



## Hydrogen production potential from renewable energy sources in Turkey

A.Coskun Avci<sup>1</sup>, K.Kaygusuz<sup>2,a</sup>

<sup>1</sup>Duzce University, Faculty of Engineering, Department of Mechanical Engineering, Duzce, Turkey.

<sup>2</sup>Karadeniz Technical University, Department of Chemistry, Trabzon, Turkey.

Accepted 20 December 2019

### Abstract

The partnership of hydrogen and renewables may provide benefits to both technologies. Renewables can use hydrogen to store excess production and provide energy on demand. Renewables can add credibility to the clean energy claims of hydrogen, ensuring that the production of hydrogen is in fact GHG emission free and independent from fossil fuels. However, there are many outstanding issues that need to be considered in determining the potential for this option. Some of those issues are the cost of hydrogen production from renewable energy, the convenience of hydrogen storage methods, the efficiency of electricity production from hydrogen, and the overall efficiency of a renewable energy/hydrogen system. There are also many other storage options for renewables that show promise and may deserve more attention. This paper will examine the current state of R&D for renewable-hydrogen integration in Turkey, and discuss the potential and challenges for this option in specific applications. Finally, hydrogen will be compared to other storage options for renewables.

*Keywords:* renewable energy, hydrogen energy, biomass, solar, wind, Turkey.

### 1. Introduction

Electricity production from renewable energy sources has been increasing rapidly in Canada over the past five years, particularly from wind energy, currently the fastest growing source of electricity in Canada. Renewable energy shows considerable growth potential due to a number of factors, including the rising prices and limited supply of oil, its emissions reduction potential, and the resulting political support for renewables. However, the renewable energy industry must address issues of intermittency and lack of predictability of their energy sources. One option that has received considerable attention in recent years is the integration of renewable energy sources and hydrogen. Research into the production of hydrogen from wind is particularly interesting because of the rapid growth of the wind energy industry [1-3].

Hydrogen is not a primary source of energy: it is an intermediary form of energy, or an energy carrier. Hydrogen is not found freely in nature like oil or coal. The principle of using hydrogen in combination

with renewable energy is to use it as an energy storage medium. Thus, energy stored in the form of hydrogen could later be used to produce energy when and/or where it is most needed. When dealing with hydrogen and renewable energy, both hydrogen production and electricity production from hydrogen have to be considered [4].

Hydrogen has many characteristics that make it a good fuel and energy carrier: it is non-toxic, is transportable, is storable, is lightweight, could have a high energy density (MJ/kg) depending on its storage form, it produces nontoxic exhaust emissions (although it can produce NO<sub>x</sub> if air is used as an oxidant such as in reciprocating piston engines or gas turbines), it can be generated from various energy sources and produced by various means, and it can be used in all sectors of the economy (transportation, thermal power and electrical power). The disadvantages of hydrogen include safety issues (combustible: hydrogen can burn) and the difficulty of storing hydrogen with a high energy density [5-7].

### 2. Hydrogen as a clean energy carrier

Hydrogen is the simplest and lightest of all chemical elements and the most spread in the universe. It is not

a primary source of energy as it occurs only in nature in combination with other elements, primarily with

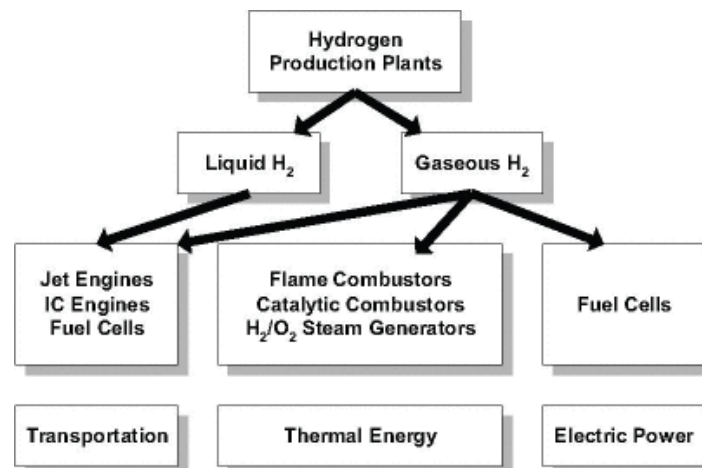
oxygen in water and with carbon, nitrogen and oxygen in living materials and fossil fuels [3]. However, when split from these other elements to form molecular hydrogen, a process requiring another source of energy, it becomes an environmentally attractive fuel [4]. It can be burned or combined with oxygen in a fuel cell without generating CO<sub>2</sub>, producing only water. Like electricity it is a very clean energy at the point of use, but like natural gas it can form explosive mixtures with air [5-8].

Some of the advantages of the hydrogen economy can be summarized as [9-12]:

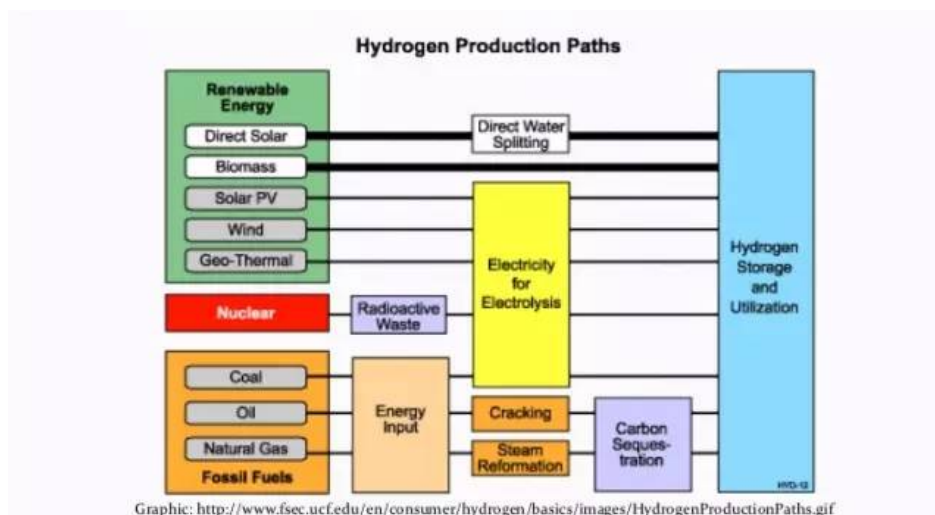
- *Energy security:* H<sub>2</sub>-powered vehicles could significantly reduce imports of foreign oil.
- *Sustainability:* H<sub>2</sub> production technologies can potentially take advantage of abundant renewable energy resources.
- *Climate change:* Vehicles produce near-zero carbon emissions when operating on H<sub>2</sub>.

