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The economics and the environmental benignity of different colors of hydrogen

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HIGHLIGHTS

- Technical, economics and environmental discussion on green hydrogen.
- Different colors of hydrogen provide different environmental benefits.
- To date, grey hydrogen production is still the most economical way to produce hydrogen.
- With technological learning, costs for green hydrogen will substantially decrease.
- Green hydrogen could support flexibility and decarbonization of the whole energy system.

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ABSTRACT

Due to the increasing greenhouse gas emissions, as well as due to the rapidly increasing use of renewable energy sources in the electricity generation over the last years, interest in hydrogen is rising again. Hydrogen can be used as a storage for renewable energy balancing the whole energy systems, and contributing to the decarbonization of the energy system, especially of the industry and the transport sector.

The major objective of this paper is to discuss various ways of hydrogen production depending on the primary energy sources used. Moreover, the economic and environmental performance of three major hydrogen colors, as well as major barriers for faster deployment in fuel cell vehicles, are analyzed.

The major conclusion is that the full environmental benefits of hydrogen use are highly dependent on the hydrogen production methods and primary sources used. Only green hydrogen with electricity from wind, PV and hydro has truly low emissions. All other sources like blue hydrogen with CCUS or electrolysis using the electricity grid have substantially higher emissions, coming close to grey hydrogen production. Another conclusion is that it is important to introduce an international market for hydrogen to lower costs and to produce hydrogen where conditions are best.

Finally, the major open question remaining is whether – including all external costs of all energy carriers, hydrogen of any color may become economically competitive in any sector of the energy system. The future success of hydrogen is very dependent on technological development and resulting cost reductions, as well as on future priorities and the corresponding policy framework. The policy framework should support the shift from grey to green hydrogen.

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Abbreviations:

ALK	Alkaline water electrolysis
ATR	Autothermal reforming
BEV	Battery electric vehicle
C	Carbon
CCS	Carbon capture and storage CCU Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CLR	Chemical looping reforming CO Carbon monoxide
CO_2	Carbon dioxide
$CO_{2\ eq}$	Carbon dioxide equivalent
EV	Electric vehicle
FCV	Fuel cell vehicle
GHG	Greenhouse gas
H_2	Hydrogen
ICE	Internal combustion engine
PEM	Polymer electrolyte membrane
POM	Partial oxidation of methane
POX	partial oxidation of oil products
RES	Renewable energy sources
SER	Sorption enhanced reforming
SMR	Steam reforming of natural gas
SOEC	Solid oxide electrolyzer cell
TTW	Tank-to Wheel
WTT	Well-to-Tank
WTW	Well-to-Wheels

Introduction

The current energy system is facing serious challenges and needs significant transformations. Over the last decades, it can be noticed continuously increasing use of renewable energy sources (RES) all over the world. A combination of renewable energy with energy-efficient technologies should allow decreasing greenhouse gas (GHG) emissions and local air pollution.

Hydrogen is like electricity, a secondary energy carrier, but it is also an energy vector, which can be used to convert, store and release energy. With the increasing electricity production from variable renewable sources such as wind and PV, hydrogen is becoming an interest as a long-term storage option for surplus electricity. Currently, hydrogen is mostly used in various industrial applications, such as refining, steel-, ammonia- and methanol production, and over the past years, demand for hydrogen was continuously increasing. In 2020 the overall demand accounted for roughly 90 Mt, from which a little over 70 Mt were utilized as pure hydrogen and 20 Mt were combined with other gases for methanol and steel production [1].

In the future, it can be expected that demand will be much higher in all applications. Due to the increasing emissions from the transport sector, as well as due to the rapidly increasing use of RES in electricity generation over the last years, interest in hydrogen use for mobility is rising again since green hydrogen can contribute to the decarbonization of the transport sector.

However, until now, hydrogen was mostly produced using the cheapest production processes without consideration of the impact on the environment. Since steam reforming of natural gas is the most developed and cheapest commercial method for hydrogen production, the largest amount of hydrogen is produced in this way. Overall, around 900 Mt of CO_2 emissions per year are released into the atmosphere by worldwide hydrogen production [1]. With the pressing environmental problems, interest in low-carbon hydrogen production is increasing. However, this increase is still very slow due to higher hydrogen production costs. Fig. 1 shows the historical development of the low-carbon hydrogen production for the period 2010 to 2020 (data for 2020 are announced).

To differ various ways of hydrogen production depending on the primary energy sources, different colors are used. With the increasing challenges to integrate variable renewables in power systems, hydrogen production by electrolysis, so-called green hydrogen, is becoming more relevant.

Over the last few years, hydrogen has increasingly been the subject of various aspects of research. In general, the technical papers can be divided into those dealing with different production possibilities for hydrogen (colors) and specific technical aspects. Another strain of literature discusses the role of hydrogen in the overall energy system, the costs of production and the environmental impact.

