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Transition toward Sustainable Hydrogen Based Economy. Scenario Analysis on Alternative Paths

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Abstract

Hydrogen is considered an alternative energy source that can help decarbonize industrial processes and economic sectors that use it (fertilizers, construction materials, petrochemicals) where reducing carbon emissions is both urgent and difficult to realize. At present, the amount of hydrogen used in the European Union remains limited and is largely produced from fossil fuels. The aim of the European Union strategy is to decarbonize hydrogen production and extend its use to sectors where it can replace fossil fuels. The current production cost for hydrogen based on fossil fuels, considering the Steam Methane Reforming (SMR) process, is highly dependent on natural gas prices and CO_2 cost. However, the cost of hydrogen from alternative sources depends on a different energy price – electricity. This article analyzes the production cost for different technologies and the associated CO_2 emission with the aim to identify the sustainable one that can provide the transition towards Sustainable Hydrogen based economy. A scenario-based analysis of the main costs drivers, evaluation of the CO_2 emission along the value chain and the impact on the relevant economic sectors for the low CO_2 Hydrogen production was performed. The goal of the article is to propose a basis for selecting the most sustainable technology, the prerequisites for an energy transition towards a hydrogen-based economy, and to investigate the critical links between a low CO_2 Hydrogen transition strategy and other energy strategies. The findings indicates that low-cost renewable electricity is one of the most important pre-requisite for facilitating the transition, together with a coherent long-term CO_2 emission policy.

Keywords: green hydrogen, renewables, low CO_2 emission hydrogen, energy transition, sustainability, zero-emission economy.

JEL Classification: Q42 Q56.

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1. Introduction

Hydrogen is used today predominantly as a raw material, mainly in the chemical and oil industries, but if it is used as a fuel or for transport and storage of energy, it 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 CO_2 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, CO_2, CH_4 (also called "brown hydrogen"). The alternative of obtaining hydrogen by catalytic reforming with water vapor of methane gas ("grey hydrogen") has a lower impact on the environment, but even in this case CO_2 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 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. (Spiers et al., 2018)

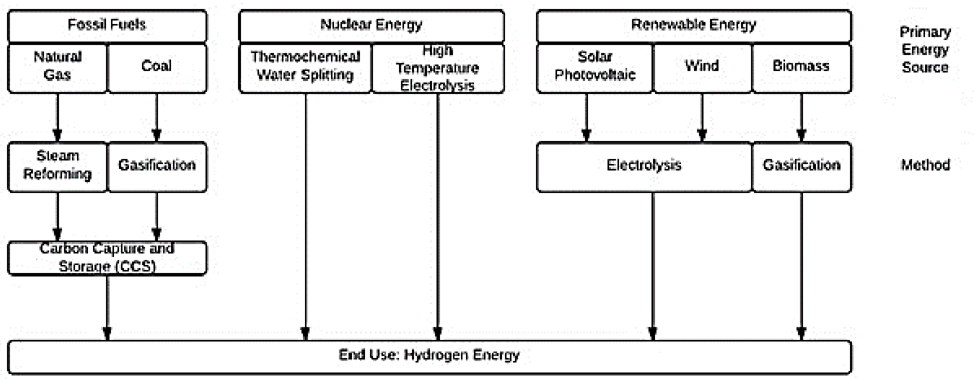
Hydrogen is considered an alternative energy source, especially for industrial processes that require high temperatures (IEA, 2019), it can help decarbonize industrial processes and economic sectors where reducing carbon emissions is both urgent and difficult to be realized. At present, the amount of hydrogen used in the European Union remains limited and is largely produced from fossil fuels (European Commission, 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 of oil equivalent in 2018 (IEA, 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 of 74.5% from fossil fuels. The transition to a zero CO_2 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 CO_2 emissions.

2. Problem Statement

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 H_2 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



Source: adapted from Rand et al., 2009.

