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Investigation of an integrated hydrogen production system based on nuclear and renewable energy sources: Comparative evaluation of hydrogen production options with a regenerative fuel cell system

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ABSTRACT

Hydrogen has risen as a sustainable and efficient energy carrier option in reducing environmental pollution, and is seen as a potential solution for the current energy crisis. Hydrogen production via water decomposition is a potential process for direct utilization of nuclear thermal energy to increase efficiency and thereby facilitate energy savings. While many of the available renewable energy resources are limited due to their reliability, quality, quantity and density, nuclear energy has the potential to contribute a significant share of energy supply with very limited impacts to climate change. The proposed model in this study is an integrated hydrogen production system combining both nuclear and solar energy sources. This integrated system includes storage of hydrogen and its conversion to electricity by a regenerative fuel cell system when needed. There are many matured water splitting processes that can be linked with the nuclear and solar energy sources to decompose water to its constituents, among which is hydrogen. In this regard, a comparative study is carried out to evaluate an optimal and feasible hydrogen production/storage process with a regenerative fuel cell that can be linked to this integrated system. Studies conducted here on hydrogen production processes show the thermochemical water decomposition to be the better option for producing hydrogen, comparing to electrolysis, due to its high efficiencies and low costs. Energy and exergy efficiencies of various hydrogen production processes, and fuel cell systems are evaluated and compared. Also, a parametric study is conducted on these efficiencies to see the effect of various operating conditions.

1. Introduction

The increase in energy demand has been an issue since the beginning of modern age. Such an unexpected rise in the energy demand has become a concern for both developing and developed countries for a long time. Developments in power generation technologies have relied mainly on coal, oil and gas or other fossil fuels. The main concern about these technologies is their negative impact on environment due to generation of pollution associated with their usage. Furthermore, the current usage of finite fossil fuels at high rates could lead to a drastic energy crisis in the future. Consequently, civilization is forced to investigate and develop alternative clean energy sources for a brighter future.

Major parts of the world are still dependent on conventional means of producing power and facing an urgent need to shift their power generation technologies to renewables. Greenhouse gases such as carbon dioxide, emitted by fossil fuels combustion, prevent the radiated solar energy from surfaces on the Earth to get transmitted back to space. This results in radiation being trapped within the Earth's atmosphere. This greenhouse effect increases severely in direct relation with pollution, which results in global warming. This in turn causes the melting of the ice caps at the poles, leading to a rise in ocean waters, and thus submerging our precious land.

During the modern age, when new industries were constructed to enhance the standard of living, pollution was not considered as a factor in development. As technology grew and people around the world realized the lethal effects that pollution could cause to our planet, new research and development began to arise. Renewable energy sources are considered to be the future in power generation, since they are abundantly available depending on the geographic conditions and pollution-free.

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Due to many global challenges, potential energy solutions are required to improve sustainability and reduce environmental pollution caused by fossil fuels used in energy generation. Renewable energies have long been considered the viable option due to their ready availability. Renewable energy sources are clean and green but the main drawback is they are not sufficient yet to satisfy the global energy demand. They too have their downsides due to quality, quantity, density, and reliability. Hence, there is a need for an additional sustainable energy source that could provide a large-scale energy supply to complement renewable energy sources. Thus, attempts are being made to combine nuclear energy to back up renewables. Apart from its waste and safety concerns, nuclear energy is clean and does not contribute to any greenhouse gas emissions. Therefore, it can be used as a transition face until renewable sources maturate and become sufficient for a fully renewable future.

Due to rise in the global energy demand at an unprecedented rate, it has become very crucial to come up with a system that is energy efficient, environmentally benign, and sustainable at the same time. There are many R&D and ongoing efforts to find a viable energy system that is capable of meeting energy demands. For a long time, hydrogen production has been researched and developed into a large and growing industry. Hydrogen has a variety of uses. It is currently used in processing fossil fuels, producing ammonia, acting as a coolant in electrical generators, serving in manufacturing plants to determine leaks, and serving as a shielding gas in atomic welding. Developing technologies also show its usage in transportation vehicles in the future and in fuel cells to produce electrical power. Hydrogen is not a primary energy source. It is an energy carrier. Hence, it has to be produced. Once manufactured, this gas would serve as a storage medium for energy generated by other means. A large amount of energy is dissipated as heat when hydrogen is burned. The temperature when hydrogen is burned in the air can roughly reach to 2000 °C.

