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Cost evaluation of two potential nuclear power plants for hydrogen production

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ABSTRACT

Hydrogen is recognized as one of the most promising alternative fuels to meet the energy demand for the future by providing a carbon-free solution. In regards to hydrogen production, there has been increasing interest to develop, innovate and commercialize more efficient, effective and economic methods, systems and applications. Nuclear based hydrogen production options through electrolysis and thermochemical cycles appear to be potentially attractive and sustainable for the expanding hydrogen sector. In the current study, two potential nuclear power plants, which are planned to be built in Akkuyu and Sinop in Turkey, are evaluated for hydrogen production scenarios and cost aspects. These two plants will employ the pressurized water reactors with the electricity production capacities of 4800 MW (consisting of 4 units of 1200 MW) for Akkuyu nuclear power plant and 4480 MW (consisting of 4 units of 1120 MW) for Sinop nuclear power plant. Each of these plants are expected to cost about 20 billion US dollars. In the present study, these two plants are considered for hydrogen production and their cost evaluations by employing the special software entitled "Hydrogen Economic Evaluation Program (HEEP)" developed by International Atomic Energy Agency (IAEA) which includes numerous options for hydrogen generation, storage and transportation. The costs of capital, fuel, electricity, decommissioning and consumables are calculated and evaluated in detail for hydrogen generation, storage and transportation in Turkey. The results show that the amount of hydrogen cost varies from 3.18 \$/kg H_2 to 6.17 \$/kg H_2.

Introduction

Efficient, environmentally benign, sustainable, and economic energy systems are getting more critical due to the increased energy demand. Fossil fuels have been used for many years to supply energy demand, but these sources are getting decreased by the time elapsed. Many studies have been carried out and still continue to find a solution to this problem [1–3]. This is not only due to resources deployment strategies for decreasing fossil fuels, but also due to environmental impacts, air, water and soil pollution along with global warming issues. An increasing investment each year in the energy sector, which is yearly almost \$1.8 trillion, has been faced to

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clean, renewable and sustainable energy solutions, rather than fossil fuels such as oil, coal and gas. The value of fossil-fuel consumption subsidies dropped in from 2014 to 2015 from $500 billion to $325 billion. Eventually, many countries have already started to gain benefit [4]. Growth in energy-related CO_2 emissions are getting decreasing owing to use of cleaner energy and gained energy efficiency. While being performing studies on energy efficiency and enhancing the power plants, new energy solutions are tried to find. Even though a particular amount of increasing energy demand can be supplied by enhancing energy efficiency, it would not be enough.

Generating electricity from nuclear power plants has attracted substantial interest among researchers around the world, since 1950s. As shown in Fig. 1, the nuclear-based electricity production is almost 11% worldwide [5]. Nuclear energy has primarily been preferred because of two critical advantages, namely being a sustainable option for base load and emitting no greenhouse gas emissions. Nuclear power plants generate electricity at a constant rate without interruption, on the contrary to renewable energy based power plants. Besides renewable energy resources are limited because of their reliability, quality, quantity, and density. However, both nuclear and renewable energy based power plants are considered as promising candidates mainly due to their environmentally benign aspects. Renewable energy resources can be utilized widely, however, we will need a stable energy generation in a particular rate. Nuclear facilities are one of the best alternatives to fossil fuel based power plants due to sustainability. The enriched uranium used as a fuel in nuclear power plants is uniform in contrast to oil and coal. Nuclear power plants are currently producing over 2500 TWh per year [6]. As shown in Fig. 2, USA and France together generate about 50% of the all nuclear based energy production with the capacity of 830 and 437 TWh, respectively. Russia, China and Korea are the other main producers [7]. In Turkey, the planned capacities are 4800 MW and 4480 MW for Akkuyu and Sinop NPPs, respectively.

