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

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 inter-ruption, 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 re-sources 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 devel-oping 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 trans-portation 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 usu-ally 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 renew-able energy source (v) high temperature electrolysis by nu-clear 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 elec-trolysis requires electrical power, it has lower efficiency compared to the thermochemical water splitting. The ther-mochemical 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 pro-posed 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 concen-tration 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 calcu-lated energy and exergy efficiencies as 31.6% and 56.2%, respectively. Furthermore, nuclear-based hydrogen produc-tion 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
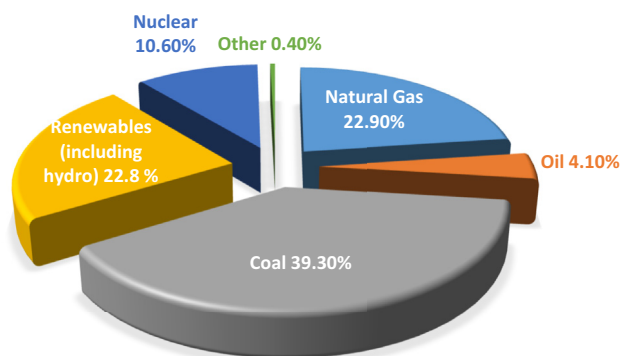
Fig. 1 – Worldwide electricity production by fuel in 2015 (data from Ref. [5]).
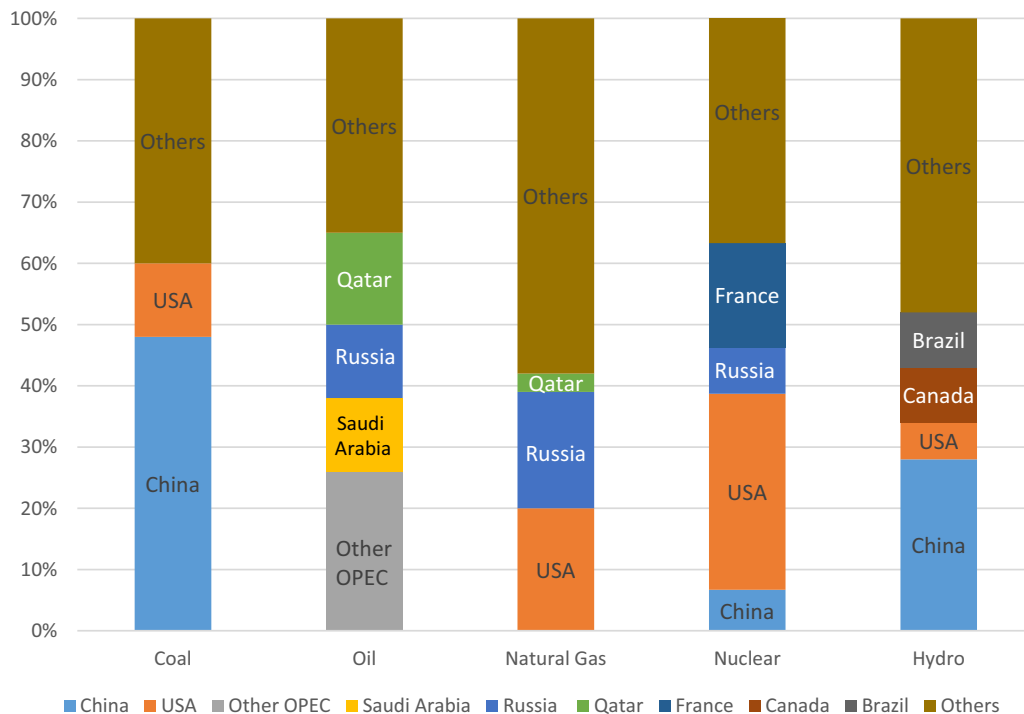
Fig. 2 – World's largest producers by fuel-based in 2015 (data from Ref. [7]).

warming potential and eutrophication potential of nuclear based hydrogen generation.

