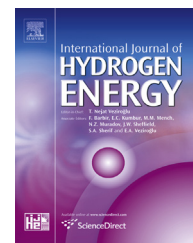


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Review

Comparative assessment of hydrogen production methods from renewable and non-renewable sources

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ABSTRACT

In this study, we present a comparative environmental impact assessment of possible hydrogen production methods from renewable and non-renewable sources with a special emphasis on their application in Turkey. It is aimed to study and compare the performances of hydrogen production methods and assess their economic, social and environmental impacts. The methods considered in this study are natural gas steam reforming, coal gasification, water electrolysis via wind and solar energies, biomass gasification, thermochemical water splitting with a Cu–Cl and S–I cycles, and high temperature electrolysis. Environmental impacts (global warming potential, GWP and acidification potential, AP), production costs, energy and exergy efficiencies of these eight methods are compared. Furthermore, the relationship between plant capacity and hydrogen production capital cost is studied. The social cost of carbon concept is used to present the relations between environmental impacts and economic factors. The results indicate that thermochemical water splitting with the Cu–Cl and S–I cycles become more environmentally benign than the other traditional methods in terms of emissions. The options with wind, solar and high temperature electrolysis also provide environmentally attractive results. Electrolysis methods are found to be least attractive when production costs are considered. Therefore, increasing the efficiencies and hence decreasing the costs of hydrogen production from solar and wind electrolysis bring them forefront as potential options. The energy and exergy efficiency comparison study indicates the advantages of biomass gasification over other methods. Overall rankings show that thermochemical Cu–Cl and S–I cycles are primarily promising candidates to produce hydrogen in an environmentally benign and cost-effective way.

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1. Introduction

During the twentieth and the beginning of the twenty-first century, world's energy consumption has increased steadily

due to global rise in population and standards of living. Fig. 1 presents world's primary energy supply, electricity generation, and the resulting CO₂ emission shares by energy source.

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World's total primary energy supply (TPES) was 12,717 MTOE in 2010 [1]. As can be seen from Fig. 1, about 80% of this amount came from fossil fuels. In the same year, the amount of worldwide electricity generation was 21,431 TWh [1]. Fig. 1 also shows that 70% of this amount was generated by using fossil fuels. The worldwide CO₂ emissions were 30,326 Mt in 2010 [1]. This amount was mainly the result of using fossil fuels. Therefore, switching to a CO₂-neutral energy carrier could greatly reduce the CO₂-related emissions.

The increasing trend in world's energy need is expected to continue in the future. As a result, a growth in energy generation capacity will be needed. Finding more secure, clean and diversified energy sources could be a successful strategy to reduce and eliminate greenhouse gas emissions and meet the world's energy needs. Compared to other alternatives, hydrogen has a large number of advantages; therefore, it could be used to reduce the emissions and dependence on imported oil.

Hydrogen is the lightest, simplest and most plentiful of all chemical elements in the universe. However, it occurs only in combination with other elements, primarily with oxygen in water and with carbon, nitrogen and oxygen in living materials and fossil fuels. Hydrogen is not a primary source of energy. But it becomes an attractive energy carrier when split from these other elements by using a source of energy. Hydrogen is very clean in terms of emissions at the point of use. In fuel cells, it is combined with oxygen without generating CO₂, the only by-product being water.

Some of the advantages of the hydrogen economy can be summarized as: (i) energy security by reducing oil imports, (ii) sustainability by taking advantage of the renewable energy sources, (iii) less pollution and better urban air quality by producing near-zero carbon, hydrocarbon, GHG and NO_x emissions at the point of use, and (iv) economic viability by potentially shaping the future global energy markets.

In this study, a comparative environmental impact study of possible hydrogen production methods from renewable and non-renewable sources is undertaken with a special emphasis on their application in Turkey. The goal is to make useful and practical recommendations to the authorities in terms of research and development. Environmental impacts (global warming potential, GWP and acidification potential, AP), production costs, energy and exergy efficiencies of eight different methods are compared. In addition to aforementioned comparison criteria, the relationship between the capital cost and the hydrogen production capacity of the selected methods is studied. The selected methods are natural gas steam reforming, coal gasification, water electrolysis via wind and solar electrolysis, thermochemical water splitting with a Cu–Cl and S–I cycles, and high temperature electrolysis.

2. Background: hydrogen production methods

Fig. 2 shows the hydrogen production methods investigated in this study.

2.1. Hydrogen production from fossil fuels

2.1.1. Steam reforming

It is currently the least expensive and most common method to produce hydrogen. In steam reforming, natural gas is first cleaned of impurities, mixed with steam and passed over an externally heated reactor, where carbon monoxide (CO) and hydrogen (H₂) are generated. After this step, a catalytic water–gas shift reaction converts the CO and water to hydrogen and carbon dioxide (CO₂). The hydrogen gas is then purified. With this technology, it is possible to reach yields

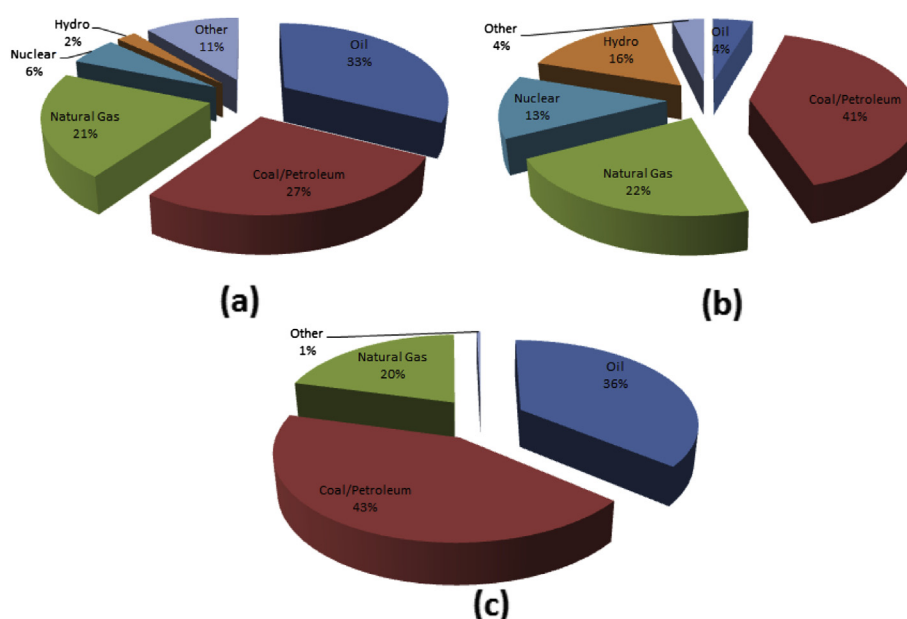


Fig. 1 – World's total (a) primary energy supply (TPES), (b) electricity generation, and (c) CO₂ emissions by energy source in 2010 (Other includes geothermal, solar, wind, heat, biofuels and waste etc.) (Data from Ref. [1]).

