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Dissertation

Blue hydrogen from natural gas: Economic, technological and environmental aspects

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I. Abstract

Blue hydrogen can use as renewable energy fuel in future. Imperative synergies exist between hydrogen and renewable vitality. Hydrogen can increment renewable power advertise development possibilities significantly and broaden the reach of renewable arrangements, such as in industry.

The development of blue hydrogen as a transition solution moreover faces challenges in terms of generation upscaling and supply logistics. Improvement of carbon capture, utilisation and storage has lagged compared to the goals set within the final decade. Extra costs posture a challenge, as well as the economies of scale that support huge projects. Synergies may exist between green and blue hydrogen deployment, for illustration economies of scale in hydrogen utilisation or hydrogen logistics.

Blue hydrogen will be needed in the five to ten years' outlook, despite its greenhouse gas emissions, because it will simply not be possible to meet H2 demand purely with green hydrogen. Thus, Blue Hydrogen appears the only viable production solution for Hydrogen in the closer future.

A. Introduction

Energy is an important component of living and economic activity in all countries. It is a good thing to support economic development and social well-being and should therefore be natural and affordable, while at the same time its use and production should be in line with the standards of sustainable development.

In the past years, many analysts and researchers have attempted to quantify societal costs of pollution and other externalities mainly related to fossil fuel combustion. In addition, some regulatory bodies have attempted to incorporate externality costs into investment decisions. In general, efforts to incorporate environmental and pollution externalities have been confined mainly to fields associated with regulated sectors and parameters of the existing energy systems (mainly electricity and natural gas systems).

However, the energy is directly related to climate change after 60% of global greenhouse gas emissions come from activities related to its production and consumption. This is mainly due to fossil fuels, which until now are the main source of energy worldwide. Renewable energy sources, which come from various physical processes such as wind and sun, they are considered an instrument that will solve the ecological problems faced by the Earth. In their exploitation was very expensive and started as an experimental application.

In addition, and with their cost being continually decreasing over the last twenty years, the promotion is a one-way street. However, there is still room for exploitation. The share of renewable energy sources as a whole also appears in the figure of global energy consumption is small, though steadily increasing.

As Europe starts to emerge from the COVID-19 crisis and the question of how to re-start ailing economies becomes more urgent, one solution that has been proposed has been investment in technology to encourage the energy transition. Within this context the gas industry faces an existential issue, as it needs to find a role within an energy economy that is set to decarbonise rapidly in order for the EU to meet its net zero emissions target by 2050 (Dickel, 2020).

One solution that has been proposed both at an EU-level, within some countries is the development of hydrogen as an alternative method for supplying gas. Hydrogen is often viewed as the fuel of the future. Scientists initially predicted it will be clean, renewable and efficient. Making it work, though, might be a problem. Some of the current technologies, including a process known as “blue” hydrogen, is examines for an energy fuel in future from all aspects, environmental, economic and technological (Kindy, 2021).

In this study, the main object will be the blue hydrogen from natural gas and the perspective to use as an energy source in future. It will be investigated the advantages or / and disadvantages of exploitation as energy in order to examine if it is a beneficial renewable energy perspective in the environment, in technology, but also the global economy.

Chapter 1. Blue hydrogen

Hydrogen is the most common element in the universe (approximately 75% of matter is hydrogen). Also, molecular hydrogen (H_2) is considered the future fuel, which produces water (H_2O) where it is oxidized, not carbon dioxide (CO_2) as with coal and hydrocarbon fuels. In the economy of hydrogen, the majority of energy needs will be met by H_2, with a current to cover the rest. An inhibitory factor to a hydrogen economy is the availability of H_2 where they are freely available in nature only to a negligible extent (Boretti, 2021).

Thus, it is required to produce from raw materials of hydrogen-containing molecules, such as methane (CH_4) without direct CO_2 emission or H_2O. In addition, not all forms of hydrogen have the same financial and environmental costs. While the current H_2 is mostly grey, from steam reforming of CH_4 with direct CO_2 emission, there are different pathways, that are recommended to produce H_2 more environmentally friendly. Grey hydrogen has a direct CO_2 emission of 8 kg CO_2 per kg H_2, economic cost 1.25$ per H_2 kg at 3$ per thousand cubic feet of gas and minimum energy cost 62 kJ / mol H_2. At the same time, blue hydrogen, through carbon capture and storage (CCS), has no direct CO_2 emissions, however, have the additional costs of capturing and CO_2 storage (Boretti, 2020).

It is worth noting that the oil and gas industry is one of the biggest supporters of blue hydrogen because it offers them a path towards clean fuels while drawing on their existing gas production, transport and storage facilities. It is argued for a large percentage of the scientific community that blue hydrogen is essential to build up a market for what will ultimately be green hydrogen. On the other hand, some other views express doubts about the beneficial exploitation of blue hydrogen in climate. The reason is that the problem of exploitation of blue hydrogen is that it depends on carbon capture storage (CCS) and natural gas (Renssen, 2020).

Carbon capture storage is the process in which CO_2 is captured, transported to empty gas field via pipelines or boats and stored indefinitely underground and is essential for blue hydrogen.

A challenge is clarity on the liabilities for long-term storage of carbon dioxide underground, however multiple studies indicate no potential threats. Scalability is an important parameter for carbon capture storage, since the feasibility increases with larger volumes, therefore requiring clusters of carbon dioxide sources. Although carbon capture storage has small operation costs, it doesn't happen the same with fixes and investments, which demand many expenditures (Cappellen, et al., 2018).

First, commercially viable carbon capture storage doesn't correspond to reality yet, but it exists as an ambitious plan in the future. Secondly, carbon capture doesn't correspond to full performance and can't be characterized efficiently at a percentage of 100%. Simultaneously, there is great anxiety about the climate impact of upstream methane leakage (Renssen, 2020).

The exploitation of blue hydrogen leads to a dilemma as to what the political strategies of Europe's leaders directed. Their focus is on reducing carbon dioxide or renewable energy sources. Blue hydrogen leads to a debate regarding if a policy focused on CO_2 reduction or renewables increase should be set in.

People know that a transition towards renewables is necessary for the security of the environment, so in the upcoming decades, there is a need for a reliance on finite resources to mitigate climate change. Therefore, a political strategy on significant reduction levels of carbon dioxide in the atmosphere is required and must succeed within the available budget. Simultaneously, a parallel strategy is necessary to determine the route of renewables and how these can be integrated at a system level, in such a way that from 2030 and after renewables will replace the finite sources.

Blue hydrogen is not relying on renewable sources but does offer the potential of a large, relatively economic efficient reduction measure. With a point to a cleaner environment and a drastic reduction in carbon dioxide emissions, blue hydrogen offers an alternative to achieving this goal (Cappellen, et al., 2018).

1.1. Physical and Chemical Properties of Blue Hydrogen

Of course, blue hydrogen has the same physical and chemical properties as it produced for hydrogen via a technology process.

Hydrogen is a chemical element with the chemical symbol H and atomic number 1. The hydrogen atom, symbol H, is formed by a nucleus with one unit of positive charge and one electron. It’s one of the main compounds of water and of all organic matter, and it’s widely spread not only in the earth, but also in the entire universe. There are three hydrogen isotopes: protium, mass 1, found in more than 99,985% of the natural element; deuterium, mass 2, found in nature in 0.015% approximately, and tritium, mass 3, which appears in small quantities in nature, but can be artificially produced by various nuclear reactions (Lenntech, xx).

Other chemical properties are that reacts with the oxides and chlorides of many metals, like silver or copper to produce free metals. It reduces some salts to their metallic state, such as nitrates and sodium. It reacts with a number of elements, metals and non-metals, to produce hydrides. Atomic hydrogen reacts with oxygen to produce hydrogen peroxide, H_2O_2.

The physical properties of hydrogen are that is the lightest element on the periodic table. In general, hydrogen is diatomic, but molecular hydrogen dissociates into free atoms at high temperatures. Hydrogen atomic weight is 1,00797 g/mol. As a gas it has a density of 0.071 g/l at 0ºC and 1 atm. Its relative density, compared with that of the air, is 0.0695. Hydrogen is the most flammable of all the known substances. Hydrogen is slightly more soluble in organic solvents than in water. Many metals absorb hydrogen.

Other physical properties are that is a colourless, odourless, tasteless, non-toxic, non-metallic, highly combustible diatomic gas with the molecular formula H_2, at standard temperature and pressure. Hydrogen can be burned in internal combustion engines. At normal temperature hydrogen is a not very reactive substance, unless it has been activated by an appropriate catalyser. Also, hydrogen is very reactive at high temperatures.

Hydrogen has a significant role in the environment. It forms a percentage 0.15 % of the earth's crust, as it is the major constituent of water. In the atmosphere exist 0.5 ppm of hydrogen H_2 and variable proportions as water vapour. Hydrogen is also a significant component of biomass, constituting the percentage of 14% by weight (Lenntech, xx).

