sciendo

Analysis on the sustainability of different low CO2 emission Hydrogen production technologies for transition towards a 'zero emission' economy

Catalin HRISTESCU
Bucharest University of Economic Studies, Bucharest, Romania
catalin.hristescu@gmail.com

Abstract. *World primary energy consumption reached 14,2 mil. tons of oil equivalent. More than 81.7% of this energy was generated from fossil fuels as primary energy source while 74.5% of the electrical energy was generated from fossil fuels. Energy transition towards zero impact from CO2 emission requires a major shift in the energy mix of the primary sources, decarbonization of the electricity generation, and the use of Hydrogen as the alternative low CO2 emission solution for the high temperature industrial process. Low CO2 Hydrogen could be produced using the conventional technologies (steam methane reform i.e.) with Carbon Capture and Storage, from renewable energy sources through water electrolysis or from biogas / biomass. At this moment none of the low CO2 Hydrogen technologies is competitive, as natural gas-based Hydrogen is around 1.5 EUR/kg while renewable based Hydrogen is in the range of 2.5-5.5 EUR/kg. From the sustainability point of view, besides the production cost issue, the whole life cycle emissions need to be considered. The main goal of this article is to assess different low CO2 emission Hydrogen production technologies by analyzing the CO2 emission along the value chain, together with a sensitive analysis on the main cost drivers, evaluating the impact on upstream and downstream economic sectors, based on case study methodology. This article provides the basis for selecting the most sustainable technology, the prerequisites for an energy transition towards a hydrogen-based economy and highlights the critical links between a Low CO2 Hydrogen transition strategy and other energy strategies. The results suggest that access to low-cost renewable electricity will be the most important factor in driving the production cost down, a decentralized onsite production will further reduce the losses and wind based renewable energy is having the lowest CO2 emission across the entire life cycle.*

Keywords: green hydrogen, renewables, low CO2 emission hydrogen, energy transition, sustainability, zero-emission economy

Introduction

Hydrogen is used today as a raw material predominantly, mainly in the chemical and oil industries, but if it is used as a fuel or for transport and storage of energy can help achieve the 2050 climate neutrality goal of the European Green Pact, being an important part of the solution, as long as hydrogen production takes place in a sustainable way, without climate impact through CO2 emissions.

Hydrogen can be produced by the process of coal gasification, a technology more than 100 years old, relatively cheap, but very polluting with significant emissions of CO, CO2, CH4 (also called "brown hydrogen"). The alternative of obtaining hydrogen by catalytic reforming with water vapor of methane gas ("gray hydrogen") has a lower impact on the environment, but even in this case CO2 emissions are significantly high not to allow the transition to an economy based on Hydrogen as an alternative to fossil fuels.

The development of "clean" technologies for hydrogen production by electrolysis ("green hydrogen") having as energy source electricity produced from renewable sources - solar, wind or biomass - opened the prospect of an energy transition to an economy based on hydrogen

DOI: 10.2478/picbe-2022-0106
© 2022 C. Hristescu, published by Sciendo.
This work is licensed under the Creative Commons Attribution 4.0 License.

consumption from clean sources instead of fossil fuels. Although the product of such technology is "clean", both the cost of production and the need for electricity from renewable sources remain the main obstacles in achieving the energy transition.

Hydrogen is considered an alternative energy source, especially for industrial processes that require high temperatures (IEA, The Future of Hydrogen, 2019), it can help decarbonize industrial processes and economic sectors where reducing carbon emissions is both urgent and difficult to be realized. At present, the amount of hydrogen used in the European Union remains limited and is largely produced from fossil fuels (European Commission, A sustainable pathway for the European Energy Transition – Hydrogen roadmap, 2020). The aim of the strategy is to decarbonize hydrogen production, which is possible by rapidly reducing the cost of renewable energy and accelerating technological developments, and to extend its use to sectors where it can replace fossil fuels.