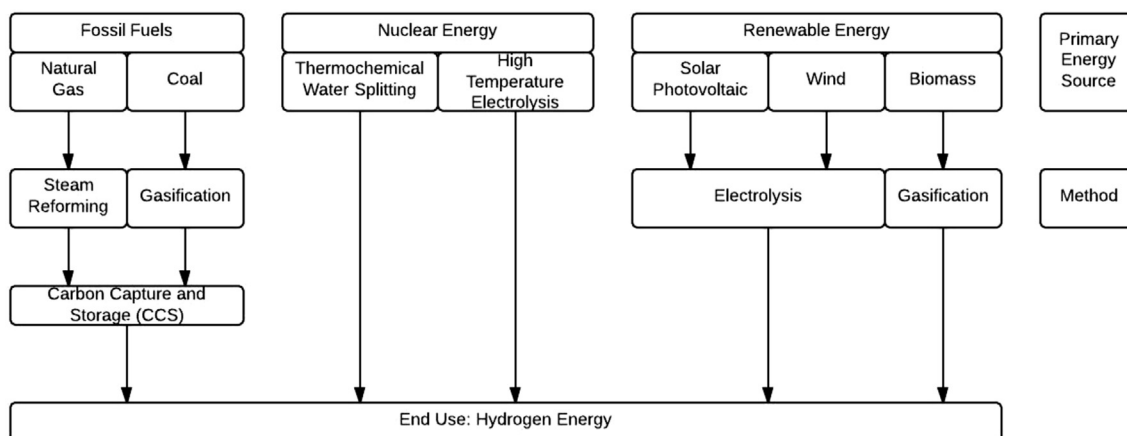


Fig. 2 – Selected hydrogen production methods. (Modified from Ref. [2]).

higher than 80% in large reformers (e.g. 100,000 tons per year) [3]. Lower efficiencies are observed in smaller scale reformers (especially for small fuel cells).

2.1.2. Gasification

Worldwide coal reserves and commercially available technologies make coal a practical option for producing hydrogen in large plants. Compared to the existing methods (i.e. electrolysis), gasification is more suitable for converting coal to hydrogen. During the coal gasification process, coal is partially oxidized with steam and oxygen in a high-temperature and high-pressure reactor. The products are mainly CO and H₂, mixed with steam and CO₂ (syngas). To increase the hydrogen yield, the syngas undergoes a shift reaction. In order to recover elemental sulphur (or make sulphuric acid), the gas can be cleaned in conventional ways. If some of the syngas is used in a gas turbine, electricity can be generated. The major concern about coal gasification is the high carbon content of coal as the CO₂ emissions are higher compared to other feedstock options. In order to address this problem, CCS (Carbon Capture and Storage) technologies are being developed. Today, the cost of producing hydrogen in a large coal gasification plant is slightly higher than if it were made from natural gas. However, coal gasification techniques are less well-defined than those used in the steam reforming of natural gas. In terms of economics, making hydrogen from coal differs from other fossil fuels: the unit raw material costs are

lower while the unit capital costs are higher for the coal gasification plants [3].

2.2. Hydrogen production from nuclear energy

2.2.1. Thermochemical water splitting

Hydrogen can be produced by thermochemical water-splitting cycles that operate at temperatures of 500 °C or more using nuclear reactors [4]. Faster reaction rates and higher efficiencies can be achieved at higher temperatures. So far, more than 100 different high temperature water-splitting thermochemical reactions have been proposed [5]. In this study, thermochemical Cu–Cl and S–I cycles are studied. The thermochemical Cu–Cl cycle was first proposed in the 1970s. Currently there are some commercially available Cu–Cl cycles that are being tested. At operating temperatures around 550 °C, Cu–Cl cycles are estimated to give efficiencies around 40% (cogeneration of electricity is ignored) [6]. Lowering the required temperatures for high efficiencies is a key challenge of thermochemical Cu–Cl cycles. With thermochemical S–I cycles, it is possible to reach higher efficiencies (around 60%, with cogeneration of electricity). However, these cycles require higher temperatures, around 825–900 °C [7,8]. These thermochemical cycles need special reactors that are constructed using special chemically inert materials capable of resisting high temperatures. Developing these special materials in an economically feasible way is another significant

Table 1 – Key benefits and critical challenges of selected hydrogen production methods. (Modified from Ref. [11]).

Natural gas steam reforming	Coal and biomass gasification	Thermo-chemical	Water electrolysis
Key benefits			
Most viable approach in the near term	Low-cost synthetic fuel in addition to H ₂	Clean and sustainable	No pollution with renewable sources
Lowest current cost	Abundant and affordable		
Existing infrastructure			
Critical challenges			
Capital, operation and maintenance costs	Reactor costs System efficiency Feedstock impurities Carbon Capture and Storage	Effective and durable materials of construction	Low efficiency Capital costs Integration with renewable energy sources

challenge of thermochemical cycles. However, thermochemical cycles show promising results to be considered as potential methods to produce hydrogen [6].

2.2.2. High temperature electrolysis

Although electricity-to-hydrogen conversion efficiency can reach as high as 80% under pressure, the overall efficiency of this method is much lower because it is limited by the efficiency of the nuclear power plant (around 33% with current reactors) [2]. Developing reactors that operate at higher outlet temperatures is a possible way to solve the low efficiency problem. For instance, the 20% efficiency at 350 °C increases to about 50% at 950 °C [9,10].