One paper giving a comprehensive analysis of different production methods is Dawood et al. [3]. In addition, they criticize that the current color scheme does not specify the exact amount of emissions generated by low carbon hydrogen and present a new color spectrum approach. El-Shafie et al. [4] give a thorough analysis of different fossil and non-fossil production methods. They further research the use of ammonia decomposition and find that it will be a commercial hydrogen production method in the future. Ratnakar et al. [5] also list all main hydrogen production methods and explain them in detail. One of the main research dealing with the production methods and all aspects from economic to environmental impacts is done by Newborough and Cooley [6]. They find that green hydrogen will be the production method of the future as it will become cheaper than the alternatives like blue hydrogen caused by cheaper renewable electricity and electrolyzers.

Other authors focus on one production method or area, with Midilli et al. [7] and Li and Cheng [8] on coal gasification, Khojasteh Salkuyeh et al. [9] on reforming of natural gas, Bauer et al. [10], Howarth and Jacobson [11] and Ali Khan et al. [12] on blue hydrogen, Amin et al. [13], Schneider et al. [14] and Leal Pérez et al. [15] on turquoise hydrogen and Gerloff [16] and Chi and Yu [17] on green hydrogen production, which all will be further

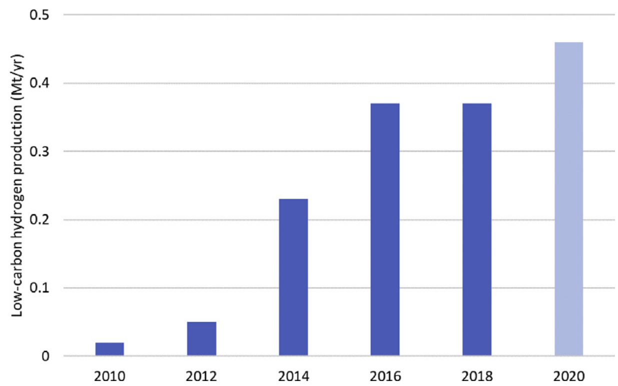

Fig. 1 – Low-carbon hydrogen production, 2010–2020 [2].

discussed in the following sections. Armaroli and Balzani [18] emphasize that in order to achieve a hydrogen economy, further research in alternative production methods is required.

Ball and Weeda [19] discuss the use of hydrogen in the overall energy system and find that a high number of operating hours and low electricity prices are essential for future hydrogen production from electrolysis. Rosen and Koohi-Fayegh [20] give a comprehensive overview of a hydrogen-based energy system and believe that the world's future energy system will be based on the two energy carriers, electricity and hydrogen. Another suggestion to overcome the problems of transport and storage of hydrogen is by converting it into methanol or ammonia, which has been proposed by Ref. [21]. In order to achieve the mentioned goal of a hydrogen economy, Majumdar et al. [22] recommend, with the focus on the US, to develop a hydrogen strategy, invest in R&D, implement hydrogen policies and also include CCUS technologies. Mac Dowell et al. [23] further implies that this transition to hydrogen can only take place when adequate zero transition pathways are formulated in line with socio-political-economic constraints.

Bartels et al. [24] conducted a purely economic assessment on different production methods and found that grey hydrogen is the most economical method at the date of the analysis. However, they point out that alternative methods might become cheaper in the future. An analysis of 14 different production methods has been conducted by Nikolaidis and Poullikkas [25], who find that thermo-chemical pyrolysis and gasification have the greatest chances of becoming competitive in the future. Steam methane reforming is still suggested as the most economical production method by Yukesh Kannah et al. [26], who provide a techno-economic assessment of different production technologies.

Ozturk and Dincer [27] compare different hydrogen colors and find that currently PEM electrolysis has a lower environmental effect than conventional production methods, however also the lowest normalized efficiency when powered by solar. They find the highest efficiencies in high-temperature electrolysis with biogas as feedstock. A throughout analysis of the environmental impact of green hydrogen production has prior been made by Dincer [28]. The paper Acar and Dincer [29] supports the findings mentioned earlier that solar power for hydrogen production is the most environmentally friendly option to date. Longden et al. [30] also compare different production methods, including costs and find that hydrogen produced through fossil fuels is not compatible with the transformation to a sustainable energy system. Still, when a part of the emissions is captured for blue hydrogen, substantial fugitive methane emissions occur, which most studies do not include. They further argue that electrolysis might become much cheaper in the future [30].

Others address the integration of hydrogen in the transport sector (e.g. Refs. [31–35]), including potential constraints [36] or its role as long-term storage for fluctuating renewables (e.g. Refs. [37–42]).

There are certainly some papers dealing with alternative production methods than the conventional and well-known ones, but this might be expanded in the future. Additionally, the topic of different electricity inputs for electrolysis is rarely discussed. It is important to emphasize that environmentally sustainable hydrogen production can only be done via electricity produced by renewable energy and not through the current electricity grid. We will also put an emphasis on this differentiation in this work and it is worth mentioning that with this, some problems occur. When only taking green electricity, the operating hours of the electrolyzer are lower due to natural circumstances of the sun and wind, except for hydropower which is highly needed for other purposes. The lower operating hours will result in higher investment costs of the electrolyzer. Renewable electricity production also has to become cheaper in order to offset this investment cost difference through cheaper electricity. The major objective of this paper is to discuss various ways of hydrogen production depending on the primary energy sources used and the conversion technologies applied. The novelty lies in the comprehensive analysis on a technical, economic and environmental level. This analysis can help to decide which hydrogen production processes to use in a future energy system. Moreover, the major barriers for the faster deployment on the example of the transport sector, are analyzed. Improvements in electrolysis technology and decreasing costs of electricity generated from RES are providing an opportunity for decarbonization of the transport sector using hydrogen.