World primary energy consumption was 14.281 million tons oil equivalent in 2018 (IEA, World Energy Statistics, 2021). More than 81.7% of it was primary energy sources from fossil fuels (coal, oil and natural gas), and the electricity consumed that year was generated in proportion to 74.5% from fossil fuels. The transition to a zero CO2 emissions economy requires both a change in the energy mix in the primary source and the decarbonization of electricity as a secondary energy source, doubled by the use of a new one, which allows both long-distance transport and high temperatures industrial processes, generated with low CO2 emissions.

Literature review

Hydrogen is not a primary source of energy but is an attractive alternative to transporting energy when hydrogen is separated from the rest of the elements. Hydrogen production methods are classified according to the primary energy used and the H2 generation method (Figure 1). According to primary energy, it is classified as follows: primary source of fossil fuels, nuclear energy and renewable energy.

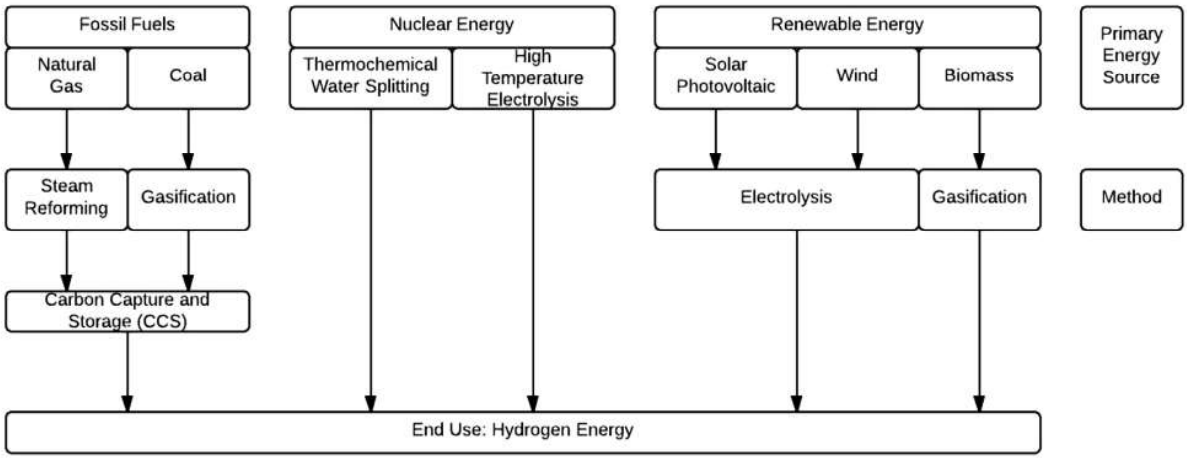


Figure 1. Hydrogen production methods (adapted from Rand DAJ, Dell RM, 2009)

"Hydrogen based on fossil fuels" refers to hydrogen produced by a variety of processes that use fossil fuels as raw material, in particular natural gas reformation or coal gasification. This type of hydrogen makes up the bulk of the hydrogen produced today. The challenges of generating hydrogen from fossil fuels from the respective significant CO2 emissions was a continuous preoccupation for scholars (Quarton, Christopher J. et all, 2020) as it can be managed with the help