2.3. Hydrogen production from renewable energies

2.3.1. Electrolysis

Providing clean hydrogen with no carbon and sulphur contamination is one of the advantages of this method. However, electrolysis has some disadvantages such as its higher cost and energy needs than the fossil fuel alternatives [8]. Regardless, because of their compactness and small-scale applications, electrolysis is still seen as a potentially cost-effective way of producing hydrogen locally. They can also be used at current fuelling stations.

2.3.1.1. Solar photovoltaic. This is one of the most costly hydrogen production methods. With current technology, the cost of hydrogen from photovoltaic electrolysis is about 25 times higher than that of fossil fuel alternatives. However, the cost of photovoltaic cells is expected to decrease and this factor is estimated to go down to 6 [2].

2.3.1.2. Wind. Using the electricity generated by wind turbines for electrolysis, this option shows possibly the highest potential among renewable sources for producing pollution-

free hydrogen, especially for distributed systems. One of the challenges of this process is the cost of wind turbines and electrolyzers. Optimization of turbine–electrolyzer–storage system is another challenge to using wind energy to produce hydrogen. The cost of producing hydrogen using wind turbines is almost 6–10 times that of fossil fuel alternatives. This gap is expected to be halved in the future [2].

2.3.2. Biomass gasification

Wood processing, forestry, and agricultural residues, municipal and animal waste, and/or crops can be used as biomass resources to produce hydrogen. Currently biomass gasification process is unable to produce hydrogen on a large scale at a competitive price. However, with this method, energy from domestic and agricultural waste can be recovered in a clean way. Since CO₂ released when the biomass is oxidized can be absorbed from the atmosphere and fixed by photosynthesis in the biomass growing process, this option has a potential over the fossil fuels to reduce the net CO₂ emissions. One important concern related to this method is the possibility of natural resource and land requirement problems as a result of growing significant quantities of biomass as energy crops.

2.4. Summary

Table 1 summarizes the key benefits and critical challenges of selected hydrogen production methods. With the given current available technologies, natural gas as feedstock to produce hydrogen in large industrial plants seems to be the cheapest method available. Secured supply is an important criterion that needs to be addressed in energy services. Optimizing capital, operating and maintenance costs as well as developing systems with high efficiencies, low impurity levels, and emissions, and increasing the role of renewable energies are some of the critical challenges of the hydrogen economy.

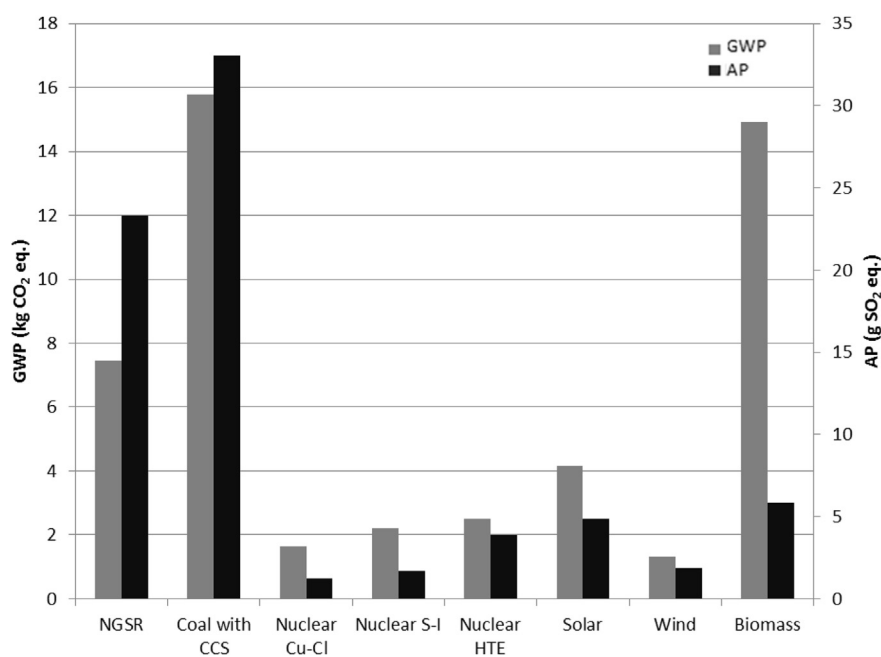


Fig. 3 – GWP and AP of selected hydrogen production methods. (Data from Ref. [15]).

3. Comparative assessment of hydrogen production methods

3.1. Environmental impact comparison

Because of their negative impact on the environment, CO₂ emissions are considered to be the primary GHGs. Reducing CO₂ emissions is one of the issues that needs to be addressed by the future energy carrier. Managing CO₂ either as a waste or as commodity for another purpose and Carbon Capture and Sequestration (CCS) are some of the methods to mitigate the CO₂ emissions. Further information on CO₂ emissions and how to minimize them can be found in Refs. [12,13].

In 2001, The Center of Environmental Science of Leiden University published the “Operational Guide to the ISO Standards” to describe the LCA procedures according to ISO standards [14]. The environmental impact categories are selected based on this operational guide. In this study, global warming potential (GWP) and acidification potential (AP) are used to evaluate the environmental impact of selected hydrogen production methods. GWP (g CO₂ eq.) is a measure of CO₂ emissions and AP (g SO₂ eq.) indicates SO₂ discharge on soil and into water [15]. AP is one of the measures of the change in the degree of acidity.

The GWP and AP comparative assessment of this study is conducted based on the life cycle assessment carried out by Ozbilen et al., 2011 [15]. Life cycle assessment generally has four main phases: (i) goal and scope definition to specify intention, application and stakeholders, (ii) the life cycle inventory data collection phase on material and energy flows during the life cycle – during this phase, emissions and consumed resources are identified and quantified, (iii) life cycle impact assessment (LCIA), builds on the inventory results by assessing the environmental significance of each, and (iv) LCIA results are evaluated and recommendations to reduce environmental impacts of products are discussed. In their study, for fossil fuel and renewable energy based hydrogen production, Ozbilen et al. [15] used the data from Koroneos et al., 2004 [16] and for nuclear energy based production, the results of Utgikar and Thiesen, 2006 [17] are used. The authors [15] also used their own thermochemical Cu–Cl cycle analysis results for comparison purposes.

The environmental impact results of selected hydrogen production methods, in terms of GWP and AP, are presented in Fig. 3. The fossil fuel based hydrogen production methods are seen to be most environmentally harmful methods. Although it has relatively low GWP, the AP of biomass gasification is the highest compared to the other selected methods. From Fig. 3, it can be seen that hydrogen production using thermochemical cycles are the most environmentally benign of the selected methods, in terms of CO₂ emissions and acidification potential.