El-Emam et al. [1] performed a cost assessment of selected nuclear hydrogen production methods with various storage and transportation cases by employing Hydrogen Economic Evaluation Program (HEEP). They compared three different nuclear reactor options which are provided by the HEEP; Prismatic core (PMR), Pebble Bed (PBR) and High Temperature Gas-cooled Reactor (HTGR). They calculated the cost of hydrogen of each system by various storage and transportation cases. Orhan et al. [13] carried out an economic analysis of a Cu–Cl thermochemical cycle for nuclear-based hydrogen production. They determined the total cost of hydrogen production, including capital cost, energy cost, operating, storage and distribution costs from 2 $/kg H_2 to 3.5 $/kg H_2 for various cases.

Lemus et al. [14] reviewed the costs of hydrogen production from various sources such as conventional, nuclear and renewable for a couple of years by taking into account the yearly inflation rates. Nuclear based hydrogen production has

decreased significantly. Furthermore, they have forecast the cost of hydrogen by using a few different techniques. They have also determined the amount of CO_2 emissions for various scenarios.

In this study, Akkuyu and Sinop Nuclear Power Plants, which will be constructed soon in Turkey, are analysed to evaluate hydrogen production costs under various scenarios. The cost evaluations are carried out by employing a 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 [15]. It is aimed to present a sustainable and environmentally benign method to supply energy demand.

Methods and analyses

The Hydrogen Economic Evaluation Program (HEEP) developed by International Atomic Energy Agency (IAEA) is used to

Table 1 – Design parameters of Akkuyu and Sinop NPPs.		
	Akkuyu NPP	Sinop NPP
Power Plant Type	PWR	PWR
Power Plant Name	VVER-1200	ATMEA1
Construction	Russian and Turkish companies	Japanese and Turkish companies
Operating	Russian companies (Rosatom company and Turkish consortium)	Consortium (consisted of French and Japanese companies and Electricity Generation Company on behalf of Turkey Government)
Planned Power Capacity	4800 MW (consisting of 4 units of 1200 MW)	4480 MW (consisting of 4 units of 1120 MW)
Planned Cost of Construction	20 billion US dollar	20 billion US dollar
Source: [16,17].		

Table 2 – Assumed parameters of construction and operation for Akkuyu and Sinop NPPs.

Parameters	Value
Discount Rate	5%
Inflation rate	1%
Equity/Debt	70%/30%
Borrowing interest	10%
Tax rate	10%
Construction	5 years
Operation	60 years
Source: [17,18].	

estimate the cost of hydrogen. HEEP is a very user friendly software and is widely used to estimate the cost of hydrogen. The HEEP's library has various nuclear reactor options, as well as hydrogen generation, storage and transportation facilities. There are different nuclear power plant options and hydrogen production plant options included in HEEP library. The cost estimations for capital, fuel, decommissioning, O&M, and consumables are evaluated for both Akkuyu and Sinop Nuclear Power Plants (NPPs) and compared comprehensively. These cost estimations include various hydrogen storage and transportation options. Compressed gas, liquefaction and metal-hydride options which are available in the HEEP database are considered for storage [15]. Two transportation options including pipe and truck systems are considered and included for cost analyses.

Table 1 tabulates the design parameters of Akkuyu and Sinop NPPs [16,17]. Both are employing pressurized water reactor (PWR) which is one of the widely accepted preferred technology in nuclear power plant reactors due to easy to operate. Less power is generated as the heat increases. After heat had created inside the core of the reactor, high-pressurized water is pumped to the core. Energy is produced by the fission of atoms inside the core. And also, PWRs are safe and easy to control due to less fissile material which decrease to occur hazardous fission events. The capital cost for establishing of these two power plants are almost the same while there is a minor difference of 320 MW in their generated power. Two different countries have been responsible for establishing of the power plants. The Akkuyu NPP is planned to build consisting of 4 units each with 1200 MW capacity by Russian companies. In addition, the Sinop NPP will be built as 4 units with a capacity of 1120 MW each unit by Japanese companies. Therefore, total capacities have taken place as 4800 MW and 4480 MW for Akkuyu and Sinop NPPs, respectively. Eventually, the construction cost is expected to be about 20 billion US dollars for both NPPs (see details elsewhere in Ref. [16]).