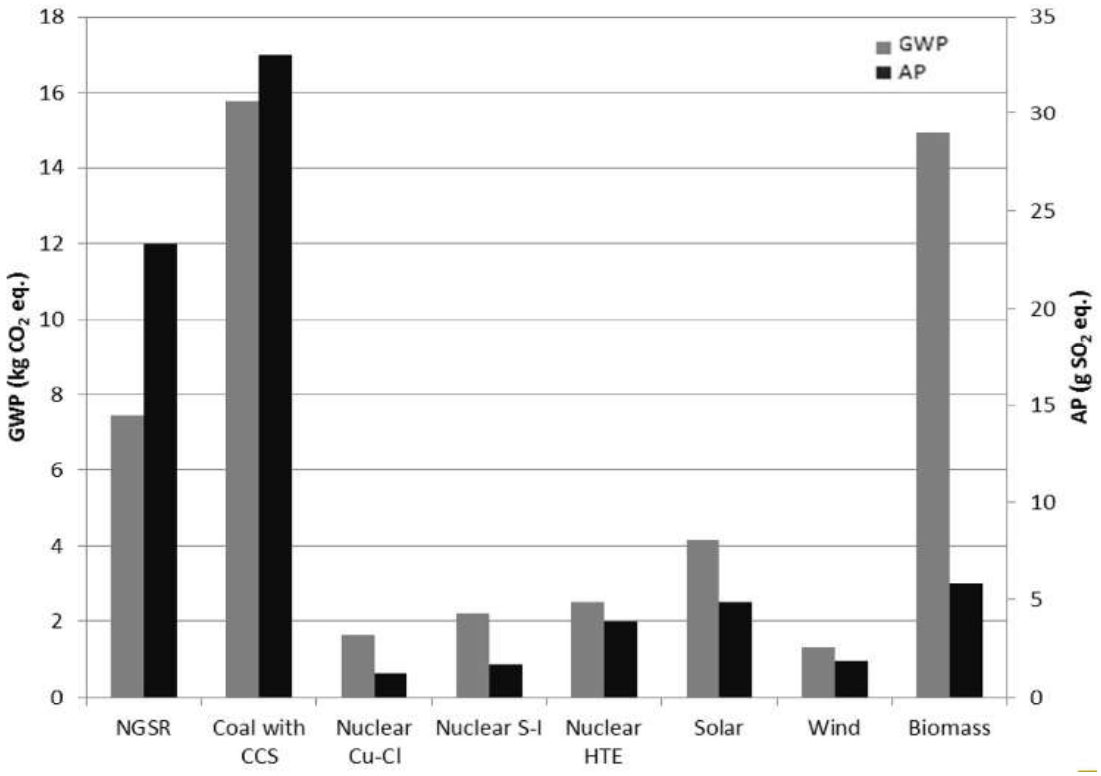
of Carbon Capture and Storage technologies (CCS). However, the economics of capturing the CO2 and the challenges of transport and storage limited the application of this technology. If the associated CO2 emission is captured or a different process to split H2 from CH4 – pyrolysis – is used, the greenhouse gas emissions from hydrogen production from fossil fuels with carbon capture or pyrolysis becomes lower than those from hydrogen from fossil fuels, but the variable efficiency of greenhouse gas capture must be considered (maximum 90%).

"Hydrogen based on electricity" refers to the hydrogen produced by the electrolysis of water (using electrolyzing process, where electricity is used to split H2 out of H2O), regardless of the source of electricity. Greenhouse gas emissions from the entire life cycle of hydrogen-based electricity production depend on how electricity is produced (J. Rissman et al., 2020).

The current estimated costs for hydrogen based on fossil fuels amount to around EUR 1.5/kg for the EU, being highly dependent on natural gas prices. However, the cost of hydrogen from alternative sources is depending on a different energy price – electricity.

Beside the economic aspect of hydrogen production, the environmental impact for the alternative low CO2 Hydrogen during the entire life cycle was assessed based on Global Warming Potential (GWP) and Acidification Potential (AP) (Ozbilen A. et al., 2011). GWP is determined in equivalent gCO2 and is determined by CO2 emission of the respective technology during the life cycle, while PA measures the equivalent gSO2 and reflects the changes in environment acidity of the lifetime use of the respective technology. Key takeaway of this research is the fact that renewable based hydrogen production has a different impact based on the source of electricity, wind or solar (Figure 2).

Figure 2.



Potential of the Global Warming Effect and Acidification potential for some of the H2 production methods

Source: Ozbilen A. et all, 2011.

Another method of analyzing hydrogen production technologies is to link the lifecycle analysis of the impact on health, the environment, and the availability of resources together with the standard cost of hydrogen production (Amjad Al-Qahtani et al, 2021). This analysis compares the alternatives of hydrogen production versus the most widespread method today, natural gas reforming (SMR), starting from the analysis of the maturity of alternative technologies (Thomas H. et al., 2018).

Methodology

As presented above, several mythologies of assessing hydrogen production technologies' environmental impact exist in the literature, most of them considering the multiple environment impact dimensions in their approaches. In order to be able to assess the suitability of different low CO2 emission Hydrogen production technologies for transition towards a 'zero emission' economy this paper is proposing the focus on one dimension for the environment impact: the life-cycle CO2 emission, one dimension for natural resources: electricity demand, and one dimension for social impact: production costs.