On figure 1, it depicts the blue hydrogen as a diatomic element.

Figure 1: The blue hydrogen (Feblowitz, 2020).

1.2. Production of Blue Hydrogen

Hydrogen can be produced from a variety of feedstocks, including electricity and water, biomass and industrial processes. The most usual method of hydrogen production in industrial sector is steam methane reforming (SMR), which includes a thermochemical reaction where natural gas or a refined petroleum product is combined with steam to release the bonded hydrogen. (Duncanson et al., 2021).

Almost the percentage of 98% of current hydrogen production is from the reformation of methane or the gasification of coal or similar materials of fossil-fuel origin, such as ashphaltene. On the other hand, only about at the percentage of 1% of hydrogen production from fossil fuels includes carbon capture and storage (CCS). At the same time, almost at the percentage of 1.9% hydrogen is produced as a by-product of chlorine and caustic soda production (zapantis, 2021).

Within the different choices for hydrogen production, a significant effort in Canada is being directed to the production of blue hydrogen. Specifically, the effort is to developing low-to-neutral carbon intensity “blue” hydrogen using SMR paired with carbon capture, utilization and storage (CCUS) to prevent the carbon dioxide by product from being emitted to the atmosphere. This result can be happened with the addition of a carbon capture loop to existing Canadian SMR operations and by exploiting oil combining with gas expertise and the geological conditions of the prairie provinces (Duncanson et al., 2021).

Successful blue hydrogen developments make essential plentiful sources of natural gas and water for feedstock and access to facilities or reservoirs to store or process the captured carbon dioxide. The process of production of blue hydrogen is from fossil fuels with carbon capture and storage which can be beneficial to the Reduce dimension of the CCE by displacing the use of unabated fossil fuels in industrial and energy applications. Hydrogen produced from biomass with carbon capture storage can also contribute to the removal dimension of the CCE as it has negative life-cycle emissions (zapantis, 2021).

Blue Hydrogen is a hybrid concept targeting to decarbonize today hydrogen production. The idea of the production of blue hydrogen is a combination of a grey hydrogen plant with a facility of carbon capture. Turning a reforming reaction of natural gas into a neutral process by reducing to zero carbon dioxide emissions.

The process of hydrogen production in the grey and blue hydrogen doesn’t differ, except for the blue the carbon dioxide emitted is immediately captured in the reaction to be later stored underground. Once trapped underground, in empty gas or oil fields or caverns, the carbon dioxide is sequestrated and has no negative affect on global warming, while the hydrogen produced can be used as an energy fuel (2B1st Consulting, 2020).

On figure 2, it depicts the production of blue hydrogen (Barnes, 2021).

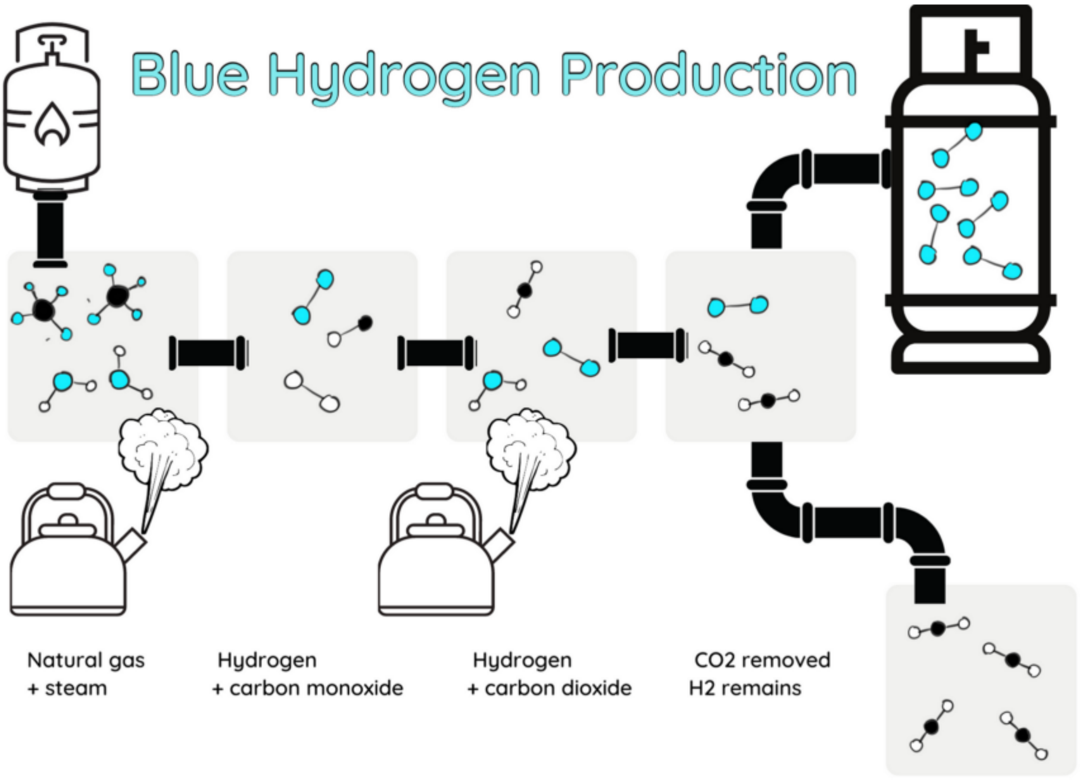


Figure 2: The production of blue hydrogen (Barnes, 2021).

The process chain of blue hydrogen involves following steps: production, carbon capture storage, hydrogen transport, daily and seasonal storage and industrial applications. In more detail (Cappellen, et al., 2018):

- Production via steam-reforming (SMR and ATR): Natural gas reacts with hot steam leading to the production of syngas. SMR and ATR are concerned about good technology due to their TRL and market share.

- Carbon capture storage. The cost plays a significant role in this stage.

- Transport: Transport of hydrogen via the existing natural gas infrastructure and a new hydrogen network.

- Storage: Daily and seasonal storage methods are researched in order to choose the best.

- Industrial applications that could potentially use hydrogen as feedstock or fuel are identified and their feasibility to implement hydrogen is examined.

1.3. Advantages of using blue hydrogen from natural gas.

Nowadays, it is very important the application of friendly manners for the production of blue hydrogen to avoid the major negatives effects on the environment. The feedstock for hydrogen production is dominated by fossil fuels and the most widely used method is steam methane reforming, although is associated with negative environmental impacts. Therefore, it is crucial to investigate and apply methods and feedstock that will not affect negatively to a large degree to environment.

Some fossil fuel raw materials that can be used to produce the hydrogen is the gas and a coal, as well as biomass. Also, the production can be realized through electrolysis using the electricity from solar, wind, hydroelectric, geothermal energy. This variety of sources makes hydrogen a very promising energy carrier for the future (Bhadari et al., 2012).

More specifically, more than the percentage of 99% of hydrogen today is produced from fossil fuels. Around 95% is produced via the steam methane reforming (SMR) process, and another 4% comes from partial oxidation (POX). Although fossil fuels provide feedstock for hydrogen production nowadays, the major percentage of production is completed without regard to the carbon dioxide released. Thus, it negates the net-zero contribution of the resulting hydrogen fuel (Rapier, 2021).

Blue hydrogen, a purer form of grey, is produced when the gas reform process is combined with capture and storage technology (CCS). Carbon dioxide (CO_2) is reduced to a percentage of 90% and stored in empty fields, such as natural gas, making hydrogen almost carbon-free (Gupta, 2021).

The International Energy Agency - IEA projects that about half of low-carbon hydrogen produced globally in 2030 will come from coal and natural gas with carbon sequestration. Industry, refineries, power plants, and the transportation sector will demand low-carbon hydrogen in order to cover their needs. Hydrogen will be increasingly blended into natural gas for use to homes and industry.

However, the most important thing for more friendly methods from the environment is to assure that carbon's production completes via low intensity. Carbon Intensity (CI) measures the amount of greenhouse gas (GHG) emissions released into the atmosphere per unit of fuel energy over the fuel's lifecycle. At the same time, it has been estimated that hydrogen production via the SMR method, has a relatively high carbon intensity, a fact that is not keeping up with a low-carbon economy, which requires hydrogen production with a lower CI.

However, the most percentage of hydrogen production nowadays is the grey, that has a negative environmental impact, as a large amount of subsequent carbon byproduct being emitted to the atmosphere. On the other hand, the production of green hydrogen affects less negatively on the environment, as it is applied to renewable sources and the result is to measure low CI. Although green hydrogen's production is most friendly for the environment, it is characterized as more expenditure, comparing to grey hydrogen (Rapier, 2021).