Table 2 provides the construction and operation parameters such as tax rates, borrowing interest, operation and construction times [18,19]. Construction and operation period for both systems are assumed as 5 years and 60 years, respectively. If compared to other power plants such as thermal power plants with approximately 30 years of useful operational periods, nuclear ones operate longer (60 years) and this is one of the main motivations to provide sustainable solutions for hydrogen production. Furthermore, it is assumed to be established by using 70% equity and by taking 30% debt with 10% interest.

Table 3 shows the estimated parameters and comparison of capacity and thermal specifications of Akkuyu and Sinop NPPs. VVER (water-cooled water-moderated power reactor) which is developed by Rosatom Company is a kind of pressurized water reactor and is used in Akkuyu NPP. While gross electric output is almost 1200 MWe, reactor thermal output is 3212 MWt [21,22]. The Sinop NPP reactors are also planned as pressurized water reactor. ATMEA1 which is developed by Areva and Mitsubishi Companies has 1150 MWe electrical output and 3150 MWt thermal output [23]. MWe and MWt is equal to MW and they are commonly used to describe electrical power and thermal power, respectively. The operation and maintenance (O&M) and decommissioning costs are assumed 1.66% and 2.8% of the capital cost, respectively. Also, the average price of the nuclear fuel is assumed to be 1500 $/kg, consisting uranium, conversion, enrichment and fuel fabrication costs [20,24].

Results and discussion

Various options, including high pressure compressed gas, liquid at very low temperature and adsorbed on metal hydrides are evaluated comparatively by using the Hydrogen Economic Evaluation Program (HEEP). The compressed gas option is compared with two transportation options of the pipe and truck based transportation systems. Furthermore, both liquefaction and metal hydride storage types are compared with pipeline transportation. Tables 4–11 show the

Table 3 – Comparison of capacity and thermal specifications of Akkuyu and Sinop NPPs.

	Akkuyu NPP	Sinop NPP
Thermal rating	3212 MWt/unit	3150 MWt/unit
Electricity rating	1198 MWe/unit	1120 MWe/unit
Number of units	4	4
Initial fuel load	75000 kg/unit	75000 kg/unit
Annual fuel feed	25000 kg/unit	25000 kg/unit
Capital Cost	5.0 B$/unit	5.0 B$/unit
Capital cost fraction for electricity generating infrastructure	10%	10%
Fuel cost	1500 $/kg	1500 $/kg
O&M cost	1.66% (of capital cost)	1.66% (of capital cost)
Decommissioning cost	2.8% (of capital cost)	2.8% (of capital cost)

Table 4 — Cost results of hydrogen generation and pipe transportation as compressed gas for Akkuyu and Sinop NPPs.

	Akkuyu NPP		Sinop NPP	
	Cost ($/kg H$_2$)	Percentage	Cost ($/kg H$_2$)	Percentage
Nuclear Power Plant	2.30	72.33%	2.46	72.33%
Hydrogen Generation Plant	0.44	13.84%	0.44	13.84%
Hydrogen Transportation	0.15	4.72%	0.15	4.72%
Hydrogen Storage	0.29	9.12%	0.29	9.12%
Total	3.18	100%	3.34	100%

Table 5 — Cost items of hydrogen generation and pipe transportation as compressed gas for Akkuyu and Sinop NPPs.

	Nuclear Power Plant ($/kg H$_2$)		Hydrogen Generation ($/kg H$_2$)		Hydrogen Transportation ($/kg H$_2$)		Hydrogen Storage ($/kg H$_2$)	
	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP
Debt	0.72	0.77	0.11	0.11	0.08	0.08	0.07	0.07
Equity	0.94	1.01	0.15	0.15	0.04	0.04	0.09	0.09
O&M	0.42	0.45	0.17	0.17	0.02	0.02	0.13	0.13
Decommissioning	0.02	0.03	0.01	0.01	0	0	0	0
Fuel	0.19	0.2	—	—	—	—	—	—

Table 6 — Cost of hydrogen generation and transportation by truck as compressed gas for Akkuyu and Sinop NPPs.

