# THE DEVELOPMENT OF GREEN HYDROGEN: ASSESSMENT OF APPROACHES

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**Abstract**

The hydrogen economy is the vision of the future for the global economy, where hydrogen is becoming a new global energy carrier. It is beginning to play a role comparable to that of coal, oil or gas and much more important than the current role of hydropower, nuclear power plants and bioenergy combined. The growing role of hydrogen technologies in sustainable development has prompted many countries to integrate these technologies into their national energy strategies. In this article, the authors conduct an extensive literature review of the development of green hydrogen. The main research methods are bibliographic and comparative analysis. The study revealed the role of hydrogen as a key reason in the development of green energy. It is shown the need for the widespread introduction of technology. An economic assessment of various approaches to pricing has been carried out. It has been determined that the development of green hydrogen shortly will be able to compete in price with the most common energy sources. The expansion of green hydrogen technologies based on renewable energy sources brings the average production cost to 3-4 USD / kg.

**Key words:** green hydrogen, sustainable development.

**JEL Code:** O13, Q4.

## Introduction

Energy is critical to a high quality of life and is the foundation of sustainable development. The role of energy in modern society is generally recognized; trends towards the expansion of the use of alternative energy sources are becoming widespread (Ratner, Gomonov, Revinova, & Lazanyuk, 2020). Hydrogen plays an increasingly important role in this segment. However, the specific physicochemical properties and the high cost of its production have not yet allowed hydrogen to be widely used in the fuel and energy complex. Due to the increasing influence on the development of international energy markets of the course of decarbonization of the global economy, the world community is striving for a progressive transition to the use of low-carbon and carbon-free energy sources. And it is hydrogen as an environmentally friendly fuel that can play one of the key roles in achieving carbon neutrality.

Economic growth, in the concept of the traditional linear production model, built on the principle of "get - produce - use - throw away", leads to a constant increase in the burden on the environment, an increase in emissions of pollutants during the production, operation and disposal of various types of products. This problem is especially acute in the operation of limited hydrocarbon energy resources, rare earth elements, some metals, the use of which has increased significantly in recent decades due to the development of renewable energy sources and electric vehicles.

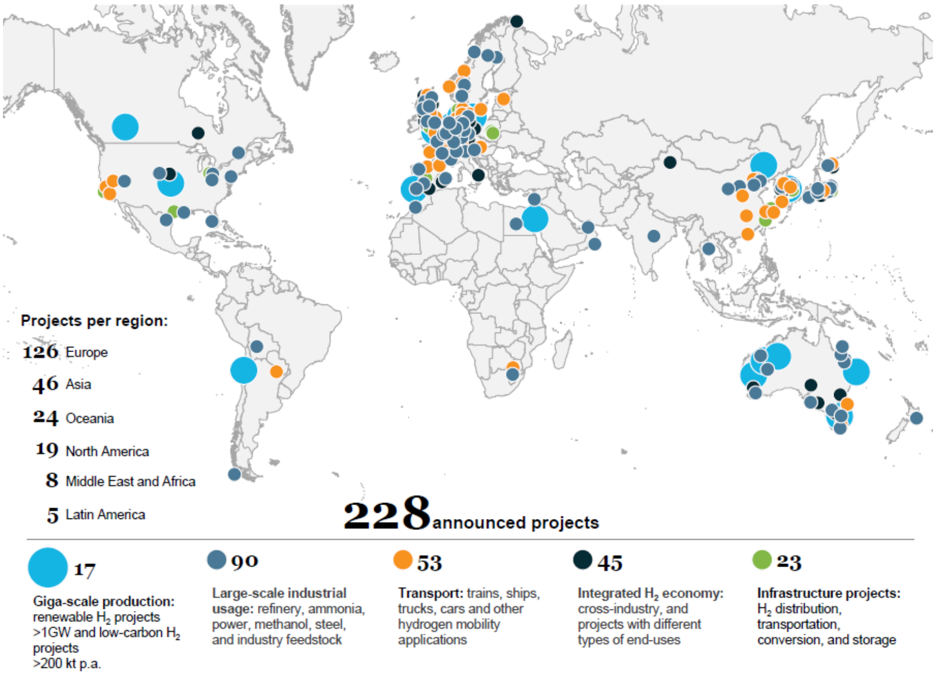
The global energy system requires a major transformation to achieve the goals of the Paris Climate Agreement. From this point of view, low-carbon renewable electricity could be the preferred energy source. The share of renewable electricity in all energy should be increased to 40% in 2050 to meet the decarbonization targets set out in the Paris Agreement. In absolute terms, this means that the total installed capacity of renewable energy sources should increase by almost 10 times and amount to 15,000 GW in 2050 (Gomonov, Balashova, & Matyushok, 2019). The natural disasters and energy lockdown of 2021 in Texas (USA) have once again confirmed that the complete decarbonization of certain sectors, such as transport, industry and residential sector, can be hampered solely by electrification using renewable energy sources. However, a possible solution to the problem is seen in the introduction of green hydrogen obtained electrochemically from renewable energy sources, which will allow directing large volumes of renewable electricity from the energy sector to these end-use sectors.