3.2. Social cost of carbon comparison

The social cost of carbon (SCC) is a measure of the marginal external cost of a unit of CO₂ emissions, due to the environmental damages caused by that emission. An integrated assessment modelling (IAM) framework is used to estimate

the value of SCC. This framework uses a baseline socio-economic scenario, a model that identifies the relationship between emissions and temperature change, and a function to relate this temperature change to economic damages.

In order to estimate the social cost of carbon, first, reference socio-economic scenarios (characterized in reduced-form analyses by output, population and emissions) are used to calculate climate changes (characterized by greenhouse gas concentrations and temperature), which cause an increase in the baseline scenarios that include economic damages from climate change. Next, the baseline scenarios are marginally perturbed by the addition or removal of a marginal unit of CO₂ emissions. Social welfare, which depends upon consumption and the choice of discounting parameters, is calculated for each baseline and marginally perturbed scenario. The SCC is the (normalized) difference in expected welfare between the baseline scenarios and the perturbed scenarios [18].

In this study, the work of Parry et al. (2007) [19] is taken as basis to calculate the SCC of selected hydrogen production methods and an average of \$160 per tonne of CO₂ emissions is used as the SCC. The results presented in Fig. 4 shows that thermochemical cycles are the most beneficial processes considered for hydrogen production and natural gas steam reforming and coal gasification are seen to be the most harmful.

3.3. Financial comparison

There are some uncertainties regarding the cost of hydrogen production. This cost is strongly affected by the production technology's advancement level, availability of existing infrastructure, and the feedstock price. Fig. 5 summarizes the literature survey results of average hydrogen production costs (per kg of hydrogen) of the selected methods. According to the figure, the most financially advantageous methods for hydrogen production are steam methane reforming, coal and biomass gasification. Nuclear thermochemical cycles (Cu–Cl and S–I) also seem to be competitive to fossil fuel and biomass prices. The cost of high temperature electrolysis (HTE) is presented to be 2.35 to 4.80 (\$/kg H₂) by Wang et al. [20]. In this study, an average of \$3.5/kg H₂ is taken. Wind and solar

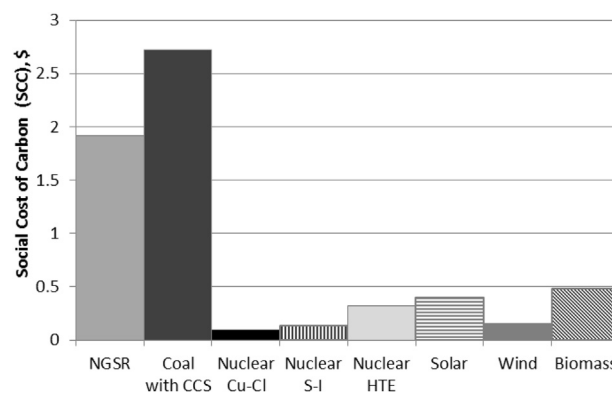


Fig. 4 – SCC of selected hydrogen production methods (per kg of hydrogen).

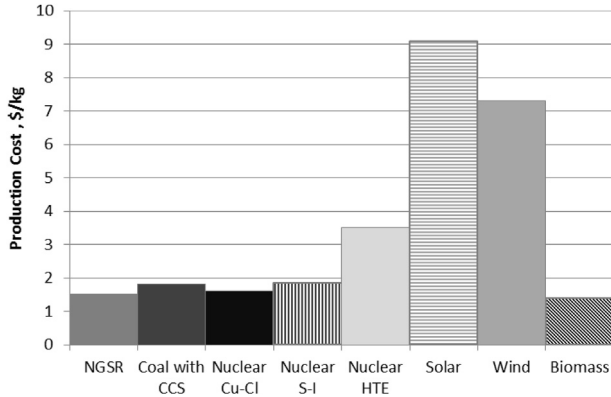


Fig. 5 – Average production cost of selected hydrogen production methods (per kg of hydrogen). (Data from Ref. [20]).

electrolysis give the highest production cost per kg of hydrogen [21,22]. Since one of the major advantages of electrolysis is its local applications, distributed, small-scale production assumption is made when calculating the cost of electrolysis. However, other alternatives are assumed to be central production. One of the reasons of this production cost gap between the solar and wind electrolysis and the other options could be attributed to the significantly high costs of distributed and small-scale production relative to massive scale central production.

In addition to hydrogen production cost per kg (\$/kg), the capital costs of steam methane reforming, coal and biomass gasification, and water electrolysis are compared based on a study carried out by Simbeck and Chang [23]. Their correlations between capital costs and production capacities of the aforementioned hydrogen production methods are presented in Table 2. In this regard, Fig. 6 is presented to show the capital costs of the selected methods at production capacities from 1 to 1000 ton/day. As seen in the figure, it can be seen that steam methane reforming has the lowest capital cost compared to other methods at all production capacities considered. Water electrolysis gives the highest capital cost. However, at lower production scales, especially for distributed production (less than 10 ton/day), water electrolysis capital costs are close to steam reforming, which make them more competitive for distributed production cases.

3.4. Energy and exergy efficiency comparisons

The literature review performed by Dincer and Zamfirescu [25] is used as a basis to present the energy and exergy efficiencies

Table 2 – Hydrogen production capital cost as a function of plant capacity (ton/day, tpd). (Data from Ref. [24]).