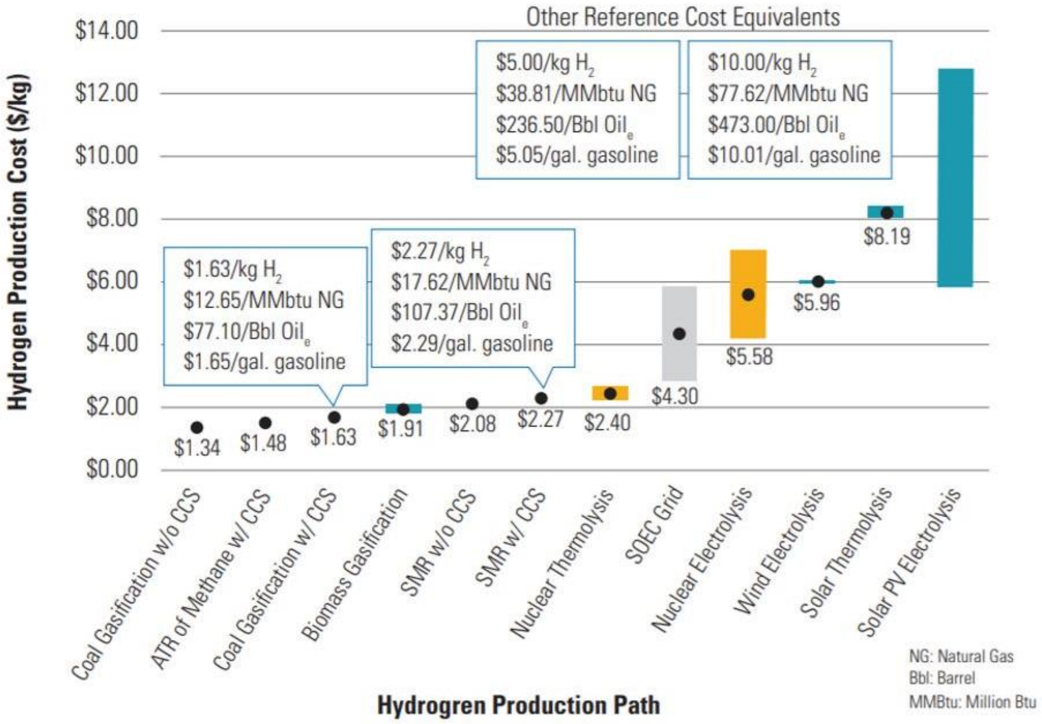


Figure 3: Current hydrogen production cost ranges and averages by technology and equivalent prices for fossil sources with CO_2 Capture and Storage (Rapier, 2021).

The alternative solution is blue hydrogen that has less negative environmental impact, comparing to grey hydrogen, and simultaneously is more economic than green hydrogen. It can serve as an ideal transitional step for passing to a low-carbon economy.

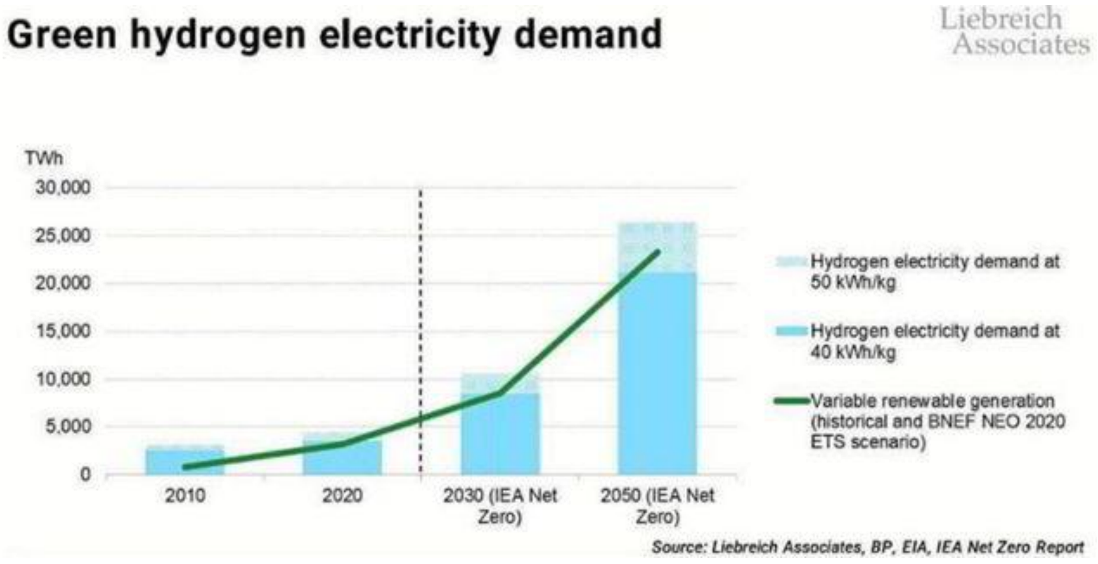
However, it is important to refer that the index of Carbon Intensity of blue hydrogen will depend to a large degree on the entire production process. In case that methane is obtained from a process with a high leakage rate, and the carbon isn’t captured and stored, then the index is going to be much higher, with the result of more carbon dioxide emitted in atmosphere (Rapier, 2021).

1.4. Blue Hydrogen as an Enabler of Green Hydrogen.

The Blue Hydrogen can be overshadowed by the Green Hydrogen in our pursuit of a clean fuel production, from an ideological standpoint. Yet, from the technological side of the matter, Green Hydrogen is not mature enough to answer today energy transition challenge.

Blue hydrogen will be needed in the five to ten years' outlook, despite its greenhouse gas emissions, because it will simply not be possible to meet H_2 demand purely with green hydrogen. Thus, Blue Hydrogen appears the only viable production solution for Hydrogen in the closer future.

It is worth to refer that a study calculated that just replacing the current annual global demand for grey hydrogen with the green variety, would require all the wind and solar power currently installed around the world. This study was predicted the requirement for global installation of all the wind and solar power, in case that the demand forecasts of the International Energy Agency's, for purely with green H_2 hydrogen, as a net-zero scenario in its 2050 (Gupta, 2021).


Green hydrogen electricity demand

Source: Liebreich Associates, BP, EIA, IEA Net Zero Report

Figure 4: Green hydrogen electricity demand as a net-zero scenario (Gupta, 2021).

In the comparison with green hydrogen (produced using electricity from renewables with water) and has the added benefit of redeploying existing and underemployed oil and gas expertise and leveraging existing pipeline and natural gas infrastructure, blue hydrogen offers cost and scalability advantages (Zapantis, 2021).

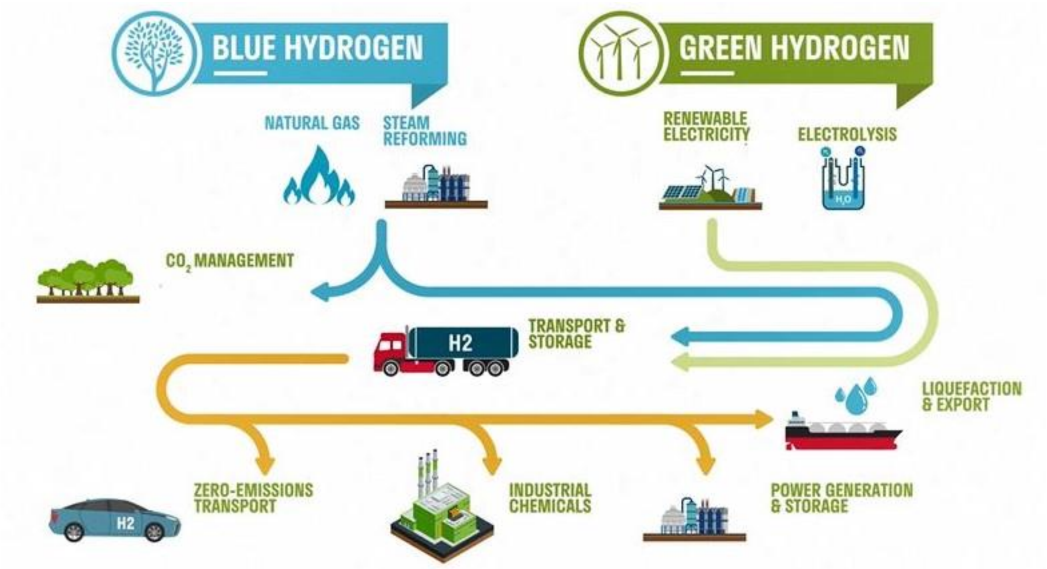


Figure 5: Process of the production for blue and green hydrogen (Gupta, 2021).

The price of green hydrogen depends on renewable energy sources. Different factors contribute to the price of green hydrogen. One factor is the cost of electrolysis, the process by which hydrogen is produced from water using renewable energy. Total global electrolysis capacity is currently limited and costly. Most industry experts expect that a significant increase in electrolysis capacity will reduce costs by about 70% over the next 10 years. However, the most critical factor for the cost of green hydrogen is the price of green electricity used in the electrolysis process.