- *Urban air quality:* H<sub>2</sub> can reduce or eliminate regulated tailpipe emissions (e.g., hydrocarbons, GHG, NO<sub>x</sub>).
- *Economic vitality:* Leading the development and commercialization of H<sub>2</sub> and fuel cell technology can shape the future global energy markets.

While the hydrogen economy represents a visionary strategy for future energy security, significant scientific and technical challenges must be overcome to achieve its implementation. The hydrogen economy spans three functional areas: production, storage, and use; each area has its special set of grand technical challenges. Recent advances in materials science, chemistry, physics, biology, computation, and nanoscience provide considerable promise for breaking through many of these current barriers. Figure 1 shows the hydrogen utilization pathways. Hydrogen production methods investigated in this study is presented in Figure 2.



Source: American Solar Energy Society, 2003  
 Figure 1. Hydrogen utilization pathways.



Graphic: <http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/images/HydrogenProductionPaths.gif>

Figure 2. Hydrogen production methods.

**2.1. Hydrogen production from water electrolysis**

Electrolysis is a process for breaking water (H<sub>2</sub>O) into its constituent elements (hydrogen and oxygen) by supplying electrical energy (see Figure 3). The advantage of this process is that it supplies a very clean hydrogen fuel that is free from carbon and sulfur impurities. The disadvantage is that the process is expensive, relative to steam reforming of natural gas, because of the cost of the electrical energy needed to drive the process. Making

electrolytic hydrogen uses considerably more energy than the hydrocarbon processes. Nevertheless, electrolysis is of interest for several reasons. First it is seen as a potentially cost-effective way of producing hydrogen locally. Electrolyzers are compact and can realistically be located at existing fuelling stations. Secondly, electrolysis offers a way to produce hydrogen with electrical power generated from renewable sources [4-8].

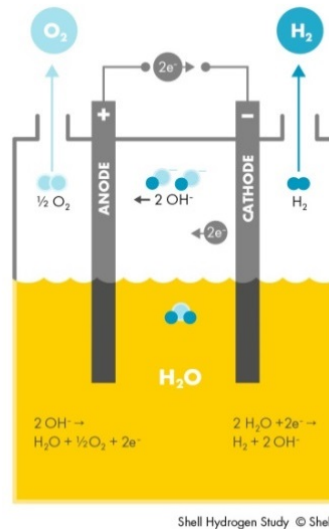


Figure 3. The electrolysis cell for water.

**2.2. Hydrogen production from renewable energies**

**2.2.1. Solar Photovoltaic**

The most efficient and also the most costly sources of solar electricity for water electrolysis are photovoltaic devices. At the present time the cost of hydrogen from PV electricity through electrolysis is 25 times higher than that of hydrogen produced from coal or natural gas plants. The expected decrease in

the cost of photovoltaic cells and of electrolyzers would bring this down to a factor of 6. The potential capacity for solar hydrogen is quite large [8-14]. Figure 4. Hydrogen production from solar PV by photoelectrolysis.

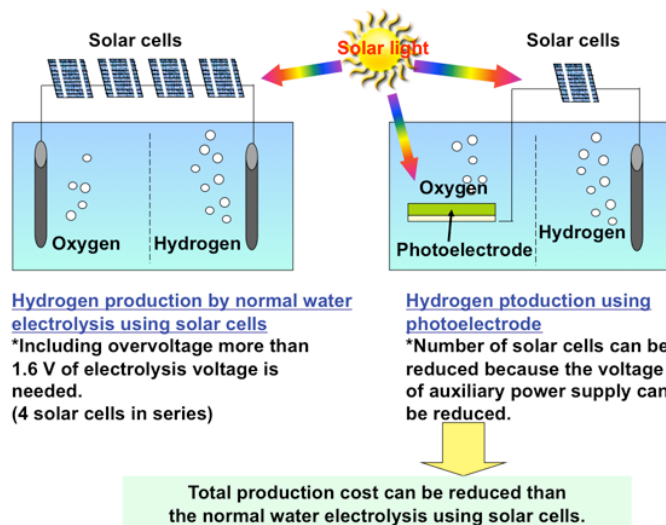


Figure 4. Hydrogen production from solar PV by photoelectrolysis.

### 2.2.2. Wind Energy

Of all renewable sources, wind shows possibly the highest potential for producing pollution-free hydrogen, using the electricity generated by the wind turbines for electrolysis. This is particularly true for distributed systems. In order to succeed the cost of the wind turbines and electrolyzers has to decrease,

and the turbine–electrolyzer–storage system has to be further optimized. Today the cost of hydrogen produced from wind amounts to six to ten times that of large-scale units using natural gas. This gap could be halved in the near future [15].