The aim of the research is to provide the basis to select the most sustainable low CO2, to identify the prerequisites for an energy transition towards a hydrogen-based economy and highlights the critical links between a Low CO2 Hydrogen transition strategy and other energy strategies.

The research hypothesis was defined as Green H2 production has different sustainability based on the source of green electricity and the transition toward low CO2 hydrogen production requires additional strategy for renewable energy generation development. For the selected Hydrogen production technologies, a case study methodology was used to model the investment and operation of Hydrogen production units, all of them generating 1 t/h Hydrogen, running 8400 hours per year.

For the environment dimension, the CO2 life-time assessment methodology was based on Standard emissions for processing according to International Sustainability & Carbon Certification 205 Greenhouse gas emissions standard.

The natural resource dimension, the electricity demand, the mass balance approach was used to determine out of each case study, the hourly electricity demand. Furthermore, using a projected scenario for low CO2 Hydrogen demand in Romania for 2030, 2040 and 2050 the overall demand in renewable capacity was determined, considering the specific green electricity of each hydrogen case. The research highlighted the freshwater demand,

Regarding the social impact dimension, the discounted free cash flow analysis was used for modeling the profitability of each selected Hydrogen production technologies (Remer, D., Nieto A., 1995). This methodology was used to determine production cost at which the investment is becoming profitable, making the transition from conventional hydrogen production technologies towards low CO2 emission ones. The main assumptions set were identical for each business case, considering a start of investment in 2023, 15 years operation, commercial operation date January 2026, 16% tax rate and 8% discount rate. As the production cost was determined to be highly dependent on the electricity price, the research methodology extended the case study with sensitivity analyses on power price and capital expenditures.

Results and discussions

The case study output in respect to mass balance, associated CO2 emission, demand for green power, water or methane or bio stock based liquefied petroleum gas (bio-LPG) overview is presented in Figure 3.

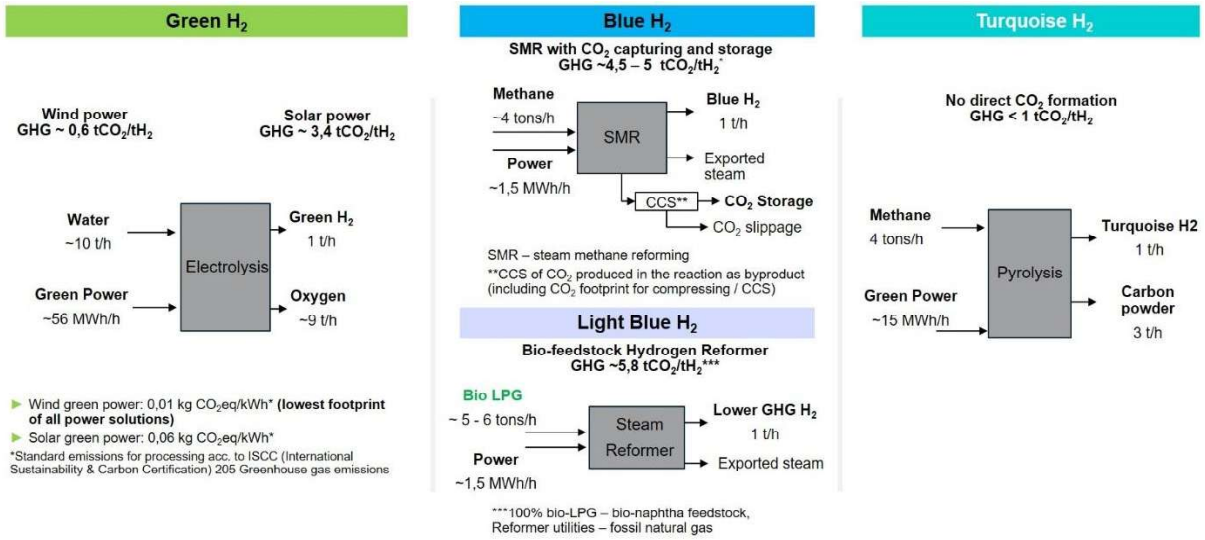


Figure 3. Relevant options to produce hydrogen with low CO2 emission and the corresponding mass balance

Source: Authors' own research results/contribution.