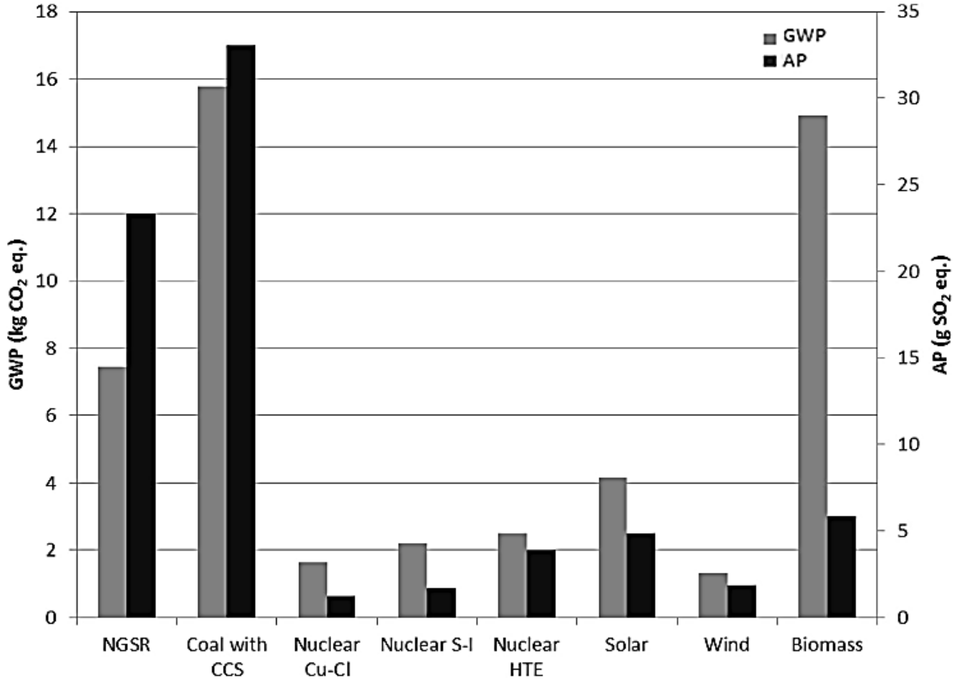
"Hydrogen based on fossil fuels" refers to hydrogen produced by a variety of processes that use fossil fuels as raw material, in particular natural gas reformation or coal gasification. This type of hydrogen constitutes the bulk of the hydrogen produced today. The challenges of generating hydrogen from fossil fuels from the respective significant CO_2 emissions were a continuous preoccupation of scholars (Quarton et al., 2020) as they can be managed with the help of Carbon Capture and Storage technologies (CCS). However, the economics of capturing CO_2 and the challenges of transport and storage limited the application of this technology. If the associated CO_2 emission is captured (Soltani et al., 2014) or a different process to split H_2 from CH_4 – pyrolysis – is used (Dagle et al., 2017), 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 an electrolyzing process, where electricity is used to split H_2 out of H_2O), 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 (Rissman et al., 2020).

The current Levelized Cost of Hydrogen (LCOH) for hydrogen based on fossil fuels is estimated to be around EUR 1.5 / kg for the EU, considering the Steam Methane Reforming (SMR) process being highly dependent on natural gas prices (Parkinson et al., 2018) and factoring the USD inflation rate and USD/EUR exchange rate in order to adjust the 2019 USD computed price of 1.35 (Al-Qahtani et al., 2021) and CO_2 cost adjustment. The range of the SMR based Hydrogen production cost without CO_2 Carbon Capture and Utilization/Storage is presented in several other research as being from 1.03 to 1.92 USD/kg, with natural gas price considered at 3.25 to 10.32 USD/GJ. However, the cost of hydrogen from alternative sources is depending on a different energy price – electricity.

In addition to the economic aspect of hydrogen production, the environment impact of the alternative low CO_2 Hydrogen during the entire life cycle was assessed based on Global Warning Potential (GWP) and Acidification Potential (AP) (Ozbilen et al., 2012). GWP is determined in equivalent gCO_2 and by CO_2 emissions of the respective technology during the life cycle, while PA measures the equivalent gSO_2 and reflects the changes in environment acidity of the lifetime use of the respective technology. The 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, wind-based hydrogen production having the lowest values (Figure 2). In case of solar based renewable electricity hydrogen production, both indicators are higher than for the hydrogen production based on thermochemical water split using nuclear energy (Ozbilen et al., 2013), indicating that further analysis on nuclear based hydrogen production is necessary.

Figure 2. Potential of the Global Warming Effect and Acidification potential for some of the H_2 production methods



Source: Ozbilen et al, 2012.