## 1 Hydrogen development nowadays

Work on hydrogen energy in many countries is one of the priority areas of socio-economic development and is supported by both governments and private business. An active search is underway to convert most energy-intensive industries, including transport, to hydrogen fuel cells into hydrogen energy. There are currently 228 hydrogen projects in the world. It is worth noting that 17 announced projects with a capacity of more than 1 GW for renewable sources and more than 200 thousand tons per year for low-carbon hydrogen. The largest projects are located around the world: in Europe, Australia, the Middle East and Chile (Figure 1).

At present, Europe is the leader in the implementation of hydrogen projects, followed by Australia, Japan, Korea, China and the United States. 105 full cycle hydrogen production projects (55%) are currently under development. In the supposed main centres of hydrogen energy demand (Europe, Japan, Korea), the focus of projects is shifting to the industrial and transport sectors.

**Fig. 1: Global hydrogen projects**




Source: Hydrogen Insights A perspective on hydrogen investment, market development and cost competitiveness, 2021

Hydrogen is an essential element of most strategies for achieving net-zero status, and an increasing number of countries are developing plans for hydrogen. More than 30 countries have created such strategies at the national level, and six are developing them.

In addition to national hydrogen roadmaps, sectoral regulation and targets are at the heart of the transition to hydrogen. In the field of transport, more than 20 countries have announced a ban on the sale of cars with internal combustion engines until 2035. More than 35 cities, covering over 100 million vehicles, are setting new, stricter emission limits, and more than 25 cities have pledged to buy only zero-emission buses from 2025. Countries around the world expect to have 4.5 million fuel cell electric vehicles (FCEVs) by 2030, with China, Japan and Korea leading the way in deployment. In parallel, stakeholders plan to allocate 10,500 hydrogen refuelling stations (HRS) to fuel these vehicles by 2030.

For industry, goals also change. For example, the European Union has invited member states to include targets for low carbon hydrogen production in the field of renewable fuels, which could give a significant boost to the use of hydrogen in refining and fuel retailers.

## 2 Hydrogen production costs

Hydrogen production is currently possible from fossil hydrocarbons, biomass, water, or a mixture of these. the main source of hydrogen is natural gas, its share is approximately 75% (70 million tons) in the total mass of production in the world. Thus, hydrogen production consumes approximately 6% of the world's gas per year. The cost of producing hydrogen from natural gas depends on some technical and economic factors, with gas price and capital cost being the two most important. Fuel costs are the largest cost component, accounting for 45% to 75% of operating costs. Low gas prices in the Middle East, Russia and North America result in some of the lowest hydrogen production costs. Gas importers such as Japan, Korea, China and India are forced to contend with higher gas import prices, leading to higher costs of hydrogen production.