The main challenge for producing pure hydrogen is to reduce the cost of production technologies to make the cost of hydrogen competitive with conventional transport fuels and this is expected to be delayed.

Indeed, there is a growing international consensus that pure hydrogen will play a key role in the world's transition to a sustainable energy future. It is important to contribute to the reduction of carbon dioxide emissions from industry and heavy transport and also to provide long-term energy storage on a large scale. But this will take time, and given that the time remaining before we exceed the carbon budget, the huge contribution of blue hydrogen is really necessary to achieve the goals of the Paris Agreement on a green emission-free future with a time limit of 2050.

Chapter 2. Blue Hydrogen: A Renewable Energy Perspective.

Energy and Climate Change (YPEKA) has prepared and submitted to European Commission in 2010, the National Action Plan on RES, according to which it has been defined the intended installed power ratio per Renewable Energy Technology and Producer Category, and its distribution over time

For the period after 2020, in April 2012 was adopted the Road Energy Map for 2050 taking into account the evolution of a series basic parameters (economic activity by industry, international prices fuel, CO_2 prices, lignite utilization level, etc.). The future image of Greek energy system can be summarized in the following 10 points (Capros et. al., 2013):

- Reducing greenhouse gas emissions by 60% -70% by 2050 as compared to 2005.
- Percentage of 85-100% of electricity from RES, with exploiting all commercially mature technologies.
- Total RES penetration of 60%-70% in gross final energy consumption by 2050.
- Stabilization of total energy consumption due energy saving measures.
- Relative increase in electricity consumption due to electrification of transport and greater use of pumps heat in the domestic and tertiary sectors.
- Significant reduction of consumption of petroleum product.
- Increase the use of biofuels in all transport to level of 31% - 34% by 2050.
- The share of electricity in passenger transport dominates short distance (45%) and a significant increase in the share of fixed track means.
- Significantly improved energy efficiency for the whole building stock and high penetration of RES applications in the building sector.
- Development of decentralized and intelligent networks.

In parallel, one of the major problems facing the penetration of renewable energy sources is local reactions. Reasons are usually a combination of the bad information or misinformation, bad investment practices, bad implementation of public consultation processes and local perceptions. To them should be added also the complete lack of participation and economic benefits from local societies, since it is limited to mild compensations benefits from investment companies to the municipality (Capros et. al., 2013).

Lastly, there is a misconception about exploiting the renewable energy sources potential of each region only up to the limit of local needs. The overall renewable energy sources growth target as one of the key levers to address climate change should be taken into account, in any case, with the need to maintain local biodiversity (primarily threatened by climate change) and the other spatial criteria, which together make up the threshold of the carrying capacity of each area.

Also, should be cultivated the dynamics that local investment by the residents themselves in clean forms of energy can have multiple benefits such as empowerment of the local economy, fixed price guarantees without external factors, production of reserves for other investments in social necessary structures, an opportunity for co-decision and broad participation, and development in multiple sectors (Capros et. al., 2013).

More particularly, blue hydrogen can utilize as renewable energy fuel in future. Critical synergies exist between hydrogen and renewable energy. Hydrogen can increment renewable power advertise development possibilities significantly and broaden the reach of renewable solutions, such as in industry. Electrolysers can include demand-side adaptability.

Especially, European nations, such as the Netherlands and Germany are facing future jolt limits in end-use divisions that can be overcome with hydrogen. Hydrogen can moreover be utilized for regular energy capacity. Low-cost hydrogen is the precondition for putting these synergies into practice.

In parallel, electrolysers are scaling up rapidly, from megawatt (MW)- to gigawatt (GW)-scale, as innovation proceeds to advance. Advance is gradual, with no radical breakthroughs anticipated. Electrolyser costs are anticipated to split by 2040 to 2050, from USD840 per kilowatt (kW) nowadays, whereas renewable power costs will proceed to drop as well. Renewable hydrogen will soon become the cheapest clean hydrogen supply choice for numerous greenfield applications (Irena, 2019).

The development of blue hydrogen as a transition solution to faces challenges in terms of generation upscaling and supply logistics. Advancement of carbon capture, utilisation and storage has lagged compared to the targets set within the final decade. Extra costs posture a challenge, as well as the economies of scale that support huge projects. Public acceptance may be an issue as well. Synergies may exist between green and blue hydrogen sending, for illustration economies of scale in hydrogen utilisation or hydrogen logistics.

Today, a different source of pure hydrogen is required for energy transition applications. Blue hydrogen production is an option. Blue hydrogen is an alternative to bridging the cost of hydrogen production from renewable energy. It offers a perspective of continuity to fossil fuel producers and can help to achieve climate targets at an acceptable cost.

As the production of large volumes of blue hydrogen may be important to support the increase in demand for hydrogen, many aspects need to be considered (Irena, 2019):

- Blue hydrogen is currently used in limited specialized applications, such as a minimum amount requires pure hydrogen for FCEV in California. On a large scale, it is quite important to ensure that all hydrogen-producing projects from fossil fuels include carbon capture storage (CCS) from the outset. Hydrogen production and use without CCUS can increase CO_2 emissions compared to direct use of fossil fuels due to energy efficiency losses in the chain.

- The development of blue hydrogen does not necessarily take place without carbon dioxide. CO_2 binding efficiencies are expected to obtain a percentage of 85-95% at best, which indicates that a percentage of 5-15% of total CO_2 is leaking. However, the current CCS flagship projects achieve much lower download rates. The Petra Nova project in the US captures just over a third of the exhaust from one of the four coal-fired plants, while the Boundary Dam project in Canada has a total carbon dioxide arrest rate 31% (FT, 2019).

H-vision is the primary potential blue hydrogen extend within Rotterdam harbour, the Netherlands. The point is to figure out the total extent by 2030. The consortium contains 14 parties from within the harbour as well as parties within the whole prepare chain. In 2018, a possibility study was begun to investigate the business case, technological challenges, hydrogen markets and carbon capture capacity (H-vision, 2019).

The H-vision extend is set out to figure out four steam-reforming plants, at a total capacity of 15-20 tons of hydrogen per hour, to store the CO_2 beneath the North Ocean and after that convey the hydrogen to industrial parties within the harbour. The primary plant is arranged to open in 2025, but moreover, the hydrogen created will be transported to parties inside the harbour or somewhere else within the Netherlands. The ultimate objective is to capture and store 8 Mt of CO_2 per year, for which the cooperation of control plant owners within the harbour is required (Cappellen et al., 2018).

Blue hydrogen from fossil fuel fuels with carbon capture storage can be a significant factor as a transition solution, strikingly in circumstances where low-cost fossil fuel saves exist, where capacity locales are accessible and where a normal gas pipeline framework exists that can be changed over to hydrogen (Irena, 2019).

2.1. The Role of Blue Hydrogen in Energy.

The goals of liberalizing the energy market such as strengthening competitiveness, efficiency and price reduction have not been achieved but in many cases gave the motivation to thousands of new investors to "get into the game" of energy and many local ones’ societies to pave the way for a clean and safe energy future.

Comparison analysis between the costs of producing green and blue hydrogen is very interesting. Three main factors are major for the economic viability of hydrogen production from renewables (Irena, 2019):

- ✓ The electrolyser capital expenditure.
- ✓ The cost of the renewable electricity to be used in the process (cost of electricity, LCOE).
- ✓ The number of operating hours (load factor) every year.

More specifically, the higher the electrolyser stack calculate, the cheaper the taken toll of one unit of hydrogen, once settled investments are weakened by a higher quantity of product output. Electrolyser stack variables ought to in common surpass a percentage of 50% at today’s investment cost levels, but nearly optimal hydrogen costs start being achieved at over a percentage of 35%, as depicted in figure 6 (Irena, 2018a).

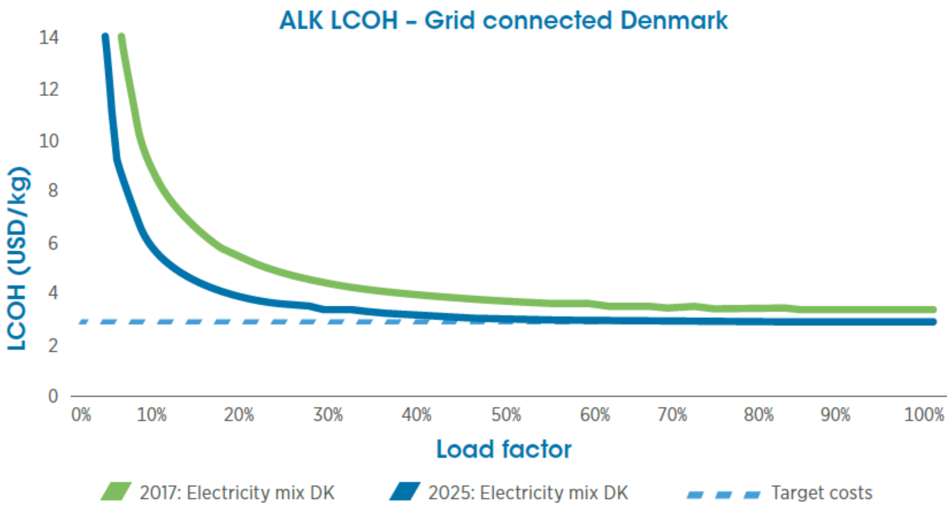


Figure 6: Hydrogen supply cost as a function of electrolyser load. (Irena,2018a)

This percentage will go down as electrolysers get cheaper. Solar-wind hybrid systems appear as a promising solution and could achieve capacity factors well above a percentage of 50% in some places.