Production technology	Capital cost (million \$)
Steam methane reforming (SMR)	$134 * (\text{Capacity}/150)^{0.75}$
Coal gasification (CG)	$352 * (\text{Capacity}/150)^{0.77}$
Biomass gasification (BG)	$360 * (\text{Capacity}/150)^{0.75}$
Water electrolysis (WE)	$598 * (\text{Capacity}/150)^{0.85}$

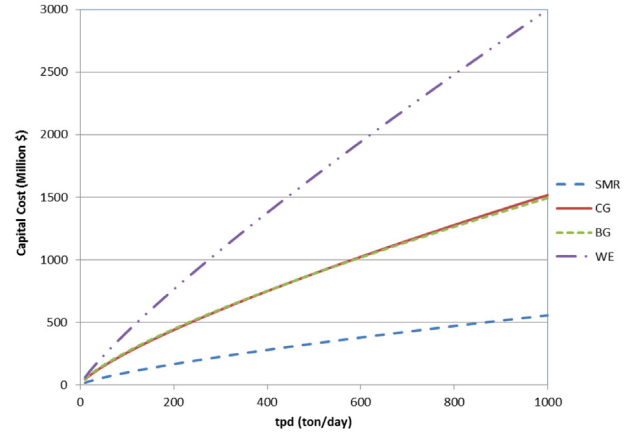


Fig. 6 – The relationship between production capacity and the capital cost of selected hydrogen production methods. (Data from Ref. [24]).

of selected hydrogen production methods. In their work, efficiency is defined as useful output by consumed input. The following equation is used to define the energy efficiency of a hydrogen generation facility:

$$\eta = \frac{\dot{m} \times \text{LHV}}{\dot{E}_{\text{in}}} \quad (1)$$

where $\dot{m}$ is the mass flow rate of produced hydrogen, LHV is the lower heating value of hydrogen (121 MJ/kg) and $\dot{E}_{\text{in}}$ is the rate of energy input to the process. The following equation is used for exergy efficiency:

$$\Psi = \frac{\dot{m} \times \text{ex}^{\text{ch}}}{\dot{E}_{\text{in}}} \quad (2)$$

where ex^{ch} is the chemical exergy of hydrogen and $\dot{E}_{\text{in}}$ is the rate of exergy input into the process.

Fig. 7 presents the energy and exergy efficiency data of selected hydrogen production methods from which it can be seen that biomass gasification has an advantage over other methods. On the other hand, solar based electrolysis shows the poorest performance among the selected production methods.

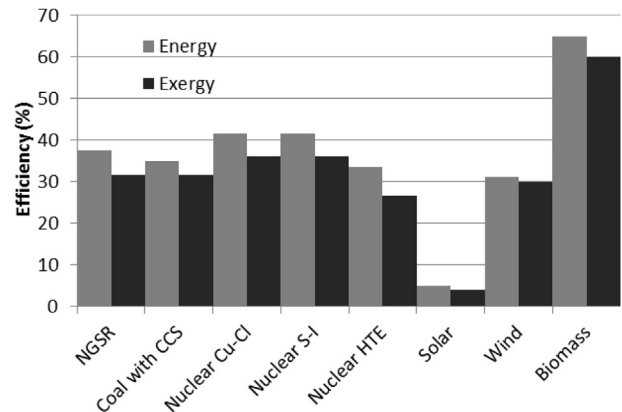


Fig. 7 – Energy and exergy efficiencies of selected hydrogen production methods. (Data from Ref. [25]).

Table 3 – Overall comparisons of selected hydrogen production methods (Normalized).

Hydrogen production method		GWP	AP	SCC	Cost	Energy efficiency	Exergy efficiency	Total	Avg.
Fossil fuel	Natural gas steam reforming	2.94	5.27	2.94	8.35	3.75	3.15	26.40	4.40
	Coal gasification with CCS	0	0	0	8.02	3.50	3.15	14.67	2.45
Nuclear energy	Thermochemical Cu–Cl cycle	9.64	8.96	9.64	8.24	4.15	3.6	44.22	7.37
	Thermochemical S–I cycle	9.49	8.60	9.49	7.97	4.15	3.6	43.30	7.22
	High temperature electrolysis	8.82	8.42	8.82	6.15	3.35	2.65	38.22	6.37
Renewable energy	Solar based electrolysis	8.53	7.37	8.53	0	0.50	0.4	25.33	4.22
	Wind based electrolysis	9.43	9.16	9.43	1.98	3.10	3.00	36.10	6.02
	Biomass gasification	8.24	0.54	8.24	8.46	6.50	6.00	37.97	6.33
Ideal (0 emissions, 0 cost, 100% efficiency)		10	10	10	10	10	10	60.00	10.00

3.5. Overall comparison

In this section, the evaluation results mentioned so far are normalized to be able to compare each method effectively. GWP, AP, SCC and production costs are normalized based on the following equation:

$$\text{Rank}(\text{method } i) = \frac{\text{Maximum} - \text{Method } i}{\text{Maximum}} \times 10 \quad (3)$$

The ranking is between 0 and 10, where 0 means poor performance and 10 indicates the ideal case (zero-cost and zero-emissions). Lower costs and emissions are given higher rankings. “0” is assigned to the highest cost and emissions in selected categories. For example, in terms of GWP and AP, coal gasification method gives the highest emissions; therefore, the GWP and AP ranking of coal gasification is assigned to be “0”. Efficiencies are normalized based on the following equation:

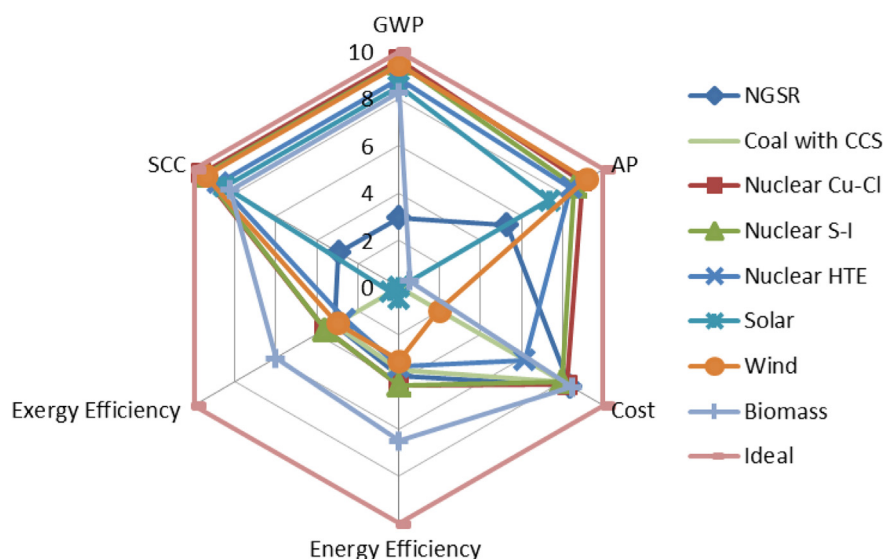
$$\text{Efficiency rank}(\text{method } i) = \text{Efficiency}(\text{method } i) \times 10 \quad (4)$$

The ranking range is again between 0 and 10, 0 means poor performance and 10 indicate the ideal case (100% efficiency). Higher rankings mean higher efficiencies.