From the electricity consumption point of view, the demand of green power is the highest in case of Green H2, more than 3 times higher than for Turquoise H2 (methane pyrolysis), while the ratio of power demand between Green H2 and conventional Steam Methane reforming with Carbon Capture and Storage or bio-feedstock based steam reforming is more than 37 times higher in case of Green H2. The research considered the green power demand as a very sensitive aspect for the assessment of the sustainability of low CO2 Hydrogen production and further assessed the impact at the Romanian power generation level.

Regarding the main feedstock, splitting 1 t/h of H2 from fresh water using electrolysis requires 10 times higher mass of feedstock. In the case of conventional Hydrogen production with Carbon Capture and Storage, the ratio is 4 to 1. The same ratio is valid for Hydrogen production out of methane pyrolysis and slightly higher in case of using bio-feedstock. It is important to mention the fact that for the last mentioned technology there is CO2 emission generated in the Steam Reforming process, but as long as the source is bio-methane, the respective emission is not considered as an additional one.

The demand of 10 t/h of freshwater for green hydrogen production will require either access to respective volume or water treatment plant for desalination and treatment to meet the technical requirements for electrolysis. This finding is indicating that further analysis on freshwater impact is needed, or assessment of additional cost impact into the business case for desalination and water treatment capacities if limiting the freshwater consumption will be considered.

The combined green energy demand and CO2 emission was considered in order to select the technologies from the environment and natural resource dimensions. Using natural gas based hydrogen production (gray H2), the most used today' H2 technology as reference, the research

identified Green Hydrogen as a better solution than Carbon Capture and Storage of the current H2 production technology from natural gas. More than this, the Solar based Green H2 is having more than 3 times higher impact compared with Wind based one, making it the attractive Green H2 production solution. Hydrogen pyrolysis (turquoise H2) is the technology that has the lowest combined CO2 emission and power demand, even if the technology is still in early stage (Figure 4).

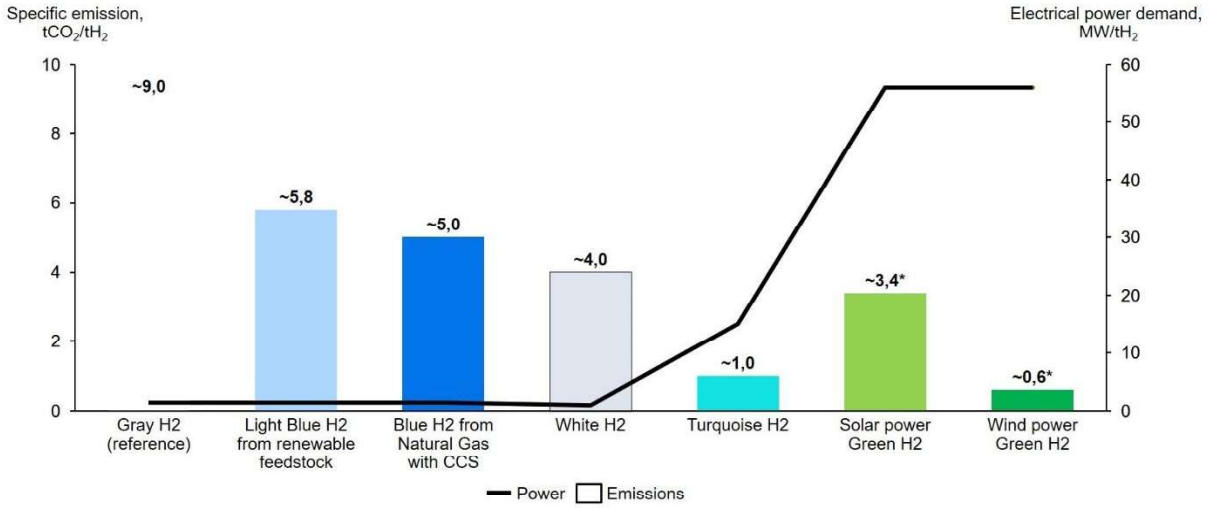


Figure 4. Overview of CO2 footprint and Power demand for selected H2 production technologies

Source: Authors' own research results/contribution.