In parallel, a prediction of hydrogen from renewable production costs can be then inferred and compared to fossil fuel options with CCS. Only a small part of CO_2 is not captured in the CCS facility for which carbon prices were considered, as depicted in figure 7 (Irena, 2019).

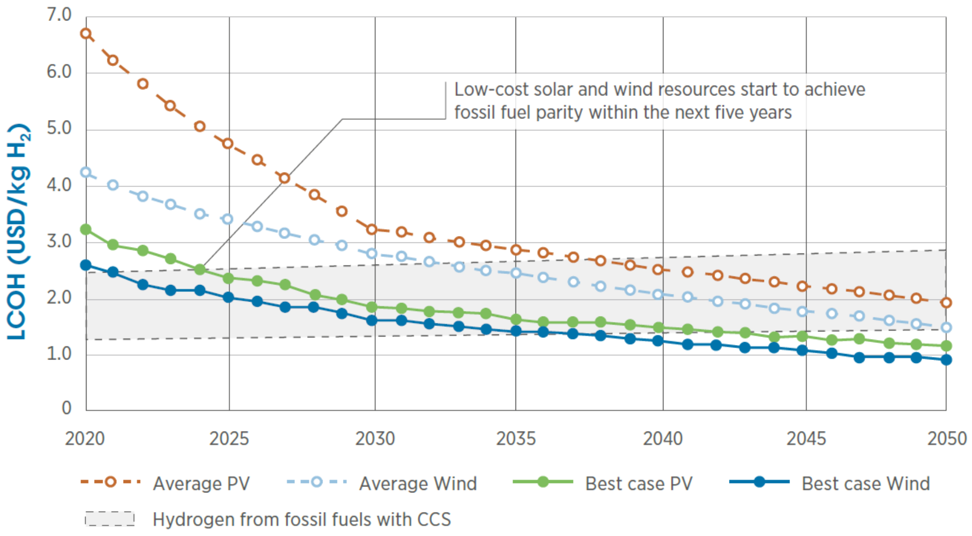


Figure 7: Hydrogen production costs from solar and wind against fossil fuels (Irena, 2019).

Also, renewable hydrogen costs dip below fossil fuel with carbon capture storage, in all cases, from the period of 2030 to 2040. It is worth noting that future costs of green hydrogen will be below those for blue hydrogen fossil fuels.

By 2035, average-cost renewables also begin to become competitive. Pricing of carbon dioxide’s emissions from fossil fuels further increases the competitiveness of green hydrogen. In the best locations, renewable hydrogen is competitive in the next three until five years, compared to fossil fuels.

2.2. Blue Hydrogen from Natural Gas. Economic Aspects.

Hydrogen is a commodity used as a raw material in various industrial applications, such as refineries, but also for the production of ammonia and methanol. Internationally, demand for pure hydrogen has increased from less than 20 Mt in 1975 to more than 70 Mt in 2018. Nevertheless, the current demand for hydrogen is mainly met by fossil fuels, including gas, oil and coal, as they now represent the most economical way, with the cost for hydrogen ranging from 1 to 3 USD per kilo (Noussan et al., 2021).

At the same time, hydrogen has also been suggested as a potential energy carrier to support the development of low-carbon energy, which is mainly produced from renewable energy sources. Visionaries have advocated the use of low-cost pure hydrogen based on an alternative to fossil fuels, which are particularly used in fuel cell applications, in the field of transport.

It is worth noting that hydrogen is characterized as an energy carrier, required to be produced from other sources. Today's demand for hydrogen is mainly met by other processes based on fossil fuels including methane vapour remodelling (SMR), autothermal reforming (ATR), partial oxidation and carbonation. In the case where they bind to CCS, they may be converted to low carbon solutions, known as blue hydrogen pathways. On the other hand, the production of hydrogen by electrolysis of water, which was abandoned due to higher cost, can be combined with the production of energy from RES, to produce green hydrogen (Noussan et al., 2021).

While current costs are higher than mineral-based production solutions, the expected curves both for the production of electricity from RES and for electrolytes could make it a viable solution in the next decades. At the same time, an estimate of future cost trends for green and blue hydrogen is reported in the figure 8, based on estimates from BNEF data [14]. The figure shows the cost for the forms of hydrogen, in the left axis, as well as in terms of energy content, taking into account the lower heating value of hydrogen (120 MJ per kg or 33.3 kWh per kg).

The cost of renewable hydrogen is based on large projects with optimistic forecasts for capital expenditures. Blue hydrogen is based on USD 1.1–10.3 / MMBtu gas prices and USD 40–116 / t. The uncertainty of future cost areas is linked to multiple aspects (BNEF, 2020).

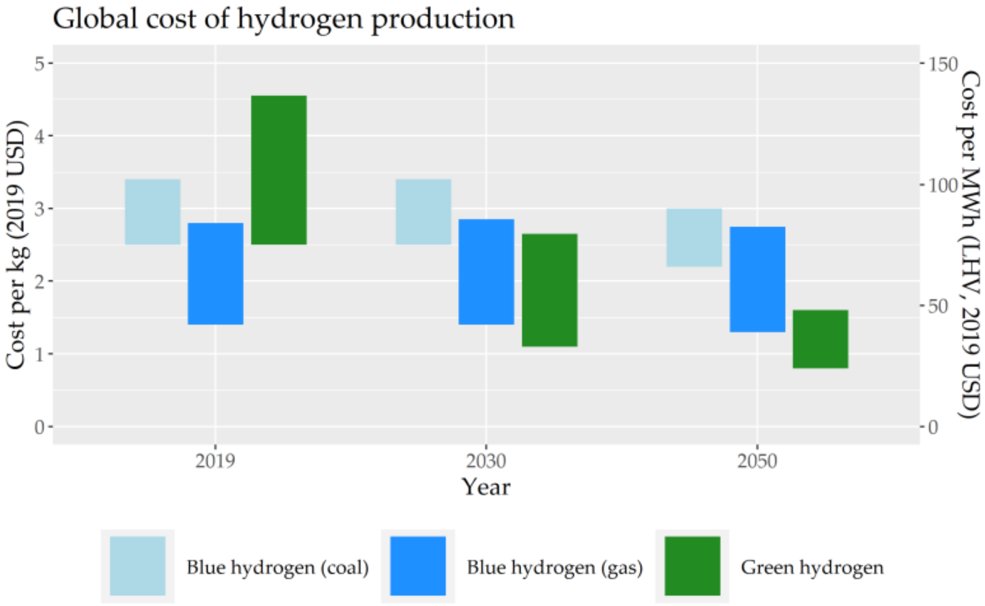


Figure 8: Estimation of future hydrogen costs for different pathways. Energy figures based on hydrogen lower heating value (LHV) (BNEF, 2020).

2.3. Blue Hydrogen from Natural Gas. Technological Aspects.

Nowadays, a growing trend is developing regarding the potential of hydrogen, especially due to a stronger climate agenda with challenging goals. Pure hydrogen is part of a group of technologies to be developed in end uses to ensure the transition to climate-friendly energy sources (Irena, 2019). Hydrogen technologies are further studied as an opportunity for the development of national industrial sectors, in a perspective of recovery after the pandemic crisis (covid-19).

Hydrogen production technologies are constantly coded, with a reference point in the plan, based on different colours. The main colours examined are (Newborough & Cooley, 2020):

- ✓ Grey (or brown / black) hydrogen, produced from fossil fuels (especially natural gas and carbon) and causes the emission of carbon dioxide during the process.

- ✓ Blue hydrogen, through the combination of grey hydrogen and carbon capture and storage (CCS), to avoid the largest percentage of process GHG emissions.

- ✓ Turquoise hydrogen, through the cracking of a fossil fuel, where the by-product is solid carbon.

- ✓ Green hydrogen, when produced from electrolytes powered by renewable electricity and sometimes through other bioenergy-based routes, such as biomethane remodelling or gasification of solid biomass.

- ✓ Yellow (or purple) hydrogen, in the case where it is produced from electrolytes powered by electricity from nuclear power plants.