In this paper, in Section: The colors of hydrogen, an overview on different colors of hydrogen is provided. Based on a comprehensive literature review in Section: Costs of hydrogen, we have documented ranges of hydrogen costs, with the focus on the costs for grey, blue and green hydrogen. Environmental aspects of hydrogen are analyzed in Section: Environmental aspects of hydrogen, and hydrogen production capacities in Section: Status quo and outlook of installed hydrogen production capacity. Since emissions from the transport sector are rapidly increasing, of special interest is the possible use of hydrogen and fuel cell vehicles in the transport sector. Besides, economic assessment also corresponding Well-to-Wheels (WTW) emission analyses are conducted in Section: Hydrogen applications and fuel cell vehicles. Finally, Section: Conclusions and outlook provides major conclusions of this work.

The colors of hydrogen

Hydrogen can be produced from different primary energy sources. Depending on the production process and kind of energy used, hydrogen costs and related emissions could be very different. This is the reason that hydrogen generation technologies are often classified based on different colors, e.g., grey, blue, turquoise, green, purple and yellow, see Fig. 2. For this analysis, we consider all hydrogen production methods that rely on fossil fuel inputs without CCUS as grey hydrogen, as this is done in the majority of scientific literature, e.g. Refs. [6,43]. [44], also summarizes all the mentioned production methods into grey hydrogen but also acknowledges that also brown or black hydrogen is in use. While the scientific literature focuses on grey hydrogen for all fossil fuels, some sources explicitly mention brown hydrogen for coal gasification [45,46] or [47] with brown hydrogen when brown coal and black hydrogen when black coal is used. As we found those classifications to be the minority, we will continue with the more common classification of grey hydrogen.

Some of the production technologies are well-developed and mature technologies, but there are also some methods (e.g., photochemical and biological methods), which are under fundamental research. Conventional production methods use natural gas, coal, or oil as feedstock and then convert them by steam reforming or gasification to hydrogen, which emits CO_2 unless it is captured and stored (CCS) or used (CCU). Another mature but not widely developed technology is thermal cracking of methane under the exclusion of oxidizing reaction partners such as oxygen, water vapor or carbon dioxide called methane pyrolysis [14]. Additionally, biomass can be used as feedstock for pyrolysis. This method is then CO_2-neutral however has the major disadvantage of varying hydrogen content due to feedstock impurities [25]. Another method with also relatively high efficiencies is dark fermentation, having the advantage of high energetic density being produced through microbial conversion of waste biomass [48]. Though, it has a quite low technology maturity level (1–3) [3]. The method mostly referred to when talking about renewable hydrogen is electrolysis, with renewable electricity as input. Another option to produce hydrogen from RES is to do it via steam reforming from biomass. The biomass-hydrogen-based processes are promising options that contribute to the hydrogen production in the future but require improvements to produce larger competitive volumes [49]. Hydrogen production from nuclear electricity is not very promoted in the European hydrogen strategies, however, it may become a practical alternative in other world regions, such as China and Russia [50–53]. However, if the electricity for hydrogen production with electrolysis is taken from the grid, then this hydrogen cannot be classified as green, since the electricity is largely produced with fossil fuel power plants (except Norway and Iceland). Electrolysis with electricity inputs from the grid is called yellow hydrogen [47]. According to Dawood et al. [3], there are also other emerging hydrogen production technologies with efficiencies up to 90%, for example, a membrane reactor or anion exchange membrane. Together with Nikolaidis et al. [25], they give the most comprehensive overview of all existing hydrogen production technologies to date, including technology maturity.

The main colors are grey, green, blue, turquoise and pink, which will be discussed in more detail in this work.

Grey hydrogen

Currently, the largest amount of hydrogen is grey hydrogen. The grey hydrogen represents hydrogen produced by steam reforming of natural gas or coal gasification without carbon capture, utilization and storage (CCUS). More than 40% of grey hydrogen is a by-product of other chemical processes [50]. Hydrogen produced as a by-product has also been unofficially classified by the North American Council for Freight Efficiency as white hydrogen [54]. Grey hydrogen is mostly used in the petrochemicals industry and for ammonia production [26]. The demand for hydrogen for those two applications increased