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 (Al-Qahtani et al., 2021). This analysis compares the alternatives to hydrogen production versus the most widespread method today, natural gas reforming (SMR), starting from the analysis of the maturity of alternative technologies (Thomas et al., 2018).

3. Research Questions / Aims of the Research

As presented above, several methods of assessing the environmental impact of hydrogen production technologies exist in the literature, most of them considering the multiple environmental impact dimensions in their approaches. In order to be able to assess the suitability of different low CO_2 emission Hydrogen production technologies for transition toward a 'zero emission' economy, this paper proposes the focus on one dimension for the environment impact: the life-cycle CO_2 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 CO_2, to identify the prerequisites for an energy transition towards a hydrogen-based economy, and to highlight the critical links between a Low CO_2 Hydrogen transition strategy and other energy strategies.

The research hypotheses were defined as: Green H_2 production has different sustainability based on the source of green electricity and the transition toward low CO_2 hydrogen production requires an 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 of Hydrogen, running 8400 hours per year.

4. Research Methods

For the environmental dimension, the CO_2 life-time assessment methodology was based on Standard emissions for processing according to the International Sustainability & Carbon Certification 205 Greenhouse gas emissions standard.

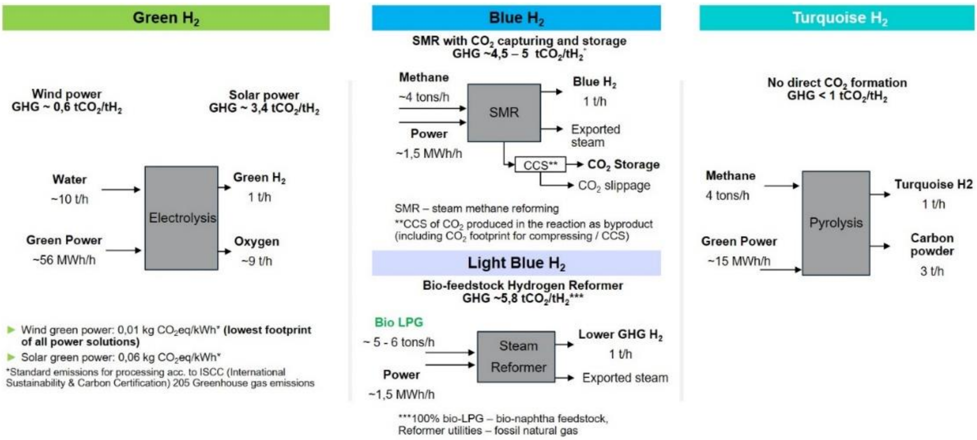
The natural resource dimension, the electricity demand, the mass balance approach was used to determine out of each case study, the hourly electricity demand. Furthermore, using a projected scenario for low CO_2 Hydrogen demand in Romania for 2030, 2040 and 2050 the overall demand in renewable capacity was determined, considering the specific green electricity of each hydrogen case. The research highlighted the need for further analysis of the freshwater demand impact and mitigation methods.

Regarding the social impact dimension, the discounted free cash flow analysis was used for modelling the profitability of each selected Hydrogen production technologies (Remer et al., 1995). This methodology was used to determine the production cost at which the investment is becoming profitable, making the transition from conventional hydrogen production technologies toward low CO_2 emission ones. The main assumptions set was 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 the power price and capital expenditures.

5. Findings

The case study output with respect to mass balance, associated CO_2 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 CO_2 emission and the corresponding mass balance



Source: Authors' own research results/contribution.