## 3. Hydrogen production from biomass gasification

Using biomass instead of fossil fuels to produce hydrogen reduces the average amount of carbon dioxide in the atmosphere, since the carbon dioxide released when the biomass is oxidized was previously absorbed from the atmosphere and fixed by photosynthesis in the growing biomass [16-20]. Hydrogen can be produced from biomass resources such as forestry, wood processing, and agricultural residues, animal and consumer (municipal) waste or crop specifically grown for energy uses. Current technologies for converting biomass into molecular hydrogen include gasification/pyrolysis of biomass coupled to subsequent steam reforming. The main conversion processes are indirect-heat gasification, oxygen-blown gasification, and anaerobic fermentation.

Biomass-to-hydrogen conversion is presently unable to produce hydrogen on a large scale at a competitive price, even when compared with hydrogen generated from distributed natural gas. It could however contribute to recover energy from domestic and agricultural waste in a very clean way. The environmental impact of growing significant quantities of biomass as energy crops, including genetically engineered, high-yield crops, will most likely place significant strains on natural resources and land availability. The cost for collecting and transporting biomass is inherently high. It would result in building many small biomass gasification plants without the economy of scale. The route to biofuels might prove more attractive [20-28].

### 3.1. Biomass gasification

Biomass gasification, or producing gas from biomass, involves burning biomass under restricted air supply for the generation of producer gas. Producer gas is a mixture of gases:

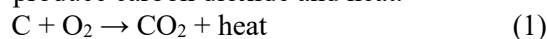
18%–22% carbon monoxide (CO), 8%–12% hydrogen (H<sub>2</sub>), 8%–12% carbon dioxide (CO<sub>2</sub>), 2%–4% methane (CH<sub>4</sub>) and 45%–50% nitrogen (N<sub>2</sub>) making up the rest.

### 3.2. Gasification reactions

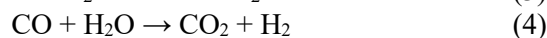
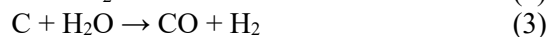
Producing gas from biomass consists of the following main reactions, which occur inside a biomass gasifier.

- **Drying:** Biomass fuels usually contain 10%–35% moisture. When biomass is heated to about 100 °C, the moisture is converted into steam.
- **Pyrolysis:** After drying, as heating continues, the biomass undergoes pyrolysis. Pyrolysis involves burning biomass completely without supplying any oxygen. As a result, the biomass is decomposed or separated into solids, liquids, and gases. Charcoal is the solid part, tar is the liquid part, and flue gases make up the gaseous part.

- **Oxidation:** Air is introduced into the gasifier after the decomposition process. During oxidation, which takes place at about 700–1,400 °C, charcoal, or the solid carbonized fuel, reacts with the oxygen in the air to produce carbon dioxide and heat.



- **Reduction:** At higher temperatures and under reducing conditions, that is when not enough oxygen is available, the following reactions take place forming carbon dioxide, hydrogen, and methane.



### 3.3. Advantages of biomass gasification technologies [6-8]

- **Mature technology:** Biomass gasifier technology is a mature technology and gasifiers are available in several designs and capacities to suit different requirements.
- **Small and modular:** The technology is suitable and economical for small, decentralized applications, typically with capacities smaller than a megawatt.
- **Flexible operation:** A gasifier based power system, unlike those based on other renewable sources such as the sun and wind, can generate electricity when required and also wherever required. Whereas large thermal power plants and solar and wind based units are very location specific, biomass gasifier based systems can be set up

at almost any place where biomass feedstock is available.

- **Economically viable:** For small-scale systems, the cost of power generation by biomass gasification technology is far more reasonable than that of conventional diesel based power generation.
- **Socio-economically beneficial:** Biomass gasifier based systems generate employment for local people.
- **Mitigate climate change:** Biomass is a CO<sub>2</sub> neutral fuel and, therefore, unlike fossil fuels such as diesel does not contribute to net CO<sub>2</sub> emissions, which makes biomass based power generation systems an attractive option in mitigating the adverse effects of climate change.

### 3.4. Types of gasifiers

Gasifiers can be classified based on the density factor, which is a ratio of the solid matter (the dense phase) a gasifier can burn to the total volume

#### 3.4.1. Downdraft or co-current gasifiers

The downdraft (also known as co-current) gasifier is the most common type of gasifier. In downdraft gasifiers, the pyrolysis zone is above the combustion zone and the reduction zone is below the combustion zone. Fuel is fed from the top. The flow of air and gas is downwards (hence the name) through the combustion and reduction zones. Figure 5 shows Downdraft and Updraft gasifiers. The term co-current is used because air moves in the same direction as that of fuel, downwards. A downdraft

gasifier can be (a) dense phase reactors, or (b) lean phase reactors.

gasifier is so designed that tar, which is produced in the pyrolysis zone, travels through the combustion zone, where it is broken down or burnt. As a result, the mixture of gases in the exit stream is relatively clean. The position of the combustion zone is thus a critical element in the downdraft gasifier, its main advantage being that it produces gas with low tar content, which is suitable for gas engines [12-20].

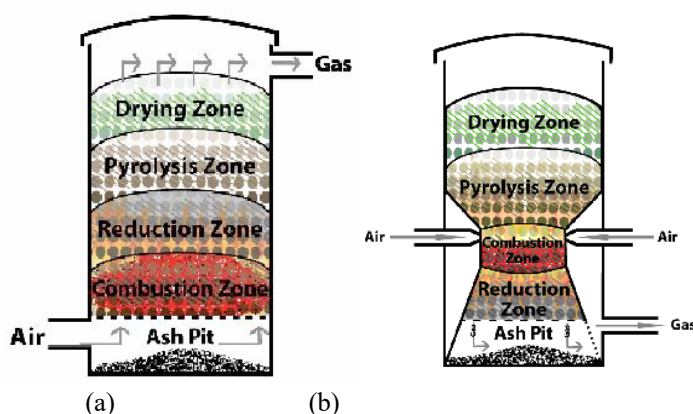


Figure 5. a) Downdraft gasifier and b) Updraft gasifier

#### 3.4.2. Updraft or counter-current gasifier

In updraft gasifiers (also known as counter-current), air enters from below the grate and flows upwards, whereas the fuel flows downwards. An updraft gasifier has distinctly defined zones for partial combustion, reduction, pyrolysis, and drying. The

gas produced in the reduction zone leaves the gasifier reactor together with the products of pyrolysis from the pyrolysis zone and steam from the drying zone (see Figs. 5-8).