Furthermore, the 56 MWh/h of green electricity necessary to produce 1 t/h H2 using electrolysis creates additional power demand compared to the baseline scenario, the one that H2 demand and production remains as per today, and the renewable capacity addition is determined by the transition of the power sector to low CO2 emission production capacities.

The capacity factor for a renewable power plant reflects the ratio between the electrical output of the respective renewable capacity over one year to the installed capacity (the maximum possible generation in one hour). It is strongly correlated with availability of the respective renewable resource for the area where the capacity is located. Considering the average capacity factor for wind, solar and hydro based power plants in Romania, each 1 MWh/h or green electricity will require 6.6 MW of photovoltaic installed capacity, 3.9 MW of wind installed capacity or 2.9 MW of hydro installed capacity.

The research generated a projection which considered that all today H2 demand will be covered from Green H2 until 2025, additional H2 demand will gradually develop because of the economic transition towards zero-emission. The existing Steam Methane Reforming Hydrogen production that covers the today demand in Romania cannot be replaced instantly with alternative low CO2 emission hydrogen production technologies, therefore a 11,000 t/year of hydrogen produced from Green H2 capacities was projected. The scenario was developed by considering transport and industrial processes (petrochemistry, metallurgy) as the first to switch and request more green hydrogen in order to meet their suitability targets. This is leading to considering 55,000 t/year of H2 demand in 2030, out of which 50,000 t/year from Green H2 and a small fraction of 5,000 t/year from low greenhouse gas technologies like bio-feedstock steam reforming. The

scenario was considering an accelerated transition starting with 2040, towards 600,000 t/year of H2 out of which 14,000 t/year from low greenhouse gas and 36,000 t/year from steam methane reforming with carbon capture and storage. Going further in time, for a significant transition on the most energy-intensive economic sectors of Romanian economy, the projected Hydrogen demand is 2,400,000 t/years out of which the gross is produced with Green H2 technology – 2,200,000 t/year – no additional production form low greenhouse gas or steam methane reforming with carbon capture and storage capacities, but the maturity of Turquoise H2 technology was considered, leading to 100,000 t/year H2 produce from natural gas pyrolysis.

Using the generated H2 demand projection and considering the capacity factor for each renewable technology installed in Romania, the H2 projection translates into the need to install 1195 MW of photovoltaic power plants just to meet the expected 182 MWh/h green power demand for producing 11,000 t/year H2 (Figure 5). This represents 31% from the expected additional 3700 MW of photovoltaic power plants promoted investments in the Romanian 2021-2030 Integrated National Energy and Climate Plan. (INECP, 2022)

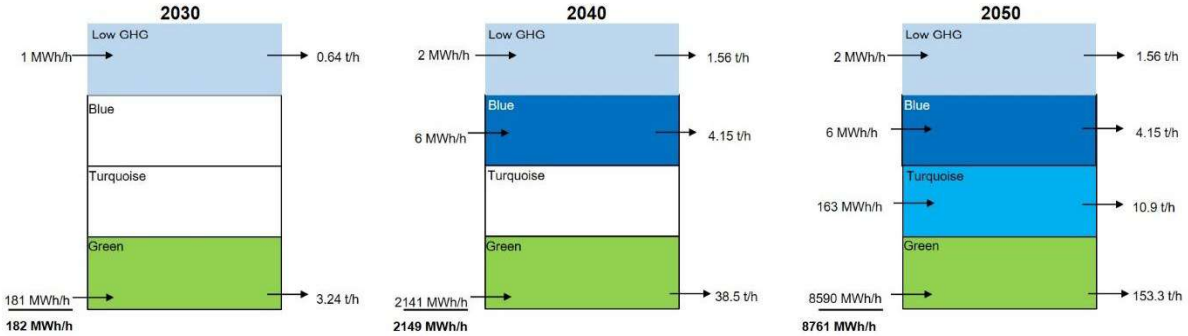


Figure 5. Renewable power demand for H2 production

Source: Authors' own research results/contribution.