The normalized emissions, cost, and efficiency rankings are presented in Table 3 and Fig. 8, respectively. The hypothetical ideal case refers to zero-cost and emissions, which

also means zero SCC. The energy and exergy efficiency of this ideal case is 100%. Based on Fig. 8, it can be concluded that in terms of energy and exergy efficiency, closest performance to the ideal case is reached by biomass gasification. However, this method gives considerably high AP (low AP ranking) compared to other selected methods. GWP and SCC rankings of biomass gasification are also low, especially compared to nuclear thermochemical cycles (Cu–Cl and S–I), solar, wind and nuclear high temperature electrolysis (HTE).

The electrolysis methods, the solar, wind and nuclear high temperature, are compared in Fig. 9 by using the data from Table 3. The corresponding figure shows that in terms of environmental impact criteria (GWP, AP, and SCC); all of the electrolysis methods have close-to-ideal rankings. The electrolysis methods presented in this study have lower emissions, and lower emission-related costs. However, in terms of energy and exergy efficiency, these options have poor performances. Compared to wind and high temperature electrolysis, solar electrolysis gives the poorest cost and efficiency performance (highest cost among the selected methods, therefore assigned a rank of “0”). When compared in financial terms to wind and solar electrolysis, HTE gives closest results to the ideal case. However, high temperature requirements negatively affect the efficiency and cost. Improving energy and exergy efficiencies and lowering the cost of the available

**Fig. 8 – Overall comparison of selected hydrogen production processes (Normalized).**

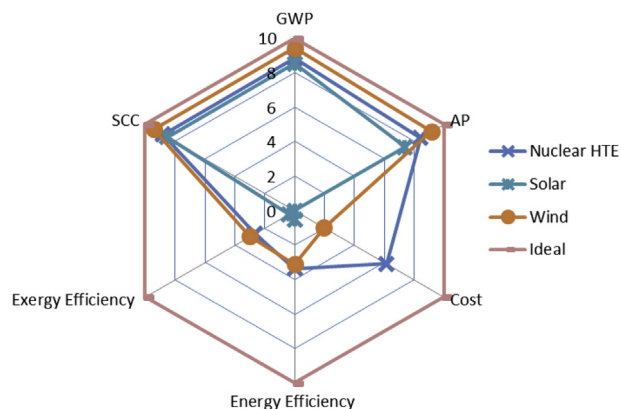


Fig. 9 – Overall comparison of selected electrolysis options (Normalized).

electrolysis systems are expected to be the areas of primary focus for future research.

The overall performance comparison of the selected nuclear options, HTE, Cu–Cl and S–I cycles, are presented in Fig. 10. Similar to electrolysis options, the selected nuclear H_2 production methods give close-to-ideal results in terms of environmental impact criterion (GWP, AP and SCC). It can be seen that the GWP, AP and SCC rankings of thermochemical Cu–Cl and S–I cycles give slightly better results than HTE. This difference is more obvious with efficiency and cost rankings. The nuclear options (Cu–Cl, S–I, and HTE) have the highest total ranking, as can be seen from Table 3. Overall, these options give closest-to-ideal results among the selected hydrogen production methods and they have a potential to be utilized as hydrogen production methods in the long run. Increasing the energy and exergy efficiencies and lowering the costs of HTE, S–I and Cu–Cl cycles by future studies would potentially make these options even more preferable.

In this section, eight different hydrogen production methods are compared based on 6 different criteria. The results are normalized and the rankings are presented in Table 3. Compared to the other selected production methods, nuclear thermochemical Cu–Cl cycle gives the highest total ranking, 44.32 (an average ranking of 7.37/10). This method is

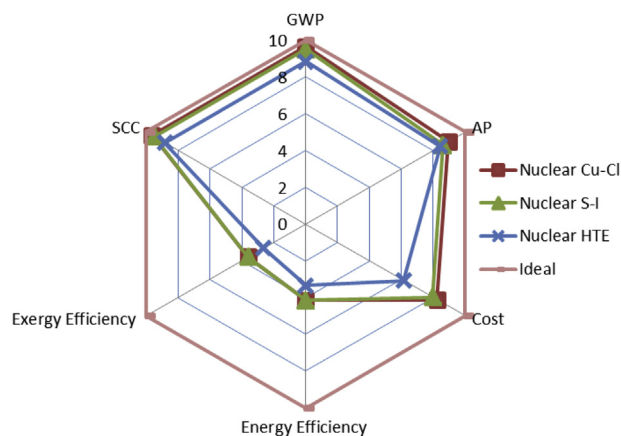


Fig. 10 – Overall comparison of selected nuclear options: HTE, S–I and Cu–Cl cycles (Normalized).

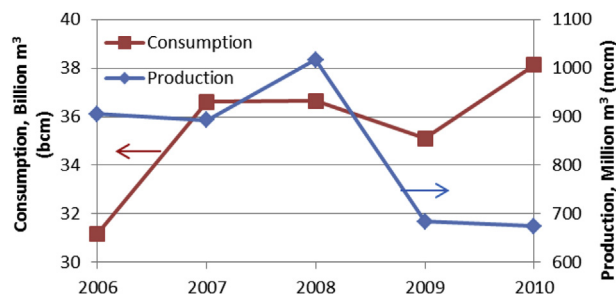


Fig. 11 – Annual natural gas production and consumption in Turkey. (Data from Ref. [26]).

immediately followed by S–I cycle, a total of 43.30 (average: 7.22/10). The third nuclear option, HTE, has a total and average ranking of 38.22 and 6.37/10, respectively. These rankings have a potential for further improvement if the low-efficiency and high-cost issues are addressed. Biomass gasification (total ranking of 37.97 and average: 6.33/10) and wind based electrolysis (total ranking of 36.10 and average: 6.02/10) give close (but lower) rankings compared to nuclear options. Biomass gasification's AP ranking is considerably low (very high SO_2 emissions) compared to the selected methods. And wind electrolysis rankings could be increased by improving the system efficiency and lowering the production costs. NGSr (total: 26.40 and average: 4.40/10) and solar based electrolysis (total: 25.33 and average: 4.22/10) have poor rankings. This is partly because of the negative environmental impact of NGSr (GWP, AP, and SCC), high production cost and lower efficiencies of solar based electrolysis. Among the selected production methods, coal gasification has the lowest rankings (total: 14.67 and average: 2.45/10). The high environmental impact of coal gasification dramatically downgrades the overall ranking of this method.