Figure 9, it is depicted the diverse hydrogen era pathways separated by colour (SSMR: steam methane transforming, ATR: autothermal transforming, CCS: carbon capture and sequestration). It is imperative to note that in each colour, there may be noteworthy inconstancy in carbon concentration, due to an expansive number of parameters. In reality, in a few cases, hydrogen may be negative for carbon, as with pathways including bioenergy in combination with CCS (Noussan et al., 2021).

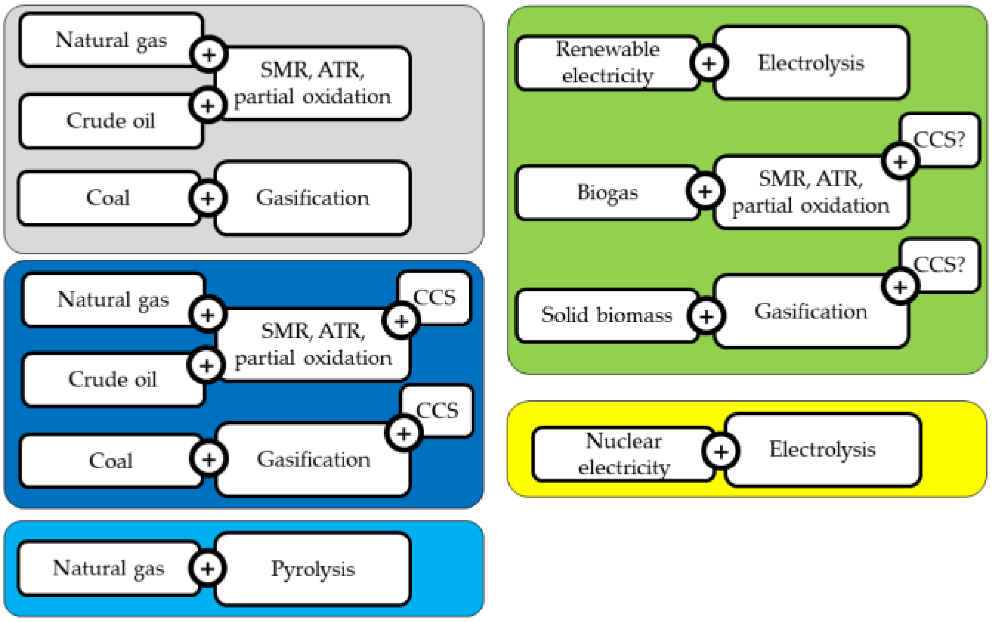


Figure 9: Different hydrogen generation pathways divided by colour (Noussan et al., 2021).

It is worth noting that cross-border hydrogen trade, due to the demand for fairly strong carbonation of energy systems in the coming decades, may evolve into a potential change in global energy games geopolitics (Van de Graaf et al., 2020).

A highly efficient growth of green hydrogen requires a sufficient amount electricity from renewable sources, where it may act as a deterrent in the short term, since RES are already needed to decarbonize existing electricity demand. Therefore, blue hydrogen is characterized as a useful option in the short and medium term, helping to prepare the road green hydrogen at a later stage (Dickel, 2020).

At the same time, it is necessary to address the various long-term technological challenges in complex hydrogen supply chain, which in general is affected by a relatively low efficiency resulting in high costs for end-users. While in general special emphasis is placed on hydrogen production, either through green or blue roads, also storage, transport and final the equipment it uses can incur additional costs and obstacles (Noussan et al., 2021).

In the case where blue hydrogen-based gas is tested, it is important the additional effect caused by methane leakage upstream phases. Although it is not easy to determine precisely, this aspect is usually overlooked in research studies. At the same time, there was a reference threshold for the definition of low carbon hydrogen (blue hydrogen), proposed within the project that developed to achieve a common Pan-European definition of green hydrogen and low carbon), taking into account 60% percent of reduction of GHG emissions compared to an SMR-based reporting process. This limit is set at 36.4 gCO_2e / MJ (131 gCO_2e / kWh), starting from a reference point price value 91 gCO_2e / MJ hydrogen (328 gCO_2e / kWh) (CertifHy, 2019).

Blue hydrogen trails have the advantage of building existing industrial experience from grey hydrogen and sometimes remodelling existing facilities may be is performed by adding CCS systems. Nevertheless, certain conditions must be met to ensure efficient and durable CO_2 storage.

Additional infrastructure may often be required to connect the production facility to the storage site, which may not be available on site. An exclusive CO_2 infrastructure can greatly increase the total cost, an aspect that is difficult to generalize as it depends on each plant. In addition, during the operation of a CCS, the system is feasible to reduce the energy efficiency of an SMR process by a percent of 5% until 14% (The Royal Society, 2018).

2.4. Environmental Aspects by using Blue Hydrogen from Natural Gas.

It is worth noting that in the case that significant amounts of CO_2 are permanently captured and stored by the gas regeneration, hydrogen could be a low carbon energy carrier. However, a recent study raises questions about the effective climatic effects of blue hydrogen on the life cycle. One study examines critical issues in detail and provides a balanced perspective on the effects of blue hydrogen-related climate change.

Through the results of this study it was shown that the climatic effects on such effects may vary over a wide range and depend solely on certain key parameters, which are:

- The methane emission rate of the gas supply chain.
- The rate of CO_2 removal in the hydrogen plant.
- The measurement of global warming where applicable.

The reformulation of advanced technology with high CO_2 capture rates combined with the supply of gas with low methane emissions provides the ability to substantially reduce greenhouse gas emissions concerning conventional gas regeneration and direct combustion. Under these circumstances, blue hydrogen is compatible with low carbon emissions and has an impact on climate change at the upper end of their range, where they are caused by the production of hydrogen from electricity based on renewable sources.

Nevertheless, at the moment, both the blue and green hydrogen production pathways render fully “net-zero” hydrogen without additional CO_2 removal (Bauer et al., 2022). At the same time, methane emissions from the oil and gas supply chain are characterized as an important contributor to global greenhouse gas emissions (Saunois et al., 2020). With a global warming potential approximately thirty and eighty-five times higher compared to that of CO_2 over 100 and 20 years, respectively, methane emissions can be a significant contributor to GHG emissions related to the natural gas supply chain (IPCC, 2021).

Later research concluded that methane emanations happen over the entire supply chain, counting generation, preparation, pipeline transportation and dispersion (Littlefield et al., 2017; Zimmerle et al., 2020). The natural impacts of blue hydrogen can hinge on the sources and size of particular outflows, due to they can make up a major division of the full GHG emanations when a huge level of CO_2 capture and capacity is connected inside the supply chain. The greater the carbon dioxide capture rates, the higher the relative commitments of such methane outflows to the complete environment climate effect of blue hydrogen.

Moreover, the life cycle effect of upstream methane emanations becomes higher with the application of shorter time skylines for measuring natural impacts. Incorporating methane emanations in an LCA show of blue hydrogen in an agent and context-specific way is non-trivial. On the opposite, the characterization of methane emanations from common supply chains in commonly utilized life cycle stock databases is characterized as conflicting and obsolete, and likely to think little of particular emissions (Grubert & Brandt, 2019; Bussa et al., 2021).

In addition, reported methane emissions from natural gas supply chains supported on field measurements exhibit large variability, making it hard to choose a representative average emission value for use in LCA calculations (Balcombe et al., 2017; Ingraffea et al., 2020).

Many factors contribute to genuine and detailed changeability in methane outflows from the oil and gas segment. Whereas numerous of these can be tended to through fitting methodological choices in LCA, others require more investigation and information collection.

The key challenges, in approximate descending order of significance to consolidating agent methane outflows within the LCA of blue hydrogen, comprises of (Bauer et al., 2022):

- Spatial and temporal variability.
- Lack of geographically representative field data.
- Lack of consistent reporting metrics.
- System boundaries.

Recent field studies have affirmed surprisingly spatial and worldly inconstancy in methane outflows over worldwide oil and gas basins. (Omara et al., 2018). The particular varieties emerge from contrasts in basin and asset characteristics, operational equipment, upkeep practices, additionally natural conditions. Also, methane outflow rates calculated in these studies contrast significantly with official inventory estimates.

At the same time, predictions of methane emanations over basins are ceaselessly being overhauled as a result of made strides in estimation approaches. Moreover, contrasts in the estimation stage (ground-based against airborne, against satellite), time of estimation and methodological approach renders coordinate comparison over considers challenging. Hence, in spite of the fact that each of these individual studies might be precisely detailed methane outflows in a particular time and put, the huge watched variety makes an oversimplified country-level representation, in LCA studies about inclined to mistakes (Bauer et al., 2022).

An LCA of blue hydrogen generation requires particular emanation variables for the characteristic gas utilized as feedstock. Subsequently, methane outflows of combined generation forms must be assigned or allocated to single products (Balcombe et al., 2017). Sometimes, methane emanations are totally assigned to the normal gas supply chain, which comes about in an overestimation.