The 3rd dimension analysis on the production costs compares the same low CO2 hydrogen technologies using the current Steam Methane Reforming (Gray H2) as reference. The breakeven cost of production for this case is 2,3 EUR/kg, while for Green H2 is 6,6 EUR/kg, 4,2 EUR/kg for Blue H2 (Steam Methane Reforming with Carbon Capture and Storage), 3,7 EUR/kg for Turquoise H2 (methane pyrolysis) and ultimately, 2,6 EUR/kg for Light Blue H2 (bio-feedstock low greenhouse gas steam reform).

The discounted cash flow analysis was considering 80 EUR/MWh for the electricity price and the break-even costs were determined at the production facility in order to be able to compare with the reference case (steam methane reforming on consumption point). If the loading facility is added, additional 0,8 EUR/MWh has to be considered, beside the transport and delivery to the consumption points.

At the electricity price from the base scenario, there was no H2 technology ready to be deployed today and the gap to the reference case (Gray H2) was the minimum for the bio-feedstock technology, the one with the most limited supply. The biggest gap was in the case of the Green H2, a technology that recorded a significant advance and is ready to be deployed today, as long as there is green energy available.

However, the sensitivity analysis on the green power price pointed out a 34% increase in the breakeven price in case of 50% electricity price increase. As the green power demand is a linear

parameter of the model the sensitivity analysis is linear, with significant deviations due to green electricity price, as it can be seen in Figure 6. The rate of return sensitivity was computed for 11%, as the model is considering in the reference case 8% rate of return.

A further analysis on capital expenditures was performed in order to identify the necessary technology cost reductions and subsidies that will make Green H2 competitive with Gray H2, the reference case. Starting from the base case of the model, a 0,6 EUR/kg cost reduction can be obtained in case of 30% non-refundable financing. Scale-up of full supply chain and industrialization of fuel cell, hydrogen tank manufacturing and economy of scale in hydrogen capacity design and construction was estimated to reduce the total investment costs by another 50%, a case that will take out another 0,55 EUR/kg cost reduction. Combining both technology cost reduction and non-refundable funds the breakeven production cost for Green H2 is reduced to 4,95 EUR/kg versus 2,3 EUR/kg for the reference case of Gray H2. Adding the loading and transportation cost it can be more than double compared with an on-site steam methane reforming production unit. While the technology development will reduce the investment costs, lowering the production cost, the technical challenges of transporting the hydrogen will be required for on site, de-centralized Green H2 production.