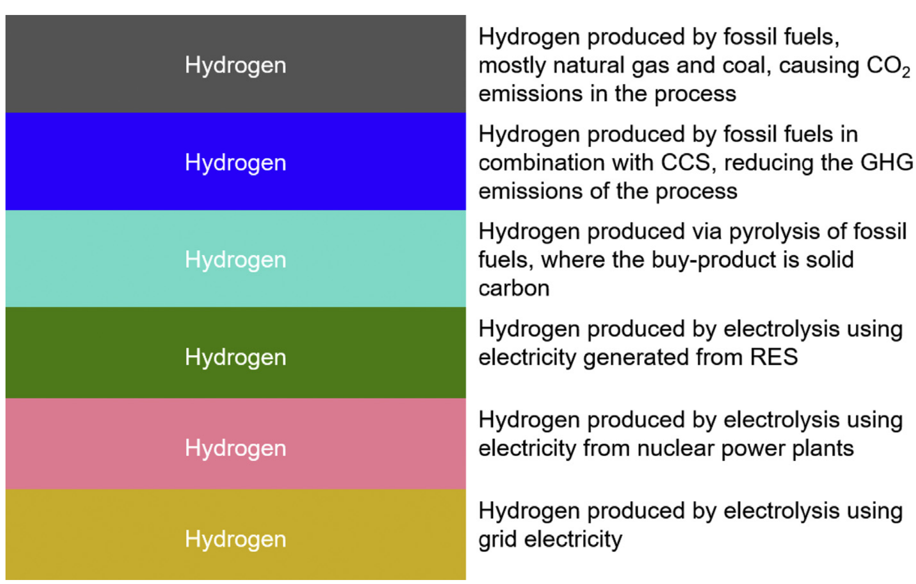

Fig. 2 – Colors of hydrogen [6,46,47] Remark: The classification can differ among studies; some additionally subdivide grey hydrogen into brown hydrogen for the coal gasification process and also cluster the biomass gasification process into brown hydrogen, e.g., Ref. [46]; others also refer to hydrogen with nuclear energy as yellow hydrogen, e.g. Ref. [44]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

substantially over the past 70 years, see Fig. 3. In general, around 6% of the worldwide extracted natural gas and 2% of coal are used for the production of grey hydrogen per year [6].

The major disadvantage of grey hydrogen is associated with significant CO_2 emissions generated during hydrogen production, which are estimated to be around 830 Mt CO_2 per year [6]. Yet, steam reforming of natural gas (SMR) without CCUS is a well-established process, resulting in low hydrogen costs. In the process, the natural gas undergoes a pre-treatment and the water is heated. The methane is then split up in the reformer with steam into syngas (Eq. (1)), having CO and H_2 as main components. This is then converted by the water gas shift reaction (Eq. (2)) into CO_2 and H_2, CO_2 is separated and the H_2 is purified, see Fig. 4 [5,43]. The size of the SMR plants is usually in the range of 50–1000 MW [6].

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

Another major production process resulting in grey hydrogen is coal gasification, which in some literature might be considered as brown hydrogen. Since coal is the fossil energy source with the largest reserves worldwide, this is also a highly used production method. Especially China produces a large amount of hydrogen with coal gasification due to high natural gas prices and large coal reserves [43]. Four distinct types of coal, namely lignite (low rank), sub-bituminous coal (low rank), bituminous coals (medium rank) and anthracites (high rank), are commonly used as gasification feedstock [7]. Besides the different coal types also specific gasification methods can be distinguished (fixed bed-, moving bed-, fluidized bed-, entrained flow- and plasma gasification), all operating at temperatures over 900 °C [7]. In this work, we do not cover all specifics but focus on the main process, as also seen in Fig. 5. In general, the dry coal and pulverized is inserted in the gasifier, where it is reacting under high temperature with oxygen and steam into syngas with the main components of CO_2 and H_2. This can be separated into two phases. First, the air is fed into the gasifier and oxidizes a fraction of the coal into CO_2 (Eq. (3)) while storing the heat in the fuel layer. As a second stage, the air inflow is cut and steam is injected. The steam, together with part of the coal, reacts to CO_2 and H_2 (Eq. (4)). Once the heat has been depleted to a particular point, some air is once again fed into the gasifier. Those are the two main reactions that alternate and are used in most gasification methods [43].

$$C + O_2 \rightarrow CO_2 \tag{3}$$

$$C + H_2O \rightarrow CO_2 + H_2 \tag{4}$$

Both SMR and coal gasification are fully mature technologies with a process efficiency of 60–85% for SMR and 74–85% for coal gasification [3]. Additional production methods are partial oxidation of methane (POM), partial oxidation (POX) of oil products and autothermal reforming (ATR) [43]. In the literature, for grey hydrogen also the colors brown and black are used.

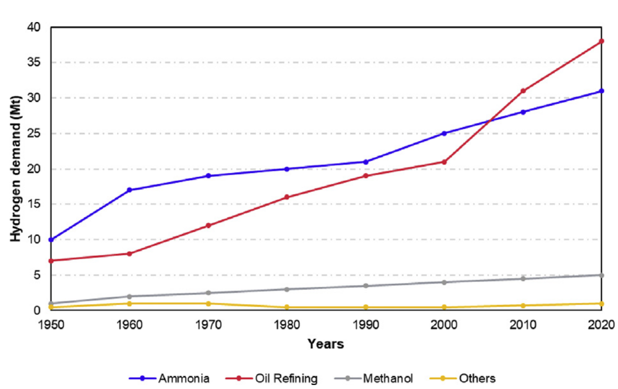

Fig. 3 – Development of worldwide hydrogen demand over the last 70 years [7].