But even if the emissions of combined generation are subdivided, this allotment can be based either on the energy substance or mass of the co-products or on the income created by offering them, which can cause considerable contrasts within the NG-specific methane emanation rates (Allen et al., 2021). Then again, a well-level reason allocation can be connected, doling out emanations totally to the product representing to the essential reason of the asset extraction framework (Burns & Grubert, 2021).

System boundaries are significant, due to the characteristic gas supply chain consisting of different steps from investigation to last distribution and it is possibly vague which of these steps are included in reported estimates (Grubert & Brandt, 2019).

Nevertheless, large-scale blue hydrogen generation will be related to the high-pressure common gas transmission grid and in this way, methane emanations from the last distribution to decentralized buyers (the low-pressure distribution network), ought to not be included in the evaluation of the natural impacts of blue hydrogen.

The particular challenges propose that more research about and information collection are must satisfied to create a reliable and comprehensive stock of the worldwide common gas framework. Too, an exploration of the inconstancy within the Nursery Gas (GHG) emissions estimates is required to be clear of the drivers of contrasts within the GHG outflows from common gas-supported hydrogen alternatives.

The assessment of any methane-based mitigation option, particular the blue hydrogen, mainly depends on the selection of the Greenhouse Gas emission metric applied to compare the impact of (fugitive) methane to carbon dioxide emissions and other greenhouse gases. The upper significant metric is the Global Warming Potential (GWP) which compares the future global warming caused by an idealized pulse of emissions of a specific greenhouse gas (Bauer et al., 2022).

Furthermore, it is worth noting that the Global Warming Potential is characterized as a metric that aggregates impacts over time, hence its estimation requires the specification of a time horizon over which future warming is considered and compared, for example, 100 years in Global Warming Potential100). Considering the short atmospheric lifetime of methane of roughly twelve years, the selection of time horizon has a significant impact on its Global Warming Potential (Stocker et al., 2013).

Thus, a significant aspect is the hope and focus of environment targets envisaged when evaluating climate mitigation options. Attention on stabilizing the climate at below 2 degrees (°C) warming in 2100 implies a longer time horizon, for example, that incorporated in the GWP100 index, which is usually applied in long-term scenario analysis and LCA.

Through the Paris Agreement in 2015, combined with increasing awareness about near-term environmental harms and potential tipping points, the scientific interest has shifted to decreasing peak warming to close to 1.5 degrees (°C) (Rogelj et al., 2019). As 1.5 degrees (°C) will likely be reached before 2050, this shift emphasizes the value of avoiding warming in the next decades, which rely on applying shorter global warming potential time horizons, for example, GWP20 in addition to GWP100, and therefore balancing short-term with longer-term emissions.

All these elements referred above are important considering the impacts of natural gas based on blue hydrogen production on climate change: only a low methane emission rate of the natural gas supply chain in a combination with a high level of carbon dioxide removal rate at the hydrogen production, allows for substantial reduction of the Greenhouse Gas emission from a life cycle perspective. The methane emission rate becomes very important with a time horizon of 20 years instead of 100 years (Bauer et al., 2022).

In figure 10, it is depicted the life cycle GHG emissions of grey and blue hydrogen production regarding the three basic sources of variability. These include applying GWP100 and also GWP20, distinctly different plant configurations representing low, the percentage of 55% and high, in the percentage of 93%, plant-wide carbon dioxide removal rates and variation of the methane emission rate of the natural gas supply chain between percentage range 0.2% to 8%. The range of methane emissions depicts their very high geographical variability, which reflects differences in extraction not only in techniques but also in procedures, transportation of the natural gas and the related methane emissions because of the venting and leaks.

In figure 10, with methane emission rates in the percentage of 0.2%, 1.5%, 8%, and two plant configurations with big and small levels of carbon dioxide removal rates, applying both GWP100 and GWP20. Stacked bars represent the origin of GHG emissions along the value chain. “CCS-low” and “CCS-high” indicate big and small levels overall plant-wide of carbon dioxide removal rates in the percentage of 55% and 93% at the hydrogen production plant, respectively (Bauer et al., 2022).

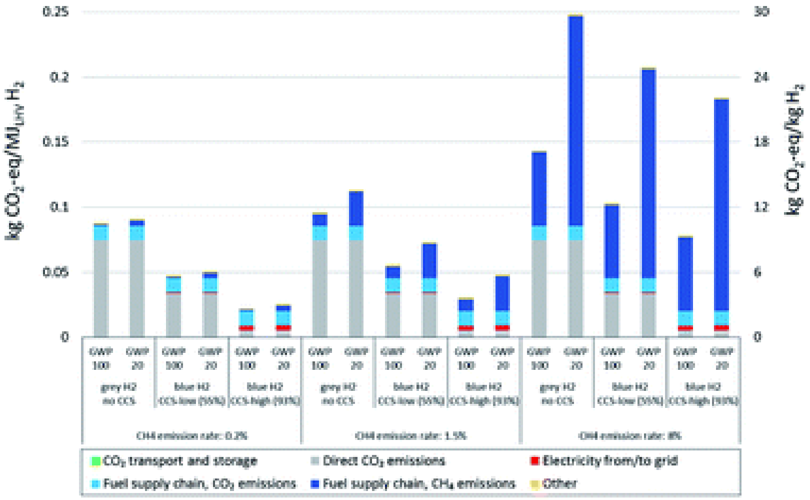


Fig. 10: Impacts on climate change associated with the production of NG-based hydrogen (Bauer et al. 2022).

The conceivable environmental impacts of blue hydrogen change based on: whereas the climate effect of including CCS with the greatest accepted methane outflow rate, in the percentage of 8%, even with high removal rates, is limited to a reduction of GHG emissions by about a percentage of 45% (GWP100) or 26% (GWP20), applying common gas from a supply chain with, as it were a rate of 0.2% methane emanation rate leads to a decrease of GHG emanations by almost a rate of 75% (GWP100) or 72% (GWP20), for a plant with a tall carbon dioxide expulsion rate.

This appears that for normal gas supply chains with little levels of methane emanations, the choice of worldwide warming potential time skyline makes an inconsequential contrast, though it picks up significance for greater spillage rates. Long natural gas supply chains, either refer for import to Europe by pipeline from Russia or as melted common gas from the USA and the Center East, by and large makes higher levels of GHG outflows since of the methane leakage, as well as carbon dioxide outflows related with energy utilization along the chain.

For natural gas supply chains with small levels of methane emissions, carbon dioxide emissions related to electricity supply along the whole value chain become the main source of emissions in the big levels of carbon dioxide capture cases. In the case that low-carbon electricity was supplied, high capture cases may be achieved emission reductions of up to a percentage of 90% in a comparison with hydrogen production without capture (Bauer et al., 2022).

In figure 11, it represents a comparison between the impacts on climate change of grey and blue hydrogen with hydrogen from electrolysis, applying renewable electricity or average grid electricity in Europe and the US, again for methane emission rates of natural gas supply chains up to a percentage of 8% and hydrogen plant configurations with big and small levels of carbon dioxide removal rates; using a global warming potential with a time horizon of 100 years on top, below with a time horizon of 20 years. The figure approves that, in the case that methane emissions from the natural gas supply are low and carbon dioxide removal rates high, environmental impacts of blue hydrogen are similar to those at the upper end of the range of environmental impacts, caused by green hydrogen (Bauer et al., 2022).

There is significant variability considering environmental impacts of green hydrogen, because GHG emissions related to renewable power generation maybe vary from close to zero (run-of-river hydropower) to about 60 g CO2-eq./kWh for solar photovoltaics (PV) at locations with rather low yields, for example, in high northern latitudes, with wind power usually at the lower end of this range (Frischknecht et al., 2020). Therefore, applying PV power in northern latitudes for electrolysis represents the upper end of the range of GHG emissions from green hydrogen represented in the following figure, and using run-of-river hydropower is the lower end.

In the following figure, the emission rate of NG supply chains for configurations with high (“CCS-high”) and low (“CCS-low”) carbon dioxide removal rates, using both GWP100 (top) and GWP20 (lower).