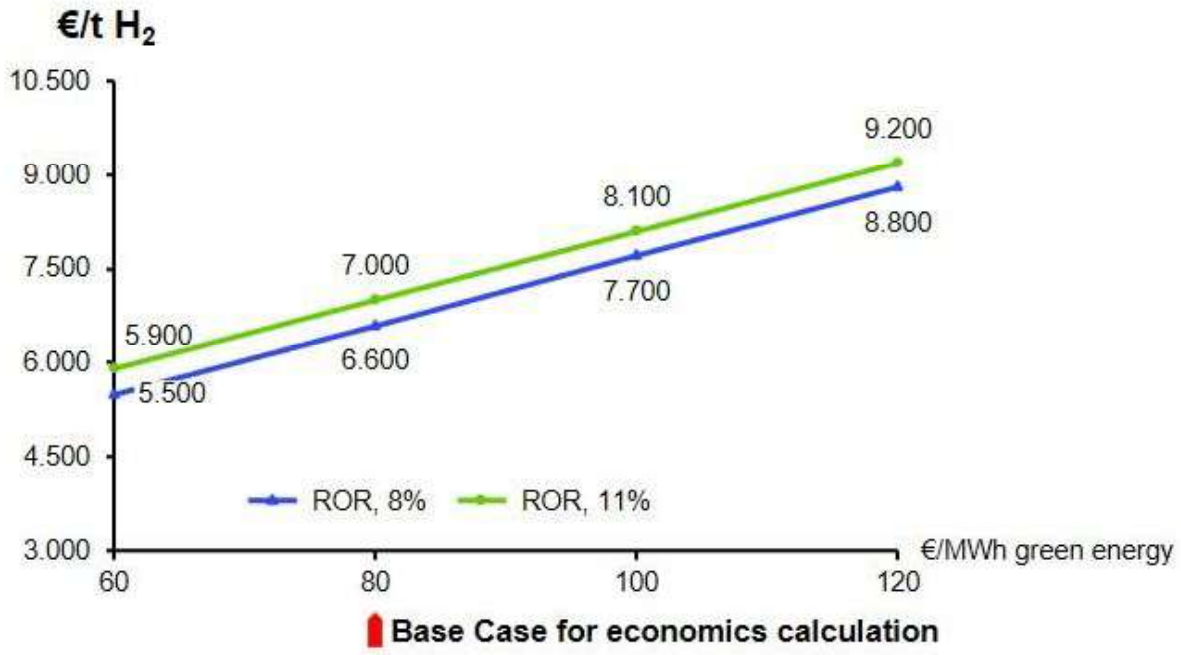


Figure 6. Green energy price sensitivity for Green H2 production

Source: Authors' own research results/contribution.

Conclusion

The hypothesis that suitability of Green H2 is not equal was demonstrated by the fact that even if the green power demand is the same, the associated life cycle CO2 emission of 1 MWh produced by a photovoltaic power plant is approx. 6 times higher than 1 MWh produced from a wind power plant.

The second research hypothesis that transition toward low CO2 hydrogen production requires additional strategy for renewable energy generation development was demonstrated by the expected additional renewable capacity needed to fulfill the green electricity demand in a low CO2

emission hydrogen demand projection. The existing Romanian Energy Strategy (INECP, 2022) is considering investments of around 2,300 MW of wind power plants and 3,700 MW of photovoltaic power plants while at the same time 1,100 MW of gas fired power plants compensate for the reduction of 700 MW of coal power plants. The demand for green electricity for H2 was projected to be 2,149 MWh/h by 2040, while the Integrated National Energy and Climate Plan increase is expected to reach 1,153 MWh/h by 2030. The additional 1,000 MWh/h that must be invested until 2040 is not considered under any current energy sector strategy and might render the investments in low CO2 hydrogen production capacities useless if they cannot use renewable generated power.

The results suggest that access to low-cost renewable electricity will be the most important factor in driving the production cost down, a decentralized onsite production will further reduce the losses and wind based renewable energy is having the lowest CO2 emission across the entire life cycle

References

Ahmet Ozbilen*, Ibrahim Dincer, Marc A. Rosen (2012). Life cycle assessment of hydrogen production via thermochemical water splitting using multi-step Cu-Cl cycles*, Journal of Cleaner Production*

Amjad Al-Qahtani, Brett Parkinson, Klaus Hellgardt, Nilay Shah, Gonzalo Guillen-Gosalbez (2021). Uncovering the true cost of hydrogen production routes using life cycle monetization, *Applied Energy*

Donald S. Remer, Armando P. Nieto H. (1995). A compendium and comparison of 25 project evaluation techniques., *Int. J of Production Economics*

European Commission (2020). A sustainable pathway for the European Energy Transition – Hydrogen roadmap

International Energy Agency (June 2019). The Future of Hydrogen

International Energy Agency (2021). World Energy Statistics

Quarton, Christopher J., Sheila Samsatli (2021). The value of hydrogen and carbon capture, storage and utilization in decarbonizing energy: Insights from integrated value chain optimization, *Applied Energy*

Rissman J., Bataille C., Masanet E., Aden N., Morrow W., Zhou N. (2020). Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070, *Applied Energy*

The 2021-2030 Integrated National Energy and Climate Plan-INECP. (n.d.) (2022). Retrieved March 7, https://ec.europa.eu/energy/sites/ener/files/documents/ro_final_necp_main_en.pdf

Thomas H, Armstrong F, Brandon N, David B, Barron A, Durrant J, et al. (2018). Options for producing low-carbon hydrogen at scale