Blue hydrogen

Blue hydrogen is hydrogen produced by steam methane reforming with CCUS, using natural gas or biomass. According to Newborough and Cooley [6], a hydrogen production facility only has to install a CCUS device in order to be counted as blue hydrogen. The certain amount that needs to be captured has not been defined. When applied to the SMR process, up to 90% capture rates, also including capturing post-combustion CO_2 (without 70%), were reported [6]. Currently, blue hydrogen is considered as a bridging technology before a full transition to green hydrogen [50] and carbon capture and sequestration were being promoted heavily a few years back. As a result, the European Union largely subsidized carbon capture and sequestration demonstration projects added to fossil power plants with 587 million EUR [55], with none of them being implemented to date [56]. Recently, also an increasing number of scientists have taken a critical look at CCS technology in view of blue hydrogen production, see e.g., Refs. [6,10,11].

Despite resulting in lower emissions, the technology is still far from being climate neutral [3]. The environmental impact has been calculated by different authors and largely depends on which parts of the hydrogen production process are included. Even when the CCS operations were powered by renewable electricity, substantial fugitive methane emissions occurred upstream from producing and transporting natural gas. When taking those into account, blue hydrogen only halves the emissions of grey hydrogen [57]. This has also been supported by a recent study by Alvarez et al. [58], finding that methane leaks in the production of natural gas and oil are largely underestimated even by Environmental protection agencies. The problem of substantial atmospheric methane growth should not be underestimated as a substantial acceleration has been reported in the last years [59].

Another problem that arises is finding adequate storage sites for the captured carbon that cannot be utilized. In some cases, in which carbon is stored underground, considerable capital costs could be required. Due to CCUS, total hydrogen costs could be significantly higher compared to grey hydrogen. Further, it is also not yet regulated who bears the responsibility for the CO_2 and the cost of storage [6].

The whole process and required steps for CCUS after SMR can be seen in Fig. 6 The overall process efficiency of the SMR (60–85%) decreases by 5–14% when the carbon capture unit is integrated [44] (see Fig. 7).

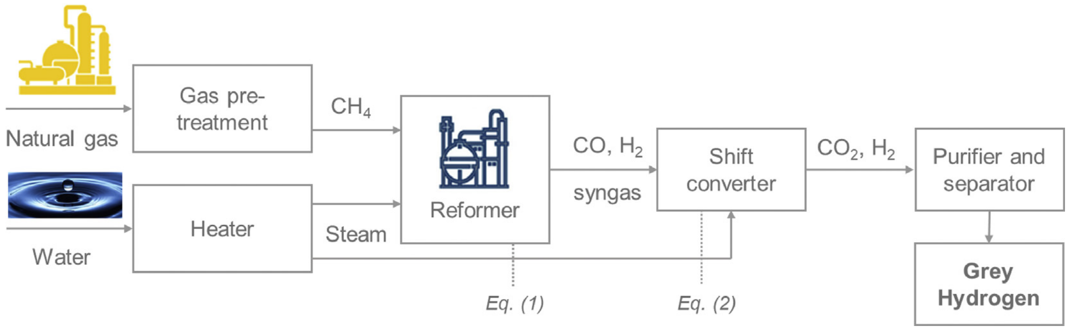

Fig. 4 – Schematic production process of Steam reforming of natural gas (SMR).

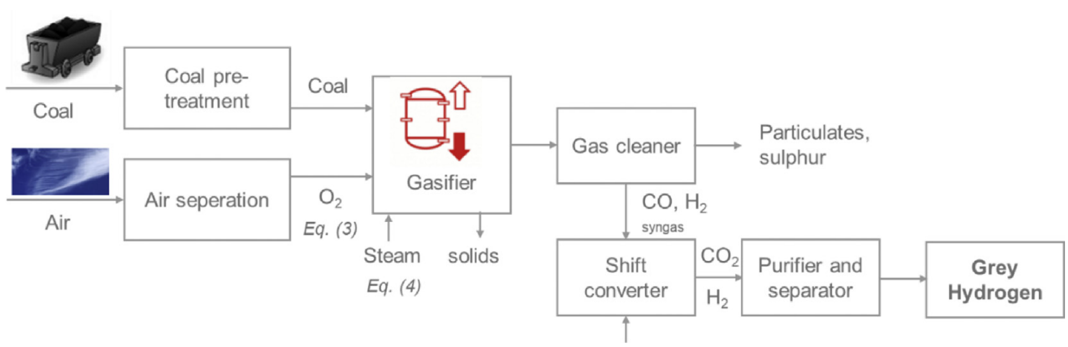

Fig. 5 – Schematic production process of coal gasification.