Dedicated generation of electricity from renewable sources or nuclear energy offers an alternative to using the electricity grid to produce hydrogen. With the declining costs of renewable electricity, in particular from solar PV and wind power, there is growing interest in electrolytic hydrogen, and several demonstration projects have been implemented in recent years. The production of all the hydrogen released today from electricity will result in an electricity requirement of 3,600 TWh, which is more than the total annual electricity production in the European Union.

Three main electrolysis technologies are developed today:

– Alkaline electrolysis cells (AEC): It is a mature technology and is used in the industry, in particular, in the chemical industry (e.g., chlorine production). The lifetime of an AEC electrolyser is currently twenty years.

– Proton exchange membrane electrolysis cells (PEM): Already available in the market, are rapidly gaining market shares. They tend to have a smaller footprint and can operate more flexibly, having a wider operating range and a shorter response time than current AEC technology.

– Solid oxide electrolysis cells (SOEC): This technology can reach higher energy efficiency, but is still in an early stage of development.

Renewable electricity can be used to produce green hydrogen via water electrolysis, a well-known process splitting acidified or alkalised water into ultrapure (up to 99.998%) H2 and O2. Such electrolytic H2 can then further be used downstream as a green and clean chemical feedstock material in sectors otherwise difficult to decarbonise through electrification. The latter includes both the chemical industry itself, as well as new applications in the transport sector. As to the first, hydrogen is currently already widely used in several industrial sectors (refineries, ammonia production, bulk chemicals, etc.), with the majority of it being produced from natural gas by steam-methane reforming (SMR), a vast CO2-intensive process. Green hydrogen from renewables could replace such fossil fuel-based feedstocks in high-emission applications. For the transport sector, fuel cell electric vehicles (mainly cars and busses) provide already today an attractive low-carbon mobility option when the hydrogen is produced from renewable energy sources, and offer driving performances comparable to conventional vehicles. In the longer run, H2-based electrofuels, i.e. liquid fuels produced from renewable power, can also replace fossil fuels in the freight sector (including aviation and heavy-duty rail and trucks), without the need to change end-use technologies.

Although water electrolysis is already a well-established H2 production technology for almost a century, its large-scale implementation for the production of green H2 has been hampered mainly by cost issues. The production cost of hydrogen from electrolysis has been extracted from a large amount of literature data, resulting in a very wide range of cost values, ranging from about 2 €/kg to 20 €/kg. This was attributed to the large variability of the underlying assumptions and working parameters of the different sources, the production scale being the most important one. Moreover, when evaluating the potential and economic viability of such green hydrogen production by water electrolysis, the current price of fossil SMR-based H2 often appears as a rather challenging benchmark. For a fair comparison though, it was pointed that one should always keep in mind that the industrial SMR production price is usually considered for immediate use, while often additional storage is necessary to meet fluctuations in demand and delivery as well. On top of that, hydrogen from SMR still needs to be purified for most applications to reach the same grade as electrolytic one. Moreover, in such cost comparisons, the potential valorisation of ultra-pure electrolytic oxygen (8 kg for each kg of H2) is neglected. In any case, on a macro-economical level, the global hydrogen feedstock market represented in 2015 a total estimated value of 115 billion €, corresponding to a hydrogen demand of about 56 Mton/yr. By dividing the total estimated market value by the total worldwide hydrogen demand at the same year, a reasonable first-order estimation of the "average" market price for fossil H2 can then be obtained as 115/56 ≅ 2,0 €/kg.

The feasibility of a hydrogen-based project needs, in the first step, the quantification of its production cost. Many examples are available in the literature in which authors assessed hydrogen production by the mean of water electrolysis with the electricity generated from renewable sources.