The resulting combustible producer gas is rich in hydrocarbons (tars) and, therefore, has a higher calorific value, which makes updraft gasifiers more suitable where heat is needed, for example in

**3.4.3. Cross-draft gasifier**

In a cross-draft gasifier, air enters from one side of the gasifier reactor and leaves from the other. Cross-draft gasifiers have a few distinct advantages such as compact construction and low cleaning requirements.

industrial furnaces. The producer gas needs to be thoroughly cleaned if it is to be used for generating electricity.

Also, cross-draft gasifiers do not need a grate; the ash falls to the bottom and does not come in the way of normal operation.

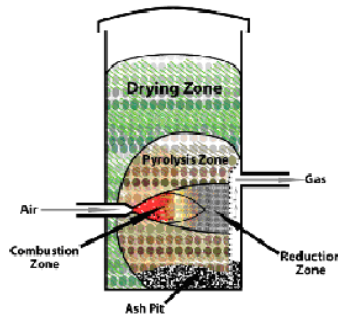


Figure 6. Cross-draft gasifier

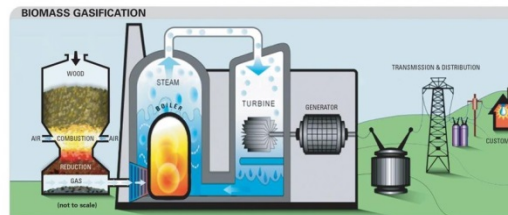
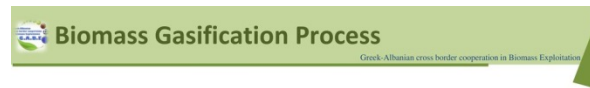


Figure 7. Biomass gasification process.

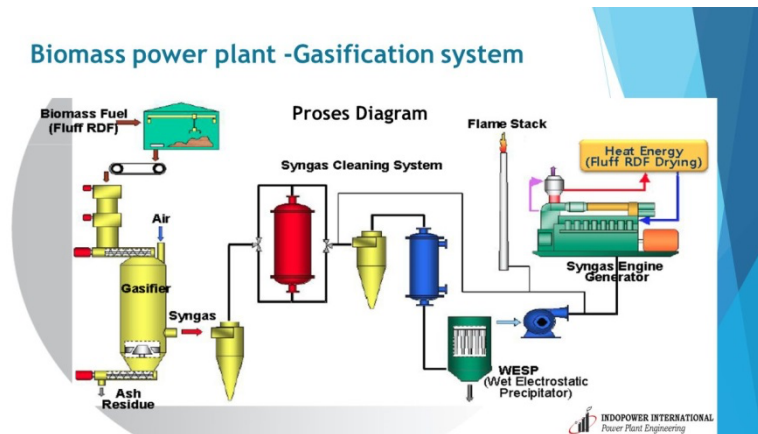


Figure 8. Biomass power plant-gasification system.

**4. Renewable energy in Turkey**

**4.1. Energy demand in Turkey**

Turkey is a poor fossil energy country; 75% of total energy requirement has been supplied by imported fuels as shown in Table 1. As shown in Table 1,

Turkey’s energy production is only 35 108 kilotons of oil equivalent (ktoe) while energy consumption was 146 758 ktoe in 2017. Petroleum, gas and coal

have the biggest share in total energy consumption as shown in Table 1. If we look to the Table 1, we saw that only 25% of the total energy consumption supplied by domestic resources. It means that Turkey is an energy imported country and it should pay a lot of money for buying these fuels. Therefore, the governments and private sector companies should use domestic and clean renewable energy sources as

soon as possible [21-24].

Table 2 shows Turkey's installed electricity capacity and generation in 2017 (GWh). As shown in Table 2, natural gas and hydropower has most great part of installed electricity capacity. Table 3 also shows the installed capacity targets for renewable power plants [21-24].

Table 1. Turkey's energy situation in 2017 (ktoe).

Energy source	Production	Consumption
Coal and Lignite	14 470	38 824
Oil	2 682	44 536
Natural gas	430	45 872
Hydropower	5 112	5 112
Geothermal	7 124	7 124
Bioenergy	2 536	2 536
Solar/Wind/Other	2 854	2 754
<b>Total</b>	<b>35 108</b>	<b>146 758</b>

ktoe: kilo tons of oil equivalent

#### 4.2. Renewable energy

Turkey saw an increase in renewable energy deployment. The share of hydro has been highly volatile year on year. Electricity demand has grown fast throughout the past decade; the Turkish power sector invested in new generation facilities, using renewable energy sources thanks to the attractive support schemes. With volatile hydropower generation, higher coal and gas use and growing electricity generation, Turkey continues to witness growing shares of renewable energy generation, with the continuous increase in total installed capacity (49 GW in 2017). In 2017, the share of renewable energy in total primary energy supply stood at 16.8%, and 42.3% in electricity generation. Turkey has good renewable electricity penetration rates. Turkey has a high potential for renewable energy resources, notably in solar, wind and geothermal. The next phase of renewable energy growth will require regulatory and administrative changes if Turkey wishes to use its full potential and accelerate the deployment in support of climate goals up to 2030 [21-25].