	Akkuyu NPP		Sinop NPP	
	Cost ($/kg H$_2$)	Percentage	Cost ($/kg H$_2$)	Percentage
Nuclear Power Plant	2.27	59.27%	2.80	62.95%
Hydrogen Generation Plant	0.44	11.41%	0.49	10.95%
Hydrogen Transportation	0.83	21.74%	0.84	18.84%
Hydrogen Storage	0.29	7.63%	0.33	7.32%
Total	3.83	100%	4.46	100%

Table 7 — Cost of hydrogen generation and transportation by truck as compressed gas for Akkuyu and Sinop NPPs.

	Nuclear power plant ($/kg H$_2$)		Hydrogen Generation ($/kg H$_2$)		Hydrogen Transportation ($/kg H$_2$)		Hydrogen Storage ($/kg H$_2$)	
	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP
Debt	0.71	0.9	0.11	0.13	0.03	0.04	0.07	0.08
Equity	0.93	1.23	0.15	0.18	0.02	0.02	0.09	0.11
O&M	0.41	0.44	0.17	0.17	0.78	0.78	0.13	0.13
Decommissioning	0.02	0.02	0.01	0.01	0	0	0	0
Fuel	0.19	0.21	—	—	—	—	—	—

Table 8 — Cost of hydrogen generation and pipe transportation as liquid for Akkuyu and Sinop NPPs.

	Akkuyu NPP		Sinop NPP	
	Cost ($/kg H$_2$)	Percentage	Cost ($/kg H$_2$)	Percentage
Nuclear Power Plant	2.70	78.61%	2.89	79.72%
Hydrogen Generation Plant	0.44	12.69%	0.44	12.03%
Hydrogen Transportation	0.15	4.27%	0.15	4.05%
Hydrogen Storage	0.15	4.48%	0.15	4.24%
Total	3.44	100%	3.63	100%

comparisons of cost calculations and their results. The major components of hydrogen generation, such as storage, transportation, hydrogen generation plant and nuclear power plant can be seen in the Figs. 3—6.

Pipe transportation of compressed gas hydrogen

In this case, compressed gaseous hydrogen is analysed which is mainly preferred for stationary applications under a high

Table 9 — Cost items of hydrogen generation and pipe transportation as liquid for Akkuyu and Sinop NPPs.

	Nuclear power plant ($/kg H$_2$)		Hydrogen Generation ($/kg H$_2$)		Hydrogen Transportation ($/kg H$_2$)		Hydrogen Storage ($/kg H$_2$)	
	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP
Debt	0.85	0.91	0.11	0.11	0.08	0.08	0.07	0.07
Equity	1.11	1.18	0.15	0.15	0.04	0.04	0.09	0.09
O&M	0.49	0.53	0.17	0.17	0.02	0.02	0	0
Decommissioning	0.03	0.03	0.01	0.01	0	0	0	0
Fuel	0.22	0.24	—	—	—	—	—	—

Table 10 — Cost of hydrogen generation and pipe transportation as metal hydrides for Akkuyu and Sinop NPPs.

	Akkuyu NPP		Sinop NPP	
	Cost ($/kg H$_2$)	Percentage	Cost ($/kg H$_2$)	Percentage
Nuclear Power Plant	2.20	36.60%	2.35	38.17%
Hydrogen Generation Plant	0.44	7.25%	0.44	7.07%
Hydrogen Transportation	0.15	2.44%	0.15	2.38%
Hydrogen Storage	3.23	53.76%	3.23	52.43%
Total	6.02	100%	6.17	100%

Table 11 — Cost items of hydrogen generation and pipe transportation as metal hydrides for Akkuyu and Sinop NPPs.