Gökçek et al. conducted a pre-feasibility study of a hydrogen refuelling station for electric vehicles with a capacity to refuel 25 vehicles daily in İzmir-Çeşme, Turkey. A photovoltaic wind hybrid system was used to provide electricity to a Proton Exchange Membrane (PEM) electrolyzer for hydrogen generation, and the simulations were carried out using HOMER software. The authors investigated various scenarios and found that the cost of hydrogen production ranges between 7.526 $/kg and 7.866 $/kg (Gökçek & Kale, 2018).

Lee et al. compared the cost of hydrogen production from water electrolysis by Alkaline and PEM electrolyzers with steam methane reforming (SMR) for threes hydrogen production rates namely: 30, 100 and 300 Nm3/h. They found that the cost of hydrogen production for the previous rates are respectively: 16.54, 10.66 and 7.72 $/kg for the PEM electrolyzer, 17.99, 11.24 and 8.12 $/kg for the Alkaline electrolyzer, and 20.18, 11.80 and 7.59 $/kg for the SMR (Lee et al., 2017).

Mohsin et al. evaluated the economic viability of hydrogen production from wind energy via water electrolysis projects in Karachi, Pakistan. They found that the selected sites were considered as favourable for such a project with a cost of hydrogen production of 4.304 $/kg and a supply cost in the range of 5.30–5.80 $/kg (Mohsin, Rasheed, & Saidur, 2018).

Sayedin et al. studied the impact of climate conditions on the performance of PV/PEM electrolyzer. To this end, the authors considered two scenarios to optimize the system: minimal losses from energy transfer and the minimal cost of hydrogen production. These scenarios were applied to six cities with different climate in Iran. The lowest cost of hydrogen production was found to be 7.32 €/Kg and 7.39 €/Kg in the cities of Shiraz and Isfahan respectively (Sayedin, Maroufmashat, Sattari, Elkamel, & Fowler, 2016).

Genç et al. investigated the variation of hydrogen production cost from wind energy for three different turbine hub heights (50 m, 80 m and 100 m) and two electrolyzers with a rated power of 40 and 120 KW in Pınarbaşı-Kayseri, Turkey. Results show that the hydrogen production cost decreases as the turbine height increase, and the lowest cost was found to be 8.5 $/kg in the case of the 100 m hub height and the 40 kW electrolyzer (Genç, Çelik, & Serdar Genç, 2012).

Similarly, Olateju et al. used real-time energy production data from a network of wind farms with a cumulative capacity of 563 MW in Alberta province in Canada to assess the optimal size and number of electrolyzers, as well as, the battery capacity to have a minimal cost of hydrogen production. The minimal cost was 9 $/kg, with 63% of this cost due to the wind farm-related costs, and therefore the cost can drop to 3.37 $/kg if already existing wind farms are used to provide electricity for the water electrolysis process (Olateju, Kumar, & Secanell, 2016).

Rahmouni et al. estimated the potential of hydrogen to meet the demand of the Algerian transport sector over the period of 2015–2045 at various market penetrations rates. The cost of hydrogen production was then calculated for a geothermal and PV based plant. The results show that for the 7% market penetration rate and depending on the location, the cost is in the range of 5 $/kg and 4.66 $/kg and it decreases to 0.9 $/kg and 3.54 $/kg in the case of 100% market penetration rate for the hydrogen produced from the PV and geothermal based plants respectively (Rahmouni, Settou, Negrou, & Gouareh, 2016).