4. Regional analysis of fuel resources: a case study for Turkey

4.1. Natural gas

The natural gas reserves are limited in Turkey. International Energy Agency estimates that this amount was around

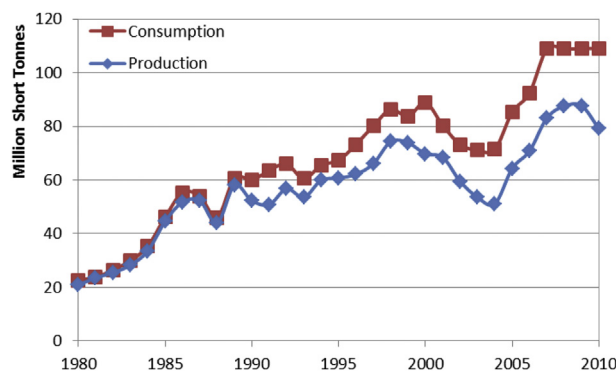


Fig. 12 – Annual coal production and consumption in Turkey. (Data from Ref. [27]).

Table 4 – Wind energy potential of Turkey compared to selected European OECD countries. (Data from Ref. [30]).

European OECD countries	Territory (thousand km ²)	Specific wind potential (class>3) (thousand km ²)	Side potential (km ²)	Technical potential	
				MW	TWh/yr
Turkey	781	418	9960	83,000	166
UK	244	171	6840	57,000	114
Spain	505	200	5120	43,000	86
France	547	216	5080	42,000	85
Norway	324	217	4560	38,000	76
Italy	301	194	4160	35,000	69
Greece	132	73	2640	22,000	44
Ireland	70	67	2680	22,000	44
Sweden	450	119	2440	20,000	41
Iceland	103	103	2080	17,000	34

6 billion m³ at the end of 2010. The reserves-to-production (R/P) ratio is the length of time that the remaining reserves would last if production were to continue at the same rate. The R/P ratio is calculated based on the reserves remaining at the end of any year divided by the net consumption (consumption – production) in that year. R/P ratio for Turkey is 8.9 years [26]. Fig. 11 presents natural gas production and consumption in Turkey between 2006 and 2010. From the same figure, it can be seen that the natural gas consumption in Turkey increased by about 7 billion m³ while the production decreased by about 300 million m³. There is an increasing gap between Turkey's natural gas production and consumption. Even though natural gas based hydrogen production has some advantages including cost, efficiency, existing technology and infrastructure, this method might not be viable in Turkey due to increasing dependency on importation of foreign natural gas and limited local reserves.

4.2. Coal

The difference between coal production and consumption rates had remained relatively static in Turkey until 1990. After 1990, the rate of consumption started exceeding production with continued annual increase in this gap. Fig. 12 graphically presents this trend. Although it has advantages in terms of cost, efficiency, existing technology and infrastructure, like natural gas, coal might not be a viable option to produce hydrogen in Turkey because of the increasing gap between the production and consumption rates of this energy source.

4.3. Solar energy

Turkey is located in the Mediterranean sun-belt, and can thus be considered to have a good solar energy potential. There are two main criteria used to identify the solar energy potential of a region: solar energy potential and solar irradiance level. Solar energy potential represents the amount of solar energy (e.g. kW) per unit area of a given location per unit time. Solar irradiance level denotes the power of solar energy per unit area of a surface. Turkey's solar energy potential and irradiance levels are considered to be comparable to those of Spain and Portugal [28]. Turkey's average solar potential is greater than 100 kW/m²-month, average sunshine duration is above 200 h/month, and sunshine duration is 7.2 h/day between the months of

April and September. The southern parts of Turkey, especially the Southeastern and Mediterranean regions, have the highest solar energy potential. Eastern and Central Turkey follow the Southeastern and Mediterranean regions. The Aegean region has higher sunshine duration than the east and central Turkey but the total solar radiation in these three regions is about the same. Marmara and Black Sea have lower total solar radiation and sunshine duration than the other regions [29].

4.4. Wind energy

In terms of wind energy, Turkey has some potentially rich regions with relatively high wind speeds. Turkey's wind energy potential compared to selected European OECD countries is presented in Table 4. According to the same table, Turkey's technical wind energy potential, which represents the achievable energy generation based on topographic limitations, environmental and land-use constraints, is 83,000 MW and higher than the selected OECD countries [30]. Turkey has a wind-based electricity production capacity of 48,000 MW, 803.55 MW of this amount is in operation, and 1000 MW of it is in built-in progress. In 2006, Turkey's wind energy potential atlas (REPA) is developed by Turkish Ministry of Energy and Natural Resources in order to determine the characteristics and distribution of the wind resources. This map can be found in reference. Some regions in Turkey have wind speeds between 3.5 and 5 m/s at 10 m altitude, a theoretical power of between about 1000–3000 kWh/(m²/yr.) [31]. The Marmara Sea, Southeast, the Mediterranean and the Aegean Sea Coasts offer the highest potential for harvesting wind energy in Turkey.

Table 5 – Land-cover classes in Turkey in 2000 and 2006. (Data from Ref. [33]).

Land class	Land size (%)		Change (million m ²)
	2000	2006	
Artificial areas	1.56	1.61	+377
Agricultural areas	42.36	42.35	–134
Forests and semi-natural areas	54.08	54.04	–259
Wetlands	0.36	0.36	–15
Water bodies	1.64	1.64	+41
Total	100	100	

4.5. Biomass

Turkey's total available bioenergy and biomass potential are estimated to be around 17.2 MTOE and 32 MTOE, respectively. Turkey's total biomass consumption was 4.8 MTOE in 2008 [32]. Turkey is planning to increase its biomass consumption gradually from 7.3 MTOE in 2015 to 8.3 MTOE in 2030. Aegean, Black Sea, Central and Eastern Anatolia have good biomass potentials; according to the Republic of Turkey Ministry of Energy and Natural Resources "Biomass" report [32]. However, the increase in population, urbanization and industrialization has raised the use of non-agricultural fields in Turkey [33]. The land-use change in Turkey can be seen in Table 5. The decrease in the size of agricultural, forest, and semi-natural areas with increasing artificial areas could be a disadvantage in terms of hydrogen production via biomass gasification process in Turkey.