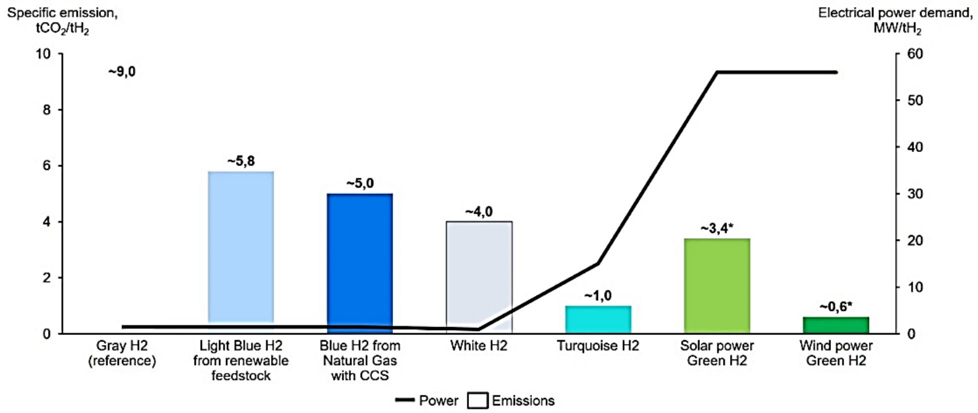
From the electricity consumption point of view, the demand for green power is the highest in the case of Green H_2, more than 3 times higher than for Turquoise H_2 (methane pyrolysis), while the ratio of power demand between Green H_2 and conventional Steam Methane reforming with Carbon Capture and Storage or bio-feedstock based steam reforming is more than 37 times higher in case of Green H_2. The research considered the green power demand as a very sensitive aspect for the assessment of the sustainability of low CO_2 Hydrogen production and further assessed the impact at the Romanian power generation level.

Regarding the main feedstock, splitting 1 t/h of H_2 from fresh water using electrolysis requires a 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 latest mentioned technology there is CO_2 emission generated in the Steam Reforming process, but as long as the source is bio-methane, the respective emissions are not considered as additional ones.

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

The combined green energy demand and CO_2 emission were considered in order to select the technologies from the environment and natural resource dimensions. Using natural gas-based hydrogen production (grey H_2), the most used today' H_2 technology as reference, the research identified Green Hydrogen as better solution than Carbon Capture and Storage of the current H_2 production technology from natural gas. More than this, the Solar-based Green H_2 is more having more than 3 times higher impact compared with Wind-based one, making it the attractive Green H_2 production solution. Hydrogen pyrolysis (turquoise H_2) is the technology with the lowest combined CO_2 emission and power demand, even if the technology is still in its early stage (Figure 4).

Figure 4. Overview of CO_2 footprint and Power demand for selected H_2 production technologies



Source: Authors' own research results/contribution.

It is important to highlight that the same ranking is observed between solar and wind-based hydrogen production, as per the research performed using CML 2001 methodology, developed by Institute of Environmental Sciences, Leiden University, and The Netherlands, to assess the environmental impact of selected hydrogen production methods. (Ozbilen et al., 2013). The Methane Pyrolysis technology has the lowest CO_2 emission from all gassed based hydrogen production ones, having the carbon black as a by-product. (Amin et al., 2011)

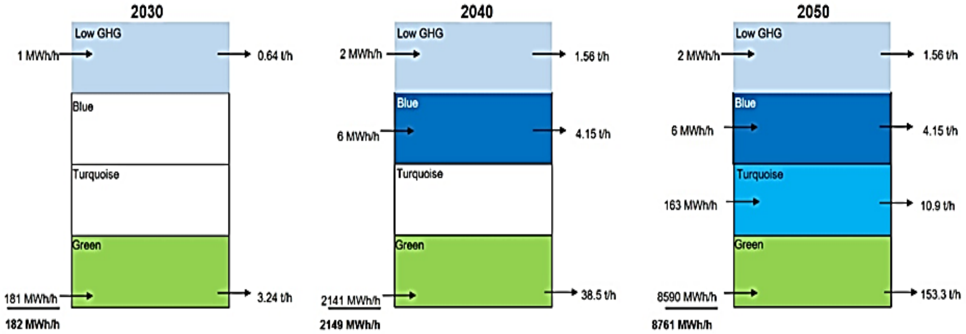
Furthermore, the 56 MWh/h of green electricity necessary to produce 1 t/h H_2 using electrolysis creates additional power demand compared to the baseline scenario, the one that H2 demand and production remains as per today, and the renewable capacity addition is determined by the transition of the power sector to low CO_2 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 the 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 H_2 demand will be covered from Green H_2 until 2025, while additional H_2 demand will gradually develop because of economy transition towards zero-emission. The exiting Steam Methane Reforming Hydrogen production that covers the today demand in Romania cannot be replaced instantly with alternative low CO_2 emission hydrogen production technologies, therefore a 11,000 t/year of hydrogen produced from Green H_2 capacities was projected. The scenario was developed by considering transport and industrial processes (petrochemistry and 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 H_2 demand in 2030, out of which 50,000 t/year from Green H_2 and a small fraction of 5,000 t/year from low greenhouse gas technologies such as bio-feedstock steam reforming. The scenario was considering an accelerated transition starting with 2040, towards 600,000 t/year of H_2 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 in the most energy-intensive economic sectors of the Romanian economy, the projected Hydrogen demand is 2,400,000 t/years out of which the gross is produced with Green H_2 technology – 2,200,000 t/year – no additional production from low greenhouse gas or steam methane reforming with carbon capture and storage capacities, but the maturity of Turquoise H_2 technology was considered, leading to 100,000 t/year H_2 produce from natural gas pyrolysis.