	Nuclear power plant ($/kg H$_2$)		Hydrogen Generation ($/kg H$_2$)		Hydrogen Transportation ($/kg H$_2$)		Hydrogen Storage ($/kg H$_2$)	
	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP	Akkuyu NPP	Sinop NPP
Debt	0.69	0.74	0.11	0.11	0.08	0.08	1.41	1.41
Equity	0.9	0.96	0.15	0.15	0.04	0.04	1.83	1.83
O&M	0.4	0.43	0.17	0.17	0.02	0.02	0	0
Decommissioning	0.02	0.03	0.0	0.01	0	0	0	0
Fuel	0.18	0.19	—	—	—	—	—	—

pressure is analysed [25]. Fig. 3 shows the components and rates of the hydrogen cost as compressed gas and transportation by pipe for both Akkuyu and Sinop NPPs. While almost 30% of cost is required for hydrogen generation, transportation and storage, more than 70% of the cost is required for nuclear power plant. Table 4 tabulates the costs and rates of hydrogen generation as compressed gas and transport by pipe for both Akkuyu and Sinop NPPs. Transportation by pipe as compressed gas is the cheapest case with 3.18 $/kg hydrogen and 3.34 $/kg hydrogen for Akkuyu and Sinop NPPs, respectively. Hydrogen generation cost consists of mainly nuclear power plant, hydrogen

generation plant, hydrogen transportation and storage costs. And also, debt, equity, O&M, decommissioning and fuel costs for each of them are determined and shown in Table 5. The debt and equity costs are estimated as approximately 1 $ and 1.25 $ per kg of hydrogen, respectively.

*Hydrogen as compressed gas transportation by truck*

Fig. 4 illustrates hydrogen cost for case 2 which is transportation by truck in compressed gas phase. Similar to the first
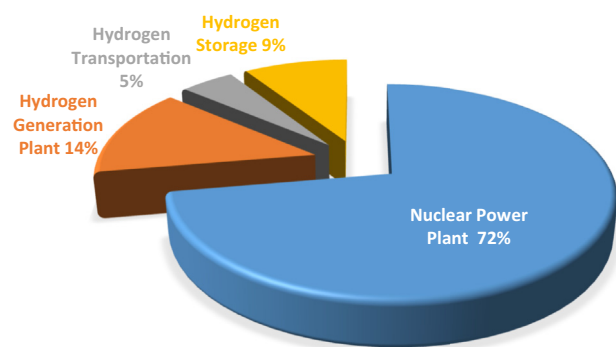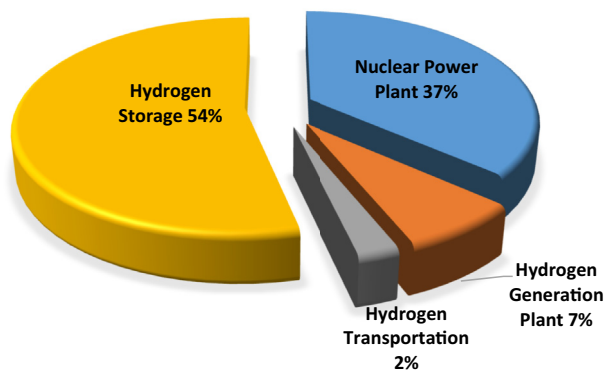

Fig. 3 — Components of cost of compressed hydrogen gas transportation by pipe for both Akkuyu and Sinop NPPs.
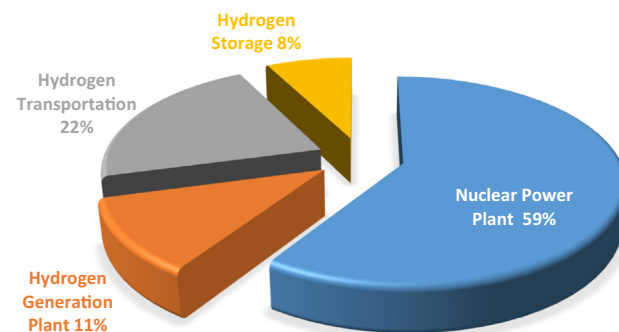
Fig. 4 — Components of cost of compressed hydrogen gas transportation by truck for both Akkuyu and Sinop NPPs.
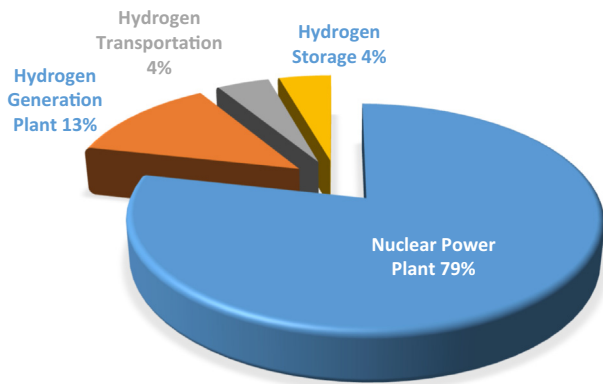
Fig. 5 – Components of cost of liquefied hydrogen transportation by pipe for both Akkuyu and Sinop NPPs.