4.6. Results and discussion

In this study, the potential environmental, financial, technical and social effects of selected hydrogen production methods are compared and their feedstock availability in Turkey is evaluated. The comparison and evaluation results are used to propose hydrogen production methods that are appropriate for Turkey. Natural gas and coal consumption rates are exceeding their production rates and Turkey is becoming more dependent on foreign natural gas and coal imports. Therefore, these energy sources are not proposed as hydrogen production feed-stocks for any region in Turkey. Also, because of the ongoing debate and social acceptance issues related to nuclear energy in Turkey, the nuclear energy based production methods are also not used as a suggested pathway.

Table 3 summarizes the overall comparison of selected hydrogen production methods by ranking their technical, environmental, financial and social performance. These data are used to construct Fig. 13, which compares biomass gasification, solar and wind electrolysis. The technical comparison of these methods is carried out based on their energy and exergy efficiency rankings. The financial comparison is based

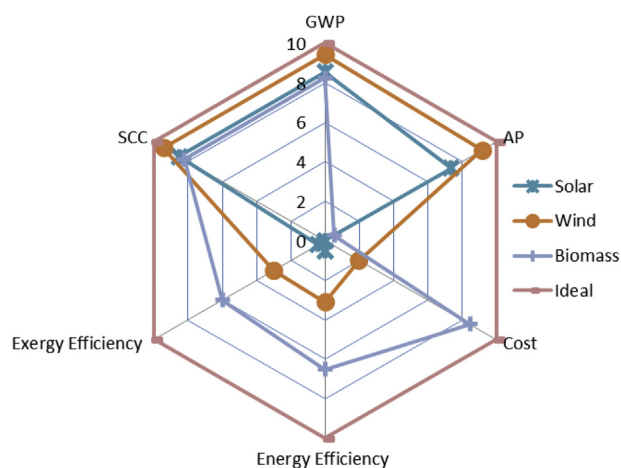


Fig. 13 – Overall performance comparison of solar and wind electrolysis and biomass gasification.

Table 6 – Region-specific suggested renewable hydrogen production methods for Turkey.

Region	Suggested H ₂ production method
Marmara	Biomass/Wind
Southeast	Biomass/Solar
Aegean	Biomass/Wind/Solar
Mediterranean	Biomass/Wind/Solar
Black Sea	Biomass/Wind
Central Anatolia	Biomass/Solar
East Anatolia	Biomass

on the production cost ranking. Table 3 and Fig. 13 show that biomass gasification gives close-to-ideal results because of its high rankings in technical and financial evaluation. Wind energy based electrolysis is ranked second. Solar energy based electrolysis gives the poorest technical and financial performance. However, the social and environmental impact comparison (GWP, AP and SCC) show that biomass gasification gives the lowest rankings. Despite the fact that it has significant technical and financial advantages compared to solar and wind based electrolysis, biomass gasification has poor performance in relation to environmental and social impact because of its high AP and GWP (low AP and GWP rankings). Wind based electrolysis has the highest environmental and social performance (lowest emissions). Solar based electrolysis gives closer results to wind in terms of GWP, AP and SCC rankings. Overall, of the six different criteria used to compare the selected methods, biomass gasification has the highest total ranking (37.97) with an average of 6.33/10. Immediately following biomass gasification, wind based electrolysis gives a total ranking of 36.10 with an average ranking of 6.02/10. Solar based electrolysis, gives a lower total ranking compared to wind and biomass, a total and average of 25.33 and 4.22/10, respectively.

The feedstock availability, technical, financial, environmental and social impact comparison performed in this study show that although it has very low AP rankings, biomass gasification can be a very promising hydrogen production method for Turkey. The decrease in agricultural and forestry areas could have a negative potential impact on Turkey's biomass potential. But Turkish government is planning to increase the country's biomass production. Table 6 summarizes the evaluation results by showing the suggested renewable pathways for hydrogen production for different regions of Turkey.

5. Conclusions

In this paper, a comparative assessment study is performed to evaluate and compare environmental, financial, social and technical performance of selected hydrogen production methods. Natural gas steam reforming, coal and biomass gasification, solar, wind, and nuclear based high temperature electrolysis, nuclear based Cu–Cl and S–I thermochemical cycles are compared based on their GWP, AP, production and capital cost, energy and exergy efficiency, and social cost of carbon. Hydrogen production options for Turkey are evaluated as a case study. The availability of the required feed-

stocks in Turkey is also investigated. The concluding remarks of this study can be summarized as follows:

- Nuclear based Cu–Cl cycle has the lowest GWP and SCC. Nuclear based S–I and wind electrolysis also have lower GWP and SCC compared to the rest of the methods evaluated.
- In terms of AP, wind electrolysis has the lowest emissions, which becomes closest to the ideal case rankings as followed by nuclear based Cu–Cl and S–I cycles.
- Among the evaluated methods, biomass gasification has the lowest hydrogen production cost (\$/kg). Natural gas steam reforming and coal gasification have lower costs than the rest of the methods as well.
- When capital costs are compared, it can be seen that natural gas steam reforming has lower costs than coal and biomass gasification.
- Biomass gasification has the best energetic and exergetic efficiencies, followed by nuclear Cu–Cl and S–I cycles.
- The high acidification potential of biomass gasification is expected to be one of the major focus areas of future research in order to render this option worthwhile to consider as a promising hydrogen-generating source.
- In Turkey, different regions have different potential promising methods for hydrogen production.

Nomenclature

AP	Acidification Potential, g SO ₂ eq.
CCS	Carbon Capture and Storage
CML	The Center of Environmental Science of Leiden University
GHG	Greenhouse Gases
GWP	Global Warming Potential, g CO ₂ eq.
HTE	High Temperature Electrolysis
IEA	International Energy Agency
LCA	Life Cycle Assessment
MTOE	Million Tonnes of Oil Equivalent
NGSR	Natural Gas Steam Reforming
SCC	Social Cost of Carbon, \$/kg hydrogen produced

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