Using the generated H_2 demand projection and considering the capacity factor for each renewable technology installed in Romania, the H_2 projection translates into the needs 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 H_2 (Figure 5). This represents 31% of 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 H_2 production



Source: Authors' own research results/contribution.

The 3rd dimension analysis on the production costs comparing the same low-CO_2 hydrogen technologies using the current Steam Methane Reforming (Grey H_2) 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 H_2 (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 H_2 (bio-feedstock low greenhouse gas steam reform).

The discounted cash flow analysis considered 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 reference case (steam methane reforming on consumption point). If the loading facility is added, an additional 0,8 EUR/MWh must be considered, in addition to the transport and delivery to the consumption points.

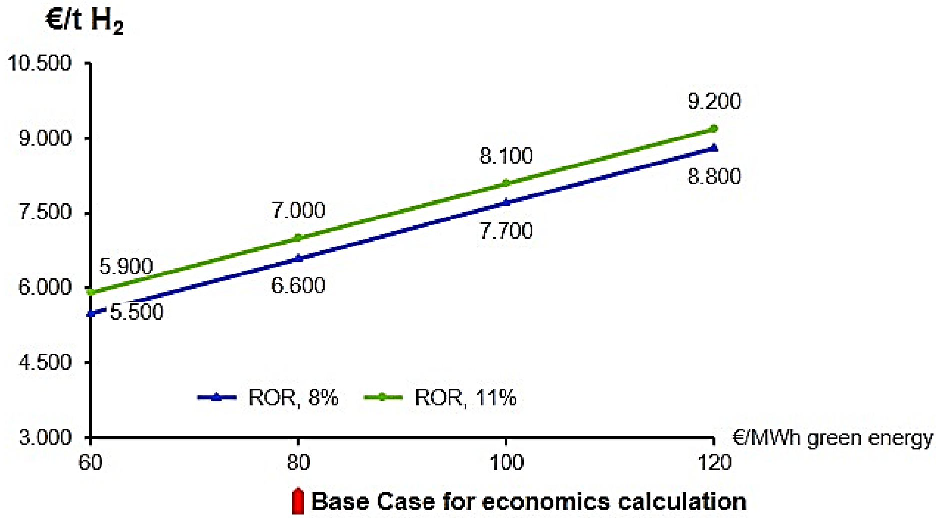
At the electricity price of the base scenario, there was no H_2 technology ready to be deployed today and the gap to the reference case (Grey H_2) was the minimum for the bio-feedstock technology, the one with the most limited supply. The biggest gap was in the case of the Green H_2, a technology that 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, while other researchers are considering a weighted average cost of capital of 10%.

A further analysis on capital expenditures was performed in order to identify the necessary technology cost reductions and subsidies that will make Green H_2 competitive with Grey H_2, the reference case. Starting from the base case of the model, a 0,6 EUR/kg cost reduction can be obtained in the 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%, 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 H_2 is reduced to 4,95 EUR/kg versus 2,3 EUR/kg for the reference case of Grey H_2. 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 require for on-site, de-centralized Green H_2 production.

Figure 6. Green energy price sensitivity for Green H2 production



Source: Authors' own research results/contribution.

6. Conclusions

The hypothesis that suitability of Green H_2 is not equal was demonstrated by the fact that even if the green power demand is the same, the associated life cycle CO_2 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 the transition toward low CO_2 hydrogen production requires additional strategy for renewable energy generation development was demonstrated by the expected additional renewable capacity needed to fulfil the green electricity demand in a low CO_2 emission hydrogen demand projection. The existing Romanian Energy Strategy (INECP, 2022) considers 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 plant compensates for the reduction of 700 MW of coal power plants. The demand for green electricity for H_2 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 CO_2 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 will have the lowest CO_2 emission across the entire life cycle.

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