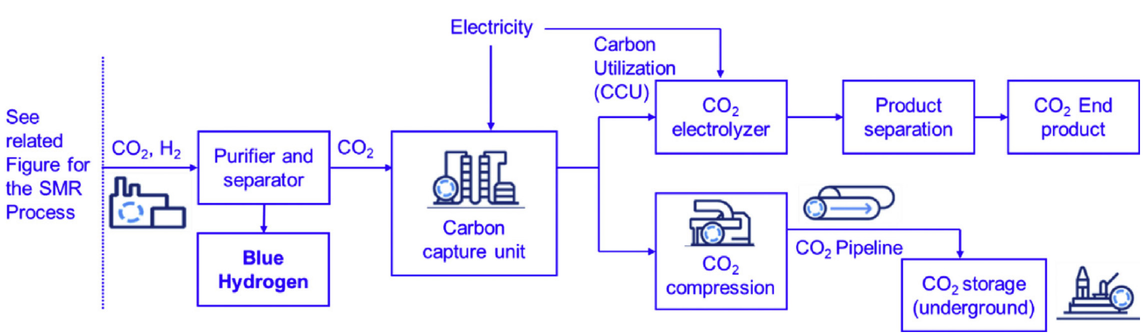

Fig. 6 – Schematic production process of carbon capture and utilization (CCU) and carbon capture and storage (CCS) [13], for the preceding SMR process, refer to Fig. 4.

Recently also new technologies for CCUS of hydrogen are emerging, with chemical looping reforming (CLR) being the only one tested on a pilot scale, according to Antzaras and Lemonidou [60]. CLR offers a less energy-intensive alternate approach to partial oxidation. Also promising is sorption enhanced reforming (SER), aiming to produce and separate CO_2 in one step and also being able to operate at a lower temperature [60].

Turquoise hydrogen

Contrary to the mentioned conventional productions methods, the by-product of turquoise hydrogen via methane-pyrolysis is solid carbon in the form of filamentous carbon or carbon nanotubes [13], which can be used for the further production process or might be easier to store, hence having a lower carbon footprint. The solid carbon can be sold depending on its type for 150–400 EUR per t for coke, 500–1000 EUR per t for carbon black, 1500–1800 EUR per t for activated carbon and up to 1 Mio. EUR per t for carbon filaments [15].

Methane-pyrolysis, which can be divided into three process categories, namely, (i) thermal decomposition, (ii) plasma decomposition (Kvaerner process) and (iii) catalytic decomposition, has been known for decades and technically realized in several processes. However, only in recent years has it raised the interest to produce hydrogen mostly via thermal decomposition as the furthest developed process [14]. Pyrolysis has not yet been commercialized from the point of view of hydrogen production. Only the thermal process (Eq. (5)) is being further developed by BASF to produce hydrogen in larger quantities [14].

$$CH_4 \rightarrow 2H_2 + C \quad (5)$$

Green hydrogen

Green hydrogen is hydrogen produced from water by electrolysis using electricity from renewable energy sources. This kind of hydrogen is of special interest in the transition toward a more sustainable energy and transport system. In literature, for green hydrogen, also expressions like "clean hydrogen," "renewable hydrogen," or "low-carbon hydrogen" are used. Dawood et al. [3] criticize that the definition for low carbon hydrogen, meaning up to which emission level hydrogen is classified as green, clean or renewable hydrogen is not universal and introduce a hydrogen cleanness index model.

Currently, there are three major electrolysis technologies, alkaline water electrolysis, polymer electrolyte membrane (PEM) electrolysis, and solid oxide electrolyzer cell (SOEC). Alkaline water electrolysis (ALK) is the most mature technology, already been used since 1920, with a market share of about 70% [52]. This technology benefits from the low costs and long operational life. A disadvantage is that the ALK electrolysis process needs to be run continuously to avoid damage so that variable renewable energy should not be a single source of power. Additionally, they have problems with low current densities and corrosive conditions [61]. Polymer electrolyte membrane (PEM) has been in operation since 1960 and is more suitable for urban areas due to the smaller system size. Furthermore, it is more efficient and can respond faster, making it suitable for capturing an oversupply of renewable electricity [61]. When hydrogen is later needed in pressurized form for use or storage, "high pressure" PEMs can already deliver the required pressure without another conversion step, leading to higher overall efficiency. However, this technology is associated with higher capital costs due to expensive electrode catalysts and membrane materials. Minke et al. [62] find that in a mature PEM market, supply problems might occur due to the socio-economic and geographical conditions of reserves, not the size of reserves themselves. They suggest recycling and a more efficient PEM technology [62]. A technology that is associated with great expectations due to low expected capital costs and high efficiency [27] is the solid oxide electrolyzer cell (SOEC), which has recently become available on the market with about 150 kW of capacity installed so far [63]. The operating temperatures of high-temperature steam electrolysis in SOEC range from 700 to 1000 °C, which should help in using less electricity as the thermodynamic conditions of the reaction are better under these conditions and also heat can be supplied into the process [64]. Some drawbacks of the technology are instability and delamination of electrodes and safety problems [27]. Table 1 shows the efficiency and maturity of each electrolysis technology. An overall benefit of hydrogen produced with electrolysis instead of other means is the high purity of >99.95% [6].