Renewable energy (RE) accounted for 17.6 million tons of oil-equivalent (Mtoe) or 49.7% of Turkey's total primary energy supply (TPES) in 2017 as given in Table 1. Renewables include biofuels and waste (2.53 Mtoe), hydropower (5.2 Mtoe), geothermal energy (7.2 Mtoe), solar (1.4 Mtoe) and wind power (1.6 Mtoe). Renewable energy as a share of TPES has decreased since 2005 and only reached back again the 2005 level in 2015, when RE represented 12.1% of total TPES. The main reason for this decline was a downward trend in the use of biofuels

and waste (down by 39.3% over the same period), as well as strong growth in the use of natural gas and coal. Solar power started growing in 2011. Since 2012, wind and geothermal power increased by 97.2% and 112.7%, respectively.

According to the highly probable scenario of an increase of 4,8% to 375,8 TWh in the base scenario, electricity consumption in the year 2023 is expected to rise by 5,5% to 357,4 TWh. By the end of the first half of 2019, power plants containing a total of 1.820,2 MW additional capacity were added to the system, and as of the end of the first half of 2019 our capacity has risen to around 90.421 MW. As of the end of the first half of 2019, 15,2% of our electricity production was obtained from natural gas, 33,2% from coal, 36,6% from hydropower, 7,2% from wind, 3,0% from geothermal, 3,0% from solar energy and 1,7% from other sources [21-25].

As of the end of the first half of 2019, EUAS ( State Electricity Generating Company) had a share of 18,6% in installed capacity of Turkey, 73,0% of the private sector, 4,8% of build-operate plants, 0,4% of build-operate-transfer plants and 3,1% of unlicensed power plants. By the end of the first half of 2019, the distribution of our installed power by resources; 31,4% hydraulic, 29,0% naturel gas, 22,4% coal, 8,0% wind, 1,5% geothermal, 6,0% solar and 1,7% other sources. In addition, As of the end of the first half of 2019, number of electricity energy production plants in our country have been 7.957. According to energy sources, number of existing plants is as follows: 664 hydraulic, 67 coal, 257 wind, 48

geothermal, 327 natural gas, 6.349 solar and 245 other power plants [21-25].

### 4.3. Hydropower

Among the various sources of energy, hydroelectricity power stations are preferred due to their being environmentally friendly and carrying low potential risk. Hydroelectricity plants work in harmony with the environment, are clean, renewable, and highly productive plants with no fuel expenses. They take on the role of an insurance in energy prices, have a long lifespan, low operating costs, and are not dependent on imports. The theoretical hydroelectricity potential of our country is 1% of

theoretical potential of the world, while its economic potential is 16% of the economic potential of Europe. Our hydraulic resources, which hold the most important position in the renewable energy potential of our country, possess a hydroelectricity potential of 433 billion kWh, while the technically usable potential is 216 kWh, and the economic hydroelectricity potential is 140 billion kWh/year [21-25].

Table 2. Turkey's installed electricity capacity and generation in 2017 (GWh).

Resources	Installed Capacity (MW)	Share (%)	Generation (TWh)	Share (%)
Natural gas	26 638	31	108.1	37
Hydropower	27 273	32	58.3	20
Domestic coal	9 872	11	44	15
Import coal	8 794	10	51.1	17
Renewables	11 000	13	26.5	10
Other	1 623	3	7.5	1
<b>Total</b>	<b>85 200</b>	<b>100</b>	<b>295.5</b>	<b>100</b>

Table 3. Installed capacity targets for renewable power plants

Resource type	Installed capacity (MW)		
	2017	2019	2023
Solar power	1 800	3 000	10 000
Geothermal	420	700	1 500
Biomass	540	700	1 000
Wind power	9 500	10 000	20 000
Hydropower	27 700	32 000	34 000
<b>TOTAL</b>	<b>39 960</b>	<b>46 400</b>	<b>66 500</b>

### 4.4. Solar energy

Due to its geographical location, Turkey can be considered to have a good potential in terms of solar energy. Turkey is located in the Mediterranean sun-belt; it has similar irradiance levels as Spain and Portugal. Between April and September, Turkey has an average solar potential greater than 100 kW/m<sup>2</sup>-month. Between these months, the average sunshine duration is above 200 h/month. On average, the daily average of solar energy is 3.6 kW/m<sup>2</sup>-day and sunshine duration is 7.2 h/day. Figure 9 shows Turkey's solar energy potential atlas [21-24].

Figure 9 shows that southeastern part of Turkey has the highest solar energy potential. The sunshine duration of Mediterranean region is almost about the

same as the southeastern region; however, the total solar radiation is lower in this region compared to southeastern Turkey. East and central Turkey follow the southeastern and Mediterranean regions. Aegean region has higher sunshine duration compared to east and central Turkey but the total solar radiation in these three regions are about the same [21]. Compared to the other regions, Marmara and Black Sea have lower total solar radiation and sunshine duration. Figure 9. Turkey's solar energy potential [22]. As shown in Figure 9, the south-east and south-west regions of Turkey has excellent solar energy potential to electricity generation for hydrogen production by water electrolysis [23-26].

### 4.5. Wind energy

Turkey is a country with wind-rich regions. Table 4 shows the wind energy potential of Turkey compared to selected European OECD countries. 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 [21-24].



Figure 9. Turkey’s solar energy potential.

Table 4. Wind energy potential of Turkey compared to selected European OECD countries

European OECD countries	Territory (1 000 km <sup>2</sup> )	Specific wind Potential (1 000 km <sup>2</sup> )	Side potential (km <sup>2</sup> )	Technical Potential MW	Generation Potential (TWh/year)
Turkey	781	418	9 960	83 000	166
UK	244	171	6 840	57 000	114
Spain	505	200	5 120	43 000	86
France	547	216	5 080	42 000	85
Norway	324	217	4 560	38 000	76
Italy	301	194	4 160	35 000	69
Greece	132	73	2 640	22 000	44
Ireland	70	67	2 680	22 000	44
Sweden	450	119	2 440	20 000	41
Iceland	103	103	2 080	17 000	34

According to TUREB, Turkey has a wind-based electricity production capacity of 48,000 MW, 803.55MW of this amount is in operation, and 1,000 MW of it is in built-in progress, according to MENR. In order to determine the characteristics and distribution of the wind resources, EIE developed Turkey Wind Energy Potential Atlas (REPA) in 2006. Figure 10 and 11 shows Turkey’s wind atlas (REPA). This figures show that some regions in

Turkey have relatively high wind speeds. These have been classified into six wind regions with a low of about 3.5 m/s and a high of 5 m/s at 10 m altitude, which corresponds to a theoretical power production of between 1,000 and 3,000 kWh/(m<sup>2</sup>/year). The most attractive sites are the Marmara Sea region, Southeast, the Mediterranean and the Aegean Sea Coast [21-24].