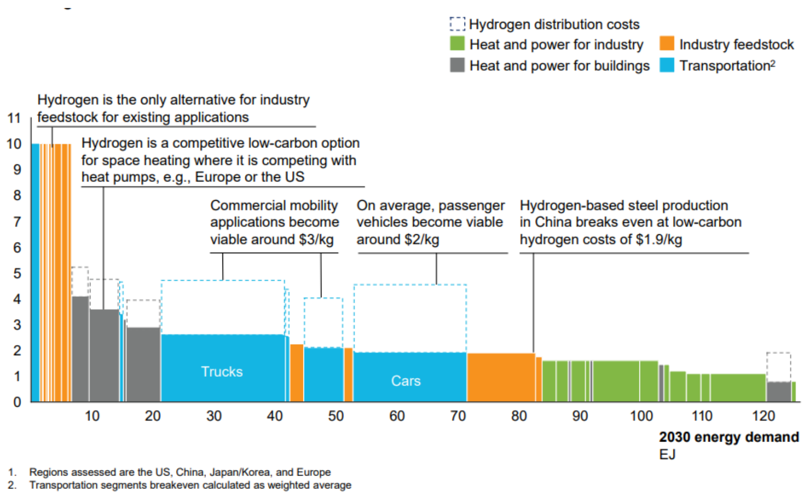
Dinh et al. developed a novel model for hydrogen production from offshore wind farms and it was used for the assessment of the viability of an offshore wind farm with a capacity of 101.3 MW for hydrogen production via water electrolysis if installed at in the East Coast of Ireland in the year 2030. The results show that the project is profitable in 2030 with a hydrogen production price of 5 €/kg (Dinh, Leahy, McKeogh, Murphy, & Cummins, 2020).

Mostafaeipour et al. investigated the use of wind energy projects by agricultural and industrial businesses in four cities located in the province of Ardebil, Iran namely: Ardebil, KhalKhal, Namin and Meshkinshahr. It was found that for the city of Ardebil the project will reach profitability after 13 and 5 years for 3.5 kW and 100 kW wind turbines respectively while for the rest of the cities, only the 100 kW wind turbine was found to be cost-effective. As for hydrogen production via water electrolysis with the electricity from the 100 kW, an annual amount of 5253, 3242, 4554 and 3557 kg can be generated in Ardebil, Khalkhal, Namin, and Meshkinshahr respectively (Mostafaeipour, Rezaei, Moftakharzadeh, Qolipour, & Salimi, 2019).

The generalizations in the price analyzes were carried out by the Hydrogen Consul. World average prices for hydrogen production, other things being equal, range from USD 4 to USD 6 per kg (Figure 2).

It is important to acknowledge that significant regional differences may still exist on a micro-economical level. This is not only due to geographical variations in the production price of SMR H2, but also depending on the availability of sufficient and low-cost renewable electricity. It is for instance well-known that the production cost of hydrogen from SMR is significantly influenced by natural gas prices, which account for 45%–75% of the total SMR production cost. As a result, the low gas prices in the Middle East, the Russian Federation, and North America give rise to some of the lowest hydrogen SMR production costs, sometimes even down to 1.5 €/kg. On the other hand, gas importers such as Japan, Korea, China and India have to contend with higher gas import prices, which inevitably results in higher hydrogen production costs. As a result, it will be much more feasible for electrolytic hydrogen produced from renewable electricity to compete effectively with SMR in countries relying on natural gas imports and characterised by good renewable resources.

**Fig. 2: Cost curve for hydrogen production across segments and regions**




Source: Hydrogen Insights A perspective on hydrogen investment, market development and cost competitiveness, 2021

## Conclusion

The novelty of this study lies in the extensive literature review, the authors conduct not only a review of the technical literature, but also carry out a comparative analysis of various studies on the calculation of economic efficiency and pricing in the development of green hydrogen. This significantly distinguishes this study from similar ones in the studied area.

The analysis showed that green hydrogen will grow rapidly in the coming years. Many ongoing and planned projects point in this direction. Hydrogen from renewable energy sources is technically viable today and is rapidly approaching economic competitiveness. The growing interest in this supply option is driven by declining renewable energy costs and system integration issues due to the increasing share of variable renewable energy supply. The transition to hydrogen energy will not happen overnight. The transition will require significant financial costs to re-equip all sectors of the economy, which will be difficult for developing countries. Therefore, hydrogen efforts should not be seen as a panacea. Instead, hydrogen represents a complementary solution that is especially relevant for countries with pro-ecological behaviour.