Fig. 6 – Components of cost of hydrogen (stored in metal hydride) transportation by pipe for both Akkuyu and Sinop NPPs.

case, hydrogen is assumed as compressed gas where transportation is assumed by truck and a comparison is performed for both Akkuyu and Sinop NPPs. As shown in Table 6, the cost of transportation by truck is higher than pipeline transportation. Transportation by truck is calculated for Akkuyu and Sinop NPPs as 0.83 $/kg H_2 and 0.84 $/kg H_2, respectively. This is because of the operation and maintenance costs. Table 7 shows the costs for each component accordingly. The cost of hydrogen transportation by truck as compressed gas is around 0.8 $/kg H_2.

Liquefied hydrogen transportation by pipe

In this case, useful output as liquefied hydrogen is analysed. Liquefaction which is essential for refrigeration and transportation systems is an important process in order to store and transport easily [26]. Fig. 5 shows the main components and rates of hydrogen cost as liquefaction and transportation by pipe. A comparison can be seen for both Akkuyu and Sinop NPPs in Tables 8 and 9. The total cost of hydrogen is determined for Akkuyu and Sinop NPPs to be 3.44 $/kg H_2 and 3.63 $/kg H_2, respectively.

Hydrogen as metal hydrides transportation by pipe

Fig. 6 shows the cost of hydrogen as metal hydride and transportation by pipe for Akkuyu and Sinop NPPs. Calculations show a higher cost for metal hydrides transportation compared to compressed gas and liquefaction. The total cost of hydrogen is determined for Akkuyu and Sinop NPPs as 6.02 $/kg H_2 and 6.17 $/kg H_2, respectively (Tables 10 and 11). In all cases, cost of hydrogen generation in the Sinop NPP is higher than the Akkuyu NPP mainly due to the nuclear power plant capacity.

Conclusions

In the current study, a nuclear based hydrogen generation cost analysis is performed. Three different storage options and two different transportation options are evaluated. Akkuyu and Sinop NPPs which will be constructed in Turkey bring two possible nuclear based hydrogen production scenarios which are evaluated economically. The amount of hydrogen cost per kg is calculated for four cases. The main findings of this study are given as follows:

- Transportation by pipe is cheaper than transportation by truck due to the vehicle costs. At the same time, considering unexpected cost of vehicles, pipe transportation will be more reasonable.
- The metal hydride storage option seems to be the most expensive option among the considered cases costing more than 6 $/kg H_2 for both Akkuyu and Sinop NPPs. However, a comprehensive study must be performed to determine specific advantages and limitations of these storage and transportation options.
- There is a need for a new calculation once detailed information for both Akkuyu and Sinop NPPs will be available. The cost of hydrogen can be calculated by determining excess electricity once power plants start to generate electricity.

Nomenclature

HEEP	Hydrogen Economic Evaluation Program
HTGR	High Temperature Gas-Cooled Reactor
IAEA	International Atomic Energy Agency
NPP	Nuclear Power Plant
O&M	Operation and Maintenance
PBR	Pebble Bed
PMR	Prismatic core
PWR	Pressurized Water Reactor
VVER	Water-cooled Water-moderated Power Reactor

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