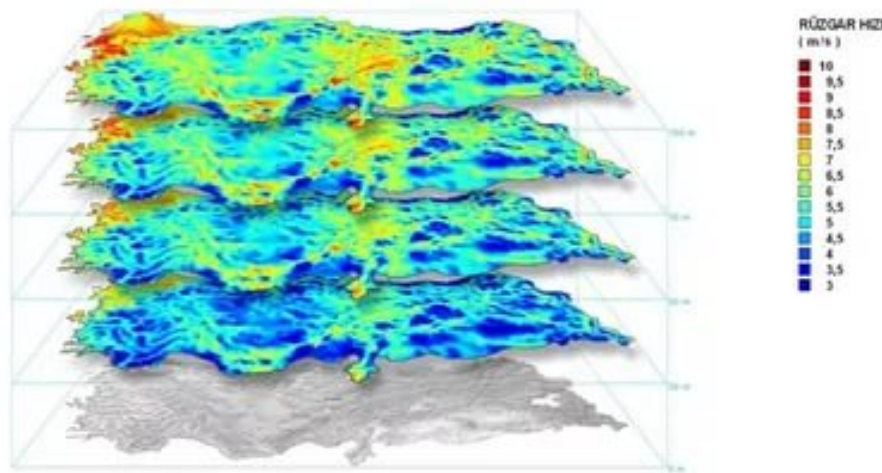


Figure 10. Turkey wind energy potential atlas.

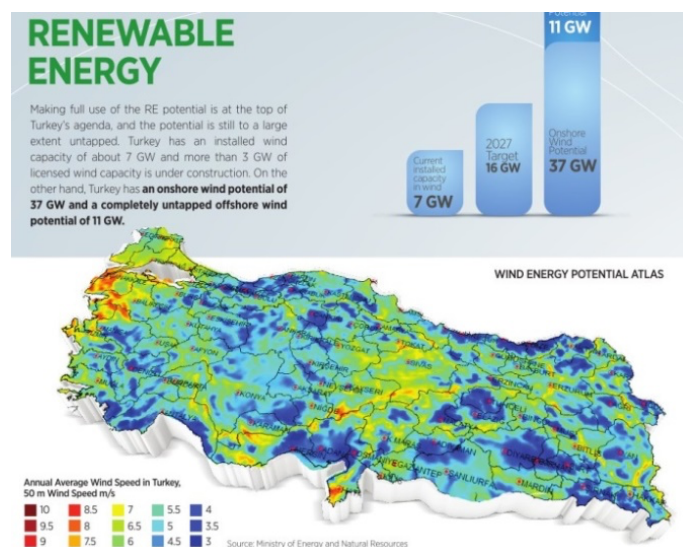


Figure 11. Wind energy potential atlas.

#### 4.6. Biomass in Turkey

Annual biomass potential of Turkey is approximately 32 Mtoe (million tons of oil equivalent). Total available bioenergy potential is estimated to be approximately 17.2 Mtoe. In 2017, Turkey's total biomass consumption was 4.8 Mtoe. According to the Republic of Turkey Ministry of Energy and Natural Resources "Biomass" report, Aegean, Black Sea, Central and Eastern Anatolia have good biomass potentials. However, the 2006 Corine land cover data show that land in Turkey consists of 42.35 % agricultural areas and 54.04 % forestry and semi-

natural vegetation where almost 96% of the country's land can be defined as natural environment. The increases in population, urbanization and industrialization have raised the use of non-intentional agricultural fields [24]. Figure 12 shows electricity capacity generation (MW) from crop residues in Turkey. As shown in these figure, there is a lot of biomass potential as a crop residues for electricity generation capacity in Turkey. In recently, the electricity generation from crop residues increased to 4.0 MW in Turkey [23; 33; 34].

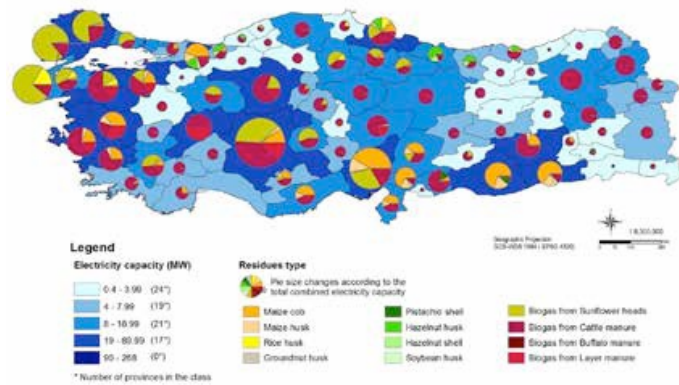


Figure 12. Electricity capacity generation (MW) from crop residues in Turkey.