The general schematic electrolysis process can be seen in Fig. 7. For electrolytes, either liquid solutions (e.g., polymeric or alkaline) for PEM or ALK or solids (e.g., solid oxide/ceramic) for SOEC electrolyzer can be used. The latter work at higher temperatures, as already discussed earlier. The specific process for ALK (Eqs. (6) and (7)) and PEM electrolyzer (Eqs. (8) and (9)) works through electricity being transmitted, the water creating hydrogen ions, which are positively charged together with oxygen at the anode. This then flows through the liquid electrolytes and merges with the electrons from the external circuit, producing hydrogen gas. When the electrolyte is solid, as in the case of SOEC (Eqs. (10) and (11)), the water dissociates and produces H_2 and negatively charged O_2 at the cathode through merging with electrons from the external circuit. The O_2 permeates across the membrane and gives up electrons at the anode to generate oxygen gas [5].

Table 1 – Electrical efficiencies (LHV), Technology maturity level (TML) and general maturity assessment of the three main electrolyzer technologies; Remarks: TML has been introduced by Ref. [3] and is a combination of the commonly known Technology readiness level (TRL) and the Commercial readiness index (CRI) of the Australian Renewable energy; the reported electrical efficiencies for SOEC are substantially higher as they use additional thermal energy.

Technology	Electrical Efficiency, Technology maturity level (TML), Maturity	Source
Alkaline electrolysis (ALK)	63–70%, 9-10, Mature and commercial	[65], [3], [63]
PEM electrolysis (PEM)	56–60%, 7-9, Commercial (earlier stage of development)	[65], [3], [63]
Solid oxide electrolyzer cell (SOEC)	74–81%, 3-5, Commercially available (150 kW)	[65], [3], [63]

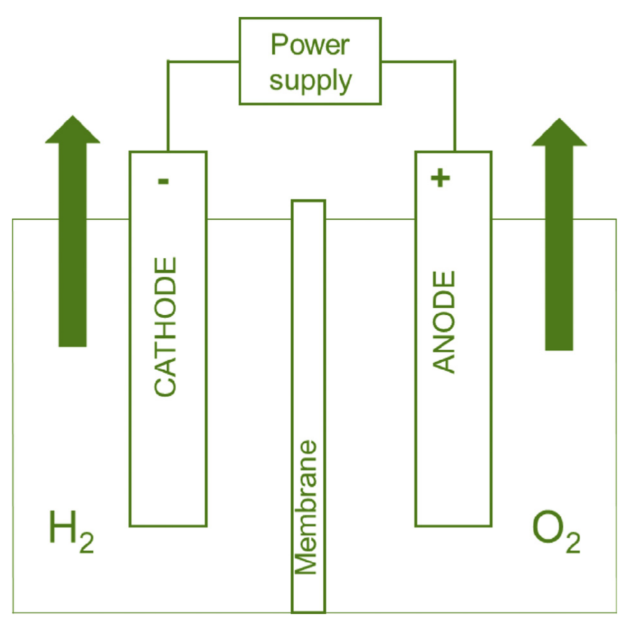

Fig. 7 – Schematic electrolysis process.

It is also important to mention that all electricity needed for the described processes has to be solely from renewable energy sources in order to be regarded as green hydrogen.

$$\text{ALK : Cathodic Reaction } 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (6)$$

$$\text{ALK : Anodic Reaction } 2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^- \quad (7)$$

$$\text{PEM : Cathodic Rraction } 2H^+ + 2e^- \rightarrow H_2 \quad (8)$$

$$\text{PEM : Anodic Reaction } H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \quad (9)$$

$$\text{SOEC : Cathodic Reaction } H_2O + 2e^- \rightarrow H_2 + O^2 \quad (10)$$

$$\text{SOEC : Anodic Reaction } O^2 \rightarrow \frac{1}{2}O_2 + 2e^- \quad (11)$$

Overall only 0.03% of global hydrogen production is done via electrolysis, also including yellow and pink hydrogen [66]. This means green hydrogen to date is still very much a niche product.

Purple hydrogen

Hydrogen production from nuclear electricity is not very promoted in the European hydrogen strategies, however, it may become a practical alternative in other world regions, such as China and Russia [53,67–69]. Purple hydrogen is obtained by electrolysis through an atomic current. Attaching a hydrogen production facility might help to reduce the curtailment of nuclear plants [70] and provide a further energy storage possibility once seasonal storage might be required. Milewski et al. [71] analyze the operation of high-temperature electrolysis SOEC in combination with nuclear power plants and find that the available steam is beneficial to the energy use efficiency of the whole operation. One other benefit mentioned in the literature is the combination of combining electrolysis with micro nuclear reactors, constructed, for example, by Rolls-Royce [6].

In the literature, purple hydrogen is also sometimes also called yellow hydrogen. We, however, use the more common description of yellow hydrogen for electrolysis with grid electricity.

A summary of all discussed hydrogen production methods is provided in Fig. 8.

