles equipped with fuel cells. However, in this case, a severe limitation was presented by the complexity of the hydrogen distribution infrastructure. Finally, a great opportunity is also represented by Power-to-X technology, where the excess renewable electricity can be used to produce green hydrogen which may be combined with the captured CO_2 to produce methane. All these possibilities make the use of green hydrogen pivotally important to reach to goal of decarbonization expected by 2050. The main limitation of green hydrogen technology is represented by its capital costs, which are so high that the profitability of the system is often poor. Therefore, suitable funding policies must be implemented in order to promote the mature commercialization of this technology and the consequent decrease in the capital costs.

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