#### 4.7. Suggested renewable hydrogen production methods for Turkey

Excess renewable electricity is used to convert water into renewable hydrogen by employing the process of electrolysis. Electrolysis splits water (H<sub>2</sub>O) into hydrogen gas (H<sub>2</sub>) and oxygen gas (O<sub>2</sub>) in a piece of equipment called an electrolyzer that contains an “anode” and a “cathode” separated by an electrolyte or membrane. In the electrolyzer apparatus, when electricity flows through the electrolyzer the water

releases oxygen and hydrogen. The oxygen is usually released into the atmosphere but the hydrogen is captured and can be mixed with natural gas and stored in the pipeline system. Figure 13 shows the schematic view of the renewable hydrogen production and utilization. Figure 14 also shows the pathways to hydrogen production from renewables and its utilization applications.

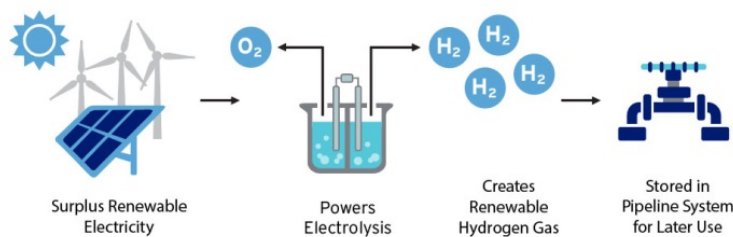


Figure 13. Renewable hydrogen production and utilization.

#### Pathways to Hydrogen Production from Renewables

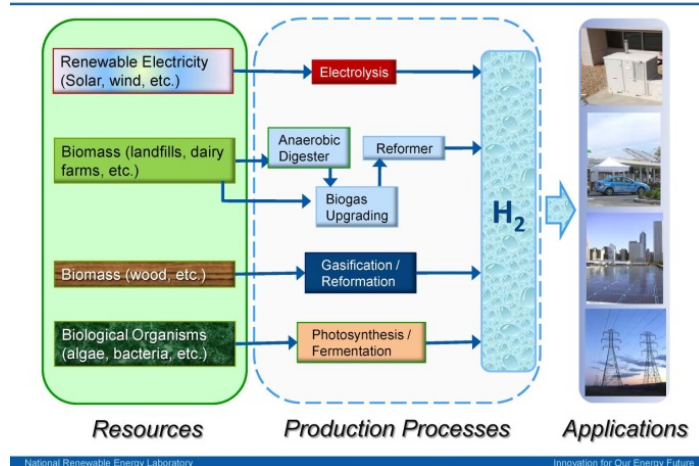


Figure 14. Pathways to hydrogen production from renewables and its applications.

Although the land cover class change might have a negative impact on biomass potential of Turkey, Turkish government is planning to increase the biomass production in Turkey, which could make the

biomass a promising hydrogen feedstock. In addition to the feedstock availability; technical, financial, environmental and social impact comparison show that although it has very low AP rankings, biomass

gasification can be a very promising hydrogen production method for Turkey. When geographical data presented in the earlier subsections is combined, the following “suggested pathway for hydrogen

production” could be made for different regions of Turkey. Table 5 summarizes the findings of this study by suggesting possible renewable hydrogen pathways for different regions of Turkey.

Table 5. Regional suggested renewable hydrogen production methods for Turkey.

Region	Suggested H <sub>2</sub> production methods
Marmara	Wind
Southeast Anatolia	Solar
Aegean	Solar/wind/biomass
Mediterranean	Solar/wind
Black Sea	Wind/biomass
Central Anatolia	Solar/biomass
East Anatolia	Solar/Biomass

## 5. Conclusions

Turkey relies heavily on fossil fuels to meet its domestic energy demand. Fossil fuels make up approximately 90% of the total primary energy supply and are heavily imported. The country’s principal objective is energy security, therefore the aim is to: diversify its energy supply routes and source countries; increase the share of renewables to the highest possible extent and include nuclear power into its energy mix; make steps towards improved energy efficiency; and contribute to Europe’s energy security. The country also estimates that there will continue to be immense growth in energy demand and wants to meet this demand in a manner that is timely, adequate and affordable.

Furthermore, Turkey has substantial potential to produce energy from renewable energy resources and the country aims to increase its use of geothermal, hydro, wind and solar energy resources as well as slowly commissioning nuclear power so as to reduce its dependency on imported fossil fuels. Turkey’s Renewable Energy Action Plan (REAP), which was created in alignment with ‘the Renewable Energy Directive’ of the European Parliament and of the Council, has set a target for renewable energy sources to contribute 20 percent of total general energy consumption by 2023 [21-25].

Hydrogen may be the novel next generation energy carrier. When produced by renewable energy forms, hydrogen could be considered environment friendly

(lower to no GHG emissions) from its production to its utilization. In addition, hydrogen improves the efficiency of renewable energy system as a long-term energy storage and a high density energy carrier. However, some R&D is still required to improve hydrogen convenience (storage methods) and to reduce production and storage costs. Also, national and international policies should be adopted to promote sustainable energy. Climate change disasters increase, fossil fuel reserves decline: it's time to adopt new renewable technologies that benefit the environment [26-33].

Turkey has a substantial amount of renewable energy potential, and the utilization of this potential has been increasing over the last decade. As of the end of February 2018, hydro and wind resources constitute the vast majority of Turkey’s renewable energy resources, accounting for 27,456 MW and 6,580 MW respectively of the total installed capacity of more than 86,100 MW. However, solar, biomass/biogas, and geothermal energy resources will also comprise a significant portion of the total capacity as rapid growth in utilization of these resources will be experienced in the coming years. In this study, the renewable energy potentials for hydrogen energy production in Turkey was discussed. The potential effect of land area on biomass gasification is briefly explained. The comparison and evaluation results are used to propose hydrogen production methods that are appropriate for Turkey.

## Acknowledgement

The authors are greatly acknowledged to the Turkish Academy of Science for financial support for this study.