The production of hydrogen from solar energy has long been studied by many scientists [1–5]. For a long time, developments in such systems had decreased due to the low efficiency of PV (photovoltaic) conversion and expensive equipments. But recently, with advancements in the technology, PV efficiencies have increased significantly. Also, the costs of equipment have decreased. Momirlan et al. [6] have presented some methods used in different countries in production of hydrogen from solar energy. Orhan et al. [7], have investigated a nuclear and renewable integrated system to produce hydrogen from water by thermochemical water splitting using a Cu–Cl cycle. Carton et al. [8] have studied renewable hydrogen production opportunities in Ireland. Abanades et al. [3] have screened water-splitting thermochemical cycles potentially attractive for hydrogen production by concentrated solar energy. Guo et al. [4] have examined solar hydrogen production and its development in China. Bozoglan et al. [1] have assessed sustainable solar hydrogen production techniques. Charvin et al. [5] have examined two-step water splitting thermochemical cycle based on iron oxide redox pair for solar hydrogen production.

Ngoh and Njomo [9] have provided an overview of hydrogen gas production from solar energy. They have showed the different methods and available technologies currently used for producing hydrogen using solar energy as the main source. The first reported process is the photochemical process, which utilizes solar light in the hydrolysis of water. There are two sub-procedures known as the photo biological procedure, which uses certain organisms to act as biological catalysts in the production of hydrogen from water, and the photo electrochemical procedure, in which a semiconductor photocatalyzer is submerged in an aqueous electrolyte or in water to decompose them into hydrogen and water. The second process is the thermochemical process, which includes solar cracking of hydrocarbons, steam reforming of hydrocarbons, and thermochemical transformation of biomass. These procedures use concentrated solar radiations as the main heat source at high temperatures to carry out the endothermic reactions. The last process is the electrochemical process in which electrolysis of water is carried out. This process is the most commonly used and developed method in industries for the production of hydrogen. It is concluded that, from an exergy analysis on these processes, the electrolysis of water is more efficient in areas where strong solar radiation potential is available [9].

Miri and Mraoui [10] have conducted a detailed analysis of an electrolysis process of hydrogen production using solar energy. The electricity supply was done using PV (photovoltaic) cells and water vapor electrolysis was done by a solar concentrating power station at high temperatures. A numerical simulation of hydrogen production was proposed. This analysis was done using values of solar radiation at different sites in Algeria. The conclusions drawn by the researchers were that for the optimal operation of the system, the complete installed system must be located at good climatic conditions. It must be located in localities with strong insulations capable of holding maximum power, taking into account the fact that an increase in temperatures decreases the output of the electric solar power stations.

Kazim and Veziroglu [11] have presented a quantitative study considering the benefits of a solar hydrogen energy system when used in the United Arab Emirates (UAE). Their study indicated that the UAE would fail to meet oil and natural gas market demands in the near future. In order to maintain the country's share in the world energy market, hydrogen was proposed to meet the demands. Certain mathematical models were used in the study to find out the technical and economical feasibility of using solar hydrogen production methods in the UAE. Some of the parameters used in the model calculations were simplified to get a better overview of the energy situation in the country. The author's recommendations were that the UAE should use the barren desert areas for photovoltaic farms. They also recommended that the UAE build pipelines as early as possible, currently for transporting natural gas to other countries and for later stages, when fossil fuels deplete and the hydrogen economy is booming, to transport hydrogen to meet the energy demands. At initial stages, the sales generated from hydrogen would be minimal but then could start increasing to generate the country's income. Future projects could also influence the government's enthusiasm in solar hydrogen production [11].

Negrou et al. [12] have presented a case study of a solar hydrogen production system sited in Algeria. A numerical simulation was conducted for the installed capacity based on the characteristic equations governing the electrolysis of water, solar towers, and hydraulic pumping system. The main aim of the research was to find the most favorable geographic conditions for better production of hydrogen. From their case study, maximum values for the hydrogen production from solar energy were calculated in the southernmost parts of Algeria. The authors also stated that the electricity generated from solar hydrogen production was much cheaper than that of generated by conventional energy [12].

There are several other methods of hydrogen production from solar energy that can be mentioned here. One is studied by Zhang et al. [13] to produce hydrogen from a solar energy-powered supercritical cycle that uses carbon dioxide (CO_2). Supercritical CO_2 was used as the working fluid for a combined production of thermal and hydrogen energy. The proposed system consisted of a heat recovery system, heat pump, power-generating turbine, electrolysis of water, and evacuated solar collectors. CO_2 was efficiently converted into a supercritical state at high temperatures. The high temperatures utilized in the production of electricity and thermal