It is worth noting that the cost of producing low carbon and/or renewable hydrogen will fall in the next 10-15 years and will be able to compete with traditional fuels. This can be attributed to the declining costs of generating electricity from renewable sources, expanding pot production, and developing low-cost carbon storage facilities.

As for the development of hydrogen technologies in Russia, the plans are quite ambitious. It is planned that by 2024 Russian exports will amount to 0.2 million tons and by 2035 - 2 million tons per year, which, given current trends, will take 20% of the global hydrogen market by 2035.

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## References

Dinh, V. N., Leahy, P., McKeogh, E., Murphy, J., & Cummins, V. (2020). Development of a viability assessment model for hydrogen production from dedicated offshore wind farms. *International Journal of Hydrogen Energy*. doi:10.1016/j.ijhydene.2020.04.232

Genç, G., Çelik, M., & Serdar Genç, M. (2012). Cost analysis of wind-electrolyzer-fuel cell system for energy demand in Pinarbaşi-Kayseri. *International Journal of Hydrogen Energy, 37*(17), 12158-12166. doi:10.1016/j.ijhydene.2012.05.058

Gökçek, M., & Kale, C. (2018). Techno-economical evaluation of a hydrogen refuelling Station powered BY Wind-PV hybrid power system: A case study for İzmir-Çeşme. *International Journal of Hydrogen Energy, 43*(23), 10615-10625. doi:10.1016/j.ijhydene.2018.01.082

Gomonov, K., Balashova, S., & Matyushok, V. (2019). The relationship of socio-economic development and the drivers of green economy. *International Days of Statistics and Economics 2019*. doi:10.18267/pr.2019.los.186.41

*Hydrogen Insights. A perspective on hydrogen investment, market development and cost competitiveness*. Hydrogen Council, McKinsey & Company. 2021.

Lee, B., Chae, H., Choi, N. H., Moon, C., Moon, S., & Lim, H. (2017). Economic evaluation with sensitivity and profitability analysis for hydrogen production from water electrolysis in Korea. *International Journal of Hydrogen Energy, 42*(10), 6462-6471. doi:10.1016/j.ijhydene.2016.12.153

Mohsin, M., Rasheed, A., & Saidur, R. (2018). Economic viability and production capacity of wind generated renewable hydrogen. *International Journal of Hydrogen Energy, 43*(5), 2621-2630. doi:10.1016/j.ijhydene.2017.12.113

Mostafaeipour, A., Rezaei, M., Moftakharzadeh, A., Qolipour, M., & Salimi, M. (2019). Evaluation of hydrogen production by wind energy for agricultural and industrial sectors. *International Journal of Hydrogen Energy, 44*(16), 7983-7995. doi:10.1016/j.ijhydene.2019.02.047

Olateju, B., Kumar, A., & Secanell, M. (2016). A techno-economic assessment of large scale wind-hydrogen production with energy storage in Western Canada. *International Journal of Hydrogen Energy, 41*(21), 8755-8776. doi:10.1016/j.ijhydene.2016.03.177

Rahmouni, S., Settou, N., Negrou, B., & Gouareh, A. (2016). GIS-based method for future prospect of hydrogen demand in the Algerian road transport sector. *International Journal of Hydrogen Energy, 41*(4), 2128-2143. doi:10.1016/j.ijhydene.2015.11.156

Ratner, S., Gomonov, K., Revinova, S., & Lazanyuk, I. (2020). Eco-Design of energy production systems: The problem of renewable energy capacity recycling. *Applied Sciences, 10*(12), 4339. doi:10.3390/app10124339

Sayedin, F., Maroufmashat, A., Sattari, S., Elkamel, A., & Fowler, M. (2016). Optimization of photovoltaic electrolyzer hybrid systems; taking into account the effect of climate conditions. *Energy Conversion and Management, 118*, 438-449. doi:10.1016/j.enconman.2016.04.021

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