## References

- [1] IEA, International Energy Agency. Key world energy statistics 2018. IEA, Paris, 2018.
- [2] IEA, International Energy Agency. World energy outlook 2018. IEA, Paris, 2018.
- [3] Rand DAJ. Fuels hydrogen production: coal gasification. Encyclopedia of electrochemical power sources. pp. 276–292, 2009.
- [4] Acar, C., Dinçer, I. Comparative environmental impact evaluation of hydrogen production methods from renewable and nonrenewable sources. In “Causes, Impacts and Solutions to Global Warming” by I. Dinçer et al. (eds.). Springer, New York, 2013.
- [5] Agbossou, K., Chahine, R., Hamelin, J., Laurencelle, F., Anouar A., St-Arnaud JM., T.K. Bose. Renewable Energy Systems based on Hydrogen for Remote Applications, Journal of Power Sources, Vol. 96, No. 1, p 168-172. 2000.
- [6] Agbossou K., Kolhe ML., Hamelin J., Bernier E., Bose, TK. Electrolytic hydrogen based renewable energy system with oxygen recovery and re-utilization. Renewable Energy 2003; 29: 1305-1318.
- [7] Agbossou K., Kolhe ML., Hamelin J., Bose, TK. Performance of a stand-alone renewable energy system based on energy storage as hydrogen. IEEE Transactions on Energy Conversion, 2004; 19: 633-640.
- [8] Berndt DW. Hydrogen energy systems: concepts and practical applications. Refocus 2004: 48-51.
- [9] Bernler E., Hamelin J., Agbossou K., Bose TK. Electric round-trip efficiency of hydrogen and oxygen-based energy storage, Int. J. of Hydrogen Energy, 2005; 30: 105-111.
- [10] Kar, T., Keleş, S., Kaygusuz, K. Thermal processing technologies for biomass conversion to clean fuels. J of Eng. Research and Applied Science 2018; 7(2): 972-979.
- [11] EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, Palo Alto, CA, and the U.S. DOE, Washington, DC: 2003. 1001834.
- [12] Houstein T., Karri, V. Analysis of component sizing for a wind-hydrogen-diesel stand-alone power system. Proceedings of the IASTED International Conference Energy and Power Systems, Krabi, Thailand , April 18-20, 2005.
- [13] Karim GA. Hydrogen as a Spark Ignition Engine Fuel, International Journal of Hydrogen Energy, 2003; 28: 569-577.
- [14] Kothari, R., Buddhi D., Sawhney, RL. Sources and technology for hydrogen production: a review, Int. Journal of Global Energy issues, 2004; 21: 154-178.
- [15] Kottenstette, R., Cotrell, J. Hydrogen storage in wind turbine towers. International Journal of Hydrogen Energy, 2004; 29: 1277-1288.
- [16] Midilli A, Ay M., Dincer I., Rosen, MA. On hydrogen and hydrogen energy strategies I: current status and needs. Renew Sustain Energy Reviews, 2005; 9: 255-271.
- [17] Momirlan, M., Veziroglu, TN. Current status of hydrogen energy. Renewable & Sustainable Energy Reviews, 2002; 6: 141-179.
- [18] Scott GA. Wind-generated hydrogen: the technology roadmap. Fuel Cell Review 2005; 2: 21-25.
- [19] Yang, WJ., Aydin, O. Wind energy-hydrogen storage hybrid power generation. Int. Journal of Energy Research, 2001; 25: 449-463.
- [20] Zhou L. Progress and problems in hydrogen storage methods. Renew Sustain Energy Reviews, 2005; 9: 395-408.
- [21] MENR, Ministry of Energy and Natural Resources, Solar energy potential of Turkey. General Directorate of Renewable Energy (YEGEM) Website <http://www.yegem.gov.tr/>
- [22] MENR, Ministry of Energy and Natural Resources of Turkey. Energy Report in 2017.
- [23] MENR, Ministry of Energy and Natural Resources, Wind energy potential of Turkey. General Directorate of Renewable Energy (YEGEM) Website <http://www.yegem.gov.tr/>
- [24] MENR, Ministry of Energy and Natural Resources, Solar energy potential of Turkey. General Directorate of Renewable Energy (YEGEM) Website <http://www.eie.gov.tr/>
- [25] IEA, International Energy Agency. Energy Policies of IEA Countries: Turkey 2016 Review. OECD/IEA, Paris, 2016.
- [26] Kaygusuz, K., Güney, MS., Kaygusuz, O. Renewable energy for rural development in Turkey. J of Engineering Research and Applied Science 2018; 7(2): 886-895.
- [27] Kaygusuz, K., Avcı, AC. Renewable energy potential, utilization and policies in Turkey for environmental friendly sustainable development. J of Engineering Research and Applied Science 2018; 7(2): 902-909.
- [28] Kaygusuz, K., Güney, MS., Kaygusuz, O. Renewable energy for rural development in Turkey. J. of Engineering Research and Applied Science 2018; 7(2): 886-895.
- [29] Kaygusuz, K. Green chemistry and green energy technologies for environmental friendly Sustainable development. J. of Eng. Research Applied Science 2018; 7(2): 953-964.

- [30] Kaygusuz, K., Keleş, S. Sustainable bioenergy policies in Turkey. *J. of Engineering Research and Applied Science* 2012; 1(1): 34-43.
- [31] Kara, B., Emir, Z., Kaygusuz, K. Thermal processing technologies for biomass conversion to energy. *J. of Engineering Research Applied Science* 2012; 1(1): 55-62.
- [32] Uyar, TS (Ed.). *Towards 100% Renewable Energy: Techniques, Costs and Regional Case-Studies*. Springer, Switzerland 2017.
- [33] Kick, C. How is 100% Renewable Energy Possible for Turkey by 2020 ?.GENI, Global Energy Network Institute, from [www.geni.org/](http://www.geni.org/)(accessed 24 Jun 2019)
- [34] FAO, Food and Agriculture Organization of the United Nations. *BEFS ASSESSMENT FOR TURKEY: Sustainable bioenergy options from crop and livestock residues*. FAO, Rome, 2016.