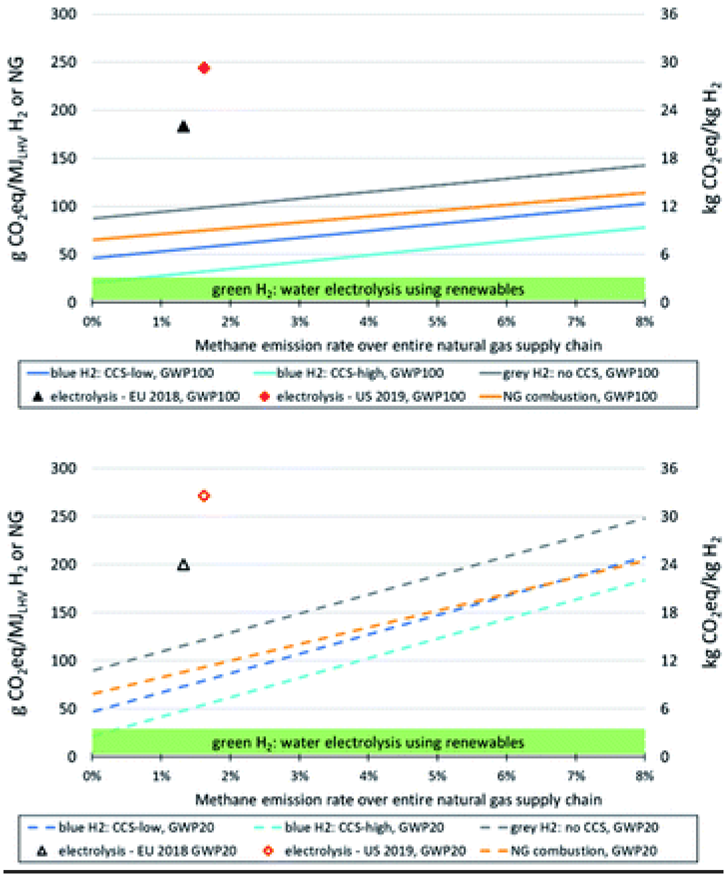


Fig. 11: Impacts on climate change associated with the production of NG-based hydrogen, as a function of the methane emission rate** (**Bauer et al. 2022).

To be compared, the environmental impacts of hydrogen delivered through electrolysis applying average grid electricity in Europe or the USA (markers), or renewables (run-of-river hydropower, wind control or photovoltaics, green shaded zone) are represented. Orange lines represent GHG emissions of NG combustion and the associated NG supply, which are further a work of NG supply chain methane outflow rates.

So, to be competitive with green hydrogen due to environmental impacts over the long-term, blue hydrogen possibly shows a life cycle GHG impression of not more than 2 kg to 3.5 kg carbon dioxide (eq./kg). It is only possible with huge levels of carbon dioxide expulsion rates and methane emanation rates underneath approximately a percentage of 1% (GWP100) or 0.3% (GWP20) (Bauer et al., 2022).

Life cycle GHG emissions of hydrogen from electrolysis applying current average grid electricity in Europe and the USA are significantly bigger than those of blue hydrogen up to a huge level of methane emission rates from natural gas supply chains, in the order of a percentage of 8% or above), even using the twenty-year time frame for global warming potentials. So, it proves that electrolyzers that are partially based on electricity from grids with relevant shares of fossil fuels, for example, to increase operational hours or buffer intermittency of renewables, will have a significantly higher GHG footprint of hydrogen production than off-grid systems.

Therefore, using a one-hundred-year time frame for global warming potentials, blue hydrogen is related to small levels of GHG outflows than natural gas combustion inside additionally past the extent of methane emanations from the normal gas supply. Relative diminishments of GHG emissions of blue against grey hydrogen generation make greater with expanding carbon dioxide capture rates and diminishing methane emanation rates.

Thus, a conclusion is that best-in-class normal gas supply chain administration, combined with enormous levels of carbon dioxide capture rates is crucial for blue hydrogen to be a practical alternative. A common gas supply can be related to little levels of GHG emissions, which implies that natural gas spills and methane outflows along the complete supply chain, involving extraction, capacity and transport, must be constrained. This is often conceivable nowadays in numerous nations, for case, Norway, the UK and the Netherlands, where the natural gas divisions have outflow rates regularly underneath a percentage of 0.5% (Meili et al., 2021).

On the other hand, many regions in the USA, too a few gas exporters like Russia, Algeria and Libya as of now have methane emanation rates around or altogether higher than a rate of 2% and will require critical investments into their existing infrastructure and operations to achieve comparably low methane emission levels (Alvarez et al., 2018).

Thus, there is huge uncertainty on these emissions, which are required to be urgently addressed by improved measurement. It is worth noting that reforming technology with consistently high carbon dioxide capture rates should be employed. An assessment is that carbon dioxide capture technology is yet sufficiently mature to permit long-term removal rates at the hydrogen production plant of above a percentage of 90%. Capture rates about the percentage of 100% are technically feasible, slightly decreasing energy efficiencies and in contrast, increasing costs, but have yet been demonstrated at scale (Bauer et al., 2022).

White Dragon Project

The national proposition for “White Dragon” was submitted on May 2021, within the system of the Greek call for expression of intrigue for Hydrogen Vital Ventures of Common European Intrigued by a gather of companies shaped by the largest energy groups within the country.

DEPA Commercial, as extend facilitator, in collaboration with Approach Innovations, Damco Energy, PPC, DESFA, HELLENIC PETROLEUM, Engine Oil, Corinth Pipeworks, TAP and Terna Energy submitted to the Greek Government and the EU their investment proposition which surpasses the sum of 8 billion Euro, for the improvement of an inventive integrated green hydrogen venture in Greece, which covers the complete hydrogen value chain (DEPA, 2021).

The “White Dragon” is completely supported by the Region of West Macedonia. At the regional level, it has the support of the Bioeconomy and Environment Cluster of West Macedonia. The core of the venture is based on the gradual substitution of the lignite control plants of West Macedonia and the move to clean energy having as the last objective the de-carbonization of the country’s energy mix.

The “White Dragon” extend will utilize large-scale renewable power (GW) for the generation of green hydrogen by electrolysis in Western Macedonia. Hydrogen will at that point be put away straightforwardly (short-term hydrogen capacity) and in a roundabout way (gushing through DESFA’s natural gas pipeline) and, along these lines, through tall temperature fuel cells will give the country’s control framework with power, as a settled base stack co-generation unit of green energy and heat.

The produced heat, as a by-product of green electricity generation, may at first have a complementary utilize to the locale farther warming systems of West Macedonia, as well as in other applications that require warm and / or cooling within the future (industries, greenhouses).

In specific, natural gas pipelines will be utilized for the transport of green hydrogen for other uses, as well as for its backhanded capacity. A vital condition is the creation of an administrative system for Energy Net Metering as a transition alternative until the total improvement of the hydrogen economy.

To quicken development within the system of “White Dragon”, the National Natural Gas Transmission System will at first be arranged so that it can get increasing rates of hydrogen, which is able to diminish the carbon impact of the fuel and offer assistance start the hydrogen showcase. In addition, the considerable development of an exclusive hydrogen backbone pipeline will be implemented in Greece, at the side of primary hydrogen ventures within the transport segment (garbage trucks, trucks, trains, cars), the suitable infrastructure for hydrogen refuelling stations (HRS) and its street transportation and dispersion.

The select hydrogen backbone pipeline will empower the interconnection between inaccessible green hydrogen generation units with expansive conclusion buyers (refineries, industrial units) to assist them “green” their generation forms, but also the interconnection with the individual frameworks of neighbouring countries.

Finally, through the coordinates “White Dragon” project, the transport and trade potential of hydrogen through the TAP Pipeline interfacing Greece to European markets.

Conclusions

1. Molecular hydrogen (H2) is considered the future fuel. Especially, blue hydrogen is essential to build up a market for what will ultimately be green hydrogen. On the other hand, some other views express doubts about the beneficial exploitation of blue hydrogen in climate. The reason is that the problem of exploitation of blue hydrogen is that it depends on carbon capture storage (CCS) and natural gas.

2. Nowadays, it is very crucial the application of friendly manners for the production of blue hydrogen to avoid the major negatives effects on the environment. It is crucial to investigate and apply methods and feedstock that will not affect negatively to a large degree to environment.

3. In the comparison with green hydrogen (produced using electricity from renewables with water) and has the added benefit of redeploying existing and underemployed oil and gas expertise and leveraging existing pipeline and natural gas infrastructure, blue hydrogen offers cost and scalability advantages.

4. The cost of renewable hydrogen is based on large projects with optimistic forecasts for capital expenditures. Blue hydrogen is based on USD 1.1–10.3 / MMBtu gas prices and USD 40–116 / t. At the same time, it is necessary to address the various long-term technological challenges in complex hydrogen supply chain, which in general is affected by a relatively low efficiency resulting in high costs for end-users. While in general special emphasis is placed on hydrogen production, either through green or blue roads, also storage, transport and final the equipment it uses can incur additional costs and obstacles.

5. Blue hydrogen trails have the advantage of building existing industrial experience from grey hydrogen and sometimes remodelling existing facilities may be is performed by adding CCS systems. Nevertheless, certain conditions must be met to ensure efficient and durable CO2 storage.

6. Hydrogen production and carbon dioxide capture must be designed in an integrated way to limit additional energy requirements for CO_2 capture, also compression of hydrogen and carbon dioxide. In the case that requires net electricity import, such demand could ideally be met by applying low-carbon electricity.

7. As long as the natural gas supply continues to have non-negligible methane emissions, the question of whether applying a global warming potential time horizon of 20 or 100 years is very important for the assessment of environmental impacts of blue hydrogen.

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