Conventional energy sources, such as wood, coal, natural gas and petroleum have been employed by the human being. One of recent technical challenges is designing and developing alternative fuels to replace for fossil fuels. Hydrogen seems to be one of the most promising alternative energy carrier to supply sustainability based on their higher energy efficiency and lower pollutant and lower greenhouse gas emissions compared with fossil fuels [8,9]. It is recognized that hydrogen will replace with petroleum products for transportation and also will replace with fossil fuels for electricity generation. Hydrogen is one of the most plentiful elements, however it is not located as single and usable form. It is usually combined with oxygen, carbon, nitrogen and consist of water, fossil fuels such as hydrocarbon, coal, oil and natural gas. Hydrogen can be mainly generated by (i) gas reforming using high temperature steam (ii) fossil fuel and biomass gasification (iii) thermochemical water splitting of nuclear energy and solar concentrators (iv) electrolysis from renewable energy source (v) high temperature electrolysis by nuclear energy (vi) liquid reforming to produce ethanol or bio-oil (vii) photoelectrochemical and photocatalytic methods [1,3]. Higher efficiencies by faster reactions can be achieved at higher temperatures by nuclear based thermochemical water splitting cycles [3,10]. Besides hydrogen generation method is significant in terms of environmental effect. Although hydrogen is a clean energy carrier, negative environmental impacts can be occurred as to its production method.

Hydrogen can be generated by thermochemical water splitting or high temperature electrolysis from nuclear energy. The electrolysis, particularly high temperature electrolysis, is employed to produce hydrogen by nuclear power. Since electrolysis requires electrical power, it has lower efficiency compared to the thermochemical water splitting. The thermochemical water splitting method is another option to convert water into hydrogen and oxygen through a series of chemical reactions using high temperature steam supplied by solar collectors or nuclear reactors. There are numerous proposed thermochemical cycle, such as sulfur-iodine, hybrid-sulfur, photolytic sulfur ammonia, zinc-oxide cadmium-oxide, sodium-manganese and hybrid copper-chloride in previous studies. Acar and Dincer [3] performed a study to evaluate and compare hydrogen production methods such as natural gas steam reforming, coal and biomass gasification, renewable and nuclear based high temperature electrolysis, nuclear based Cu-Cl and S-I thermochemical cycles as to their environmental, financial, social and technical performance. They determined the nuclear based Cu-Cl cycle has the lowest global warming potential (relates to the increasing concentration of CO_2 in the atmosphere) and social cost of carbon (as a measure of the marginal external cost of a unit of CO_2 emissions). Al-Zareer et al. [11] designed and evaluated a nuclear-based integrated system. They designed four-step Cu-Cl cycle for water decomposition. They concluded that the idea of integrating nuclear reactors to produce hydrogen has advantages due to higher output temperatures. They calculated energy and exergy efficiencies as 31.6% and 56.2%, respectively. Furthermore, nuclear-based hydrogen production is environmentally benign by providing a carbon free energy solution and potential to reduce CO_2 emission. Lubis et al. [12] carried out a life cycle assessment of nuclear-based hydrogen production using thermochemical water splitting by copper-chlorine thermochemical cycle. They calculated the environmental features such as radioactive radiation, disability-adjusted life years, ozone depletion potential, global

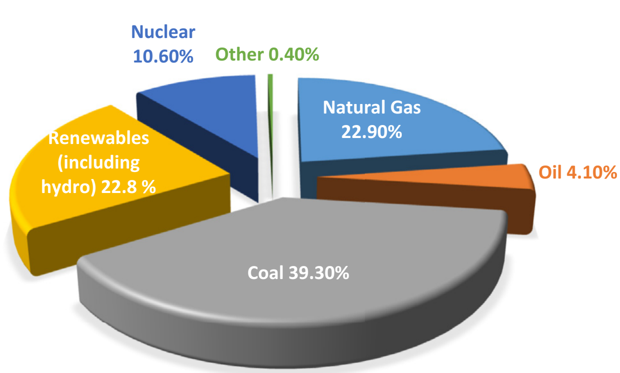

Fig. 1 – Worldwide electricity production by fuel in 2015 (data from Ref. [5]).