Other hydrogen production methods and colors

Another hydrogen production method is using biomass as feedstock through different processes. The maturest biomass processes today are thermochemical conversion, with gasification being the most researched biomass hydrogen technology [49,72]. However, also biological technologies are under research like for example, microbial electrolysis [73] and dark fermentation [74]. Pal et al. [75] provide the most comprehensive review on hydrogen production from biomass. Using biomass as feedstock always implies that it stands in competition with other use cases like biogas production or other fuels. To date, there is only a very small fraction of hydrogen produced through biomass which is, according to Newborough and Cooley [6], the reason that no individual color is assigned for the process. It is not clear if they should be clustered into green hydrogen production, as done by Noussan et al. [44] and Dincer [28].

Two new colors were introduced in the literature, namely aqua and white hydrogen. Aqua hydrogen is, according to Yu et al. [76], produced from oil sands and oil fields with a new method developed by the University of Calgary, emitting no carbon emissions. The color has been selected as it is between blue and green, produced with fossil feedstock (blue) but not emitting carbon (green). The authors claim that no emissions occur since the conversion from oil reservoirs or oil sands to hydrogen should take place in the reservoirs below the earth and only hydrogen is extracted in a final step. The technology is currently being tested in Saskatchewan, Canada. The main mentioned obstacles for this new technology are the scale-up

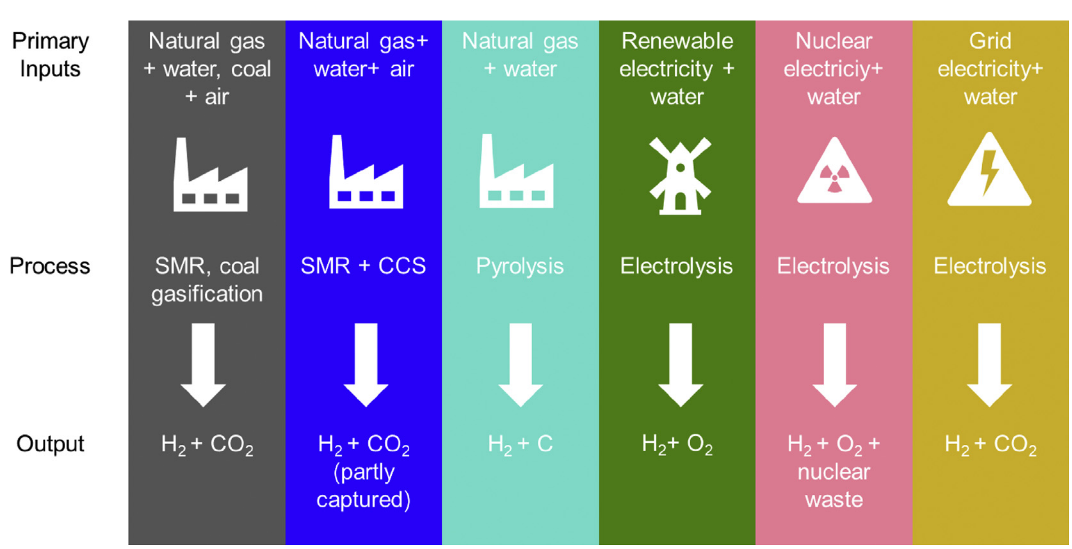

Fig. 8 – Summary of hydrogen production pathways and colors.

and concerns for the environment. The color aquamarine has also been used by Boretti [77], who uses it for the pyrolysis of natural gas, powered by concentrated solar energy, producing solid carbon and hydrogen as an end product. As white, he classifies the direct splitting of water molecules by means of concentrated solar energy [78]. Both proposed colors are still under fundamental research and are meant to be tested and applied in Saudi Arabia [77].

Some other processes under fundamental research were analyzed by Dincer and Acar [79] and they rank all technologies according to emissions (photonic H_2 production lowest, thermolysis highest), costs (thermochemical processes lowest cost, photoelectrochemical systems highest), efficiencies (thermolysis highest, photocatalysis lowest). When all three factors are included in the evaluation, thermochemical hydrogen generation seems to be the most appropriate production method, with photofermentation second and artificial photosynthesis third. The least suited according to this analysis are photoelectrochemical systems, photocatalysis and thermolysis [79].

Costs of hydrogen

As discussed above, hydrogen can be produced from different primary energy sources and in different production processes with a different level of maturity. However, currently three most discussed hydrogen colors are green, blue and grey, and in the following, their costs and environmental impacts will be analyzed.

Although hydrogen is mostly used in industrial applications (e.g., ammonia, refining, methanol, steel), demand for hydrogen is rapidly increasing. However, the largest amount of this hydrogen is produced using fossil fuels, and causing CO_2 emissions.

Depending on the hydrogen production method and kind of energy used, final hydrogen costs could be very different. The costs of the grey hydrogen are the lowest, mostly between 0.8 and 2.1 € per kg of hydrogen. The blue hydrogen could be significantly higher in comparison to grey hydrogen due to additional costs for carbon capture and storage. However, currently the highest hydrogen costs are in the case that hydrogen is produced in an electrolyzer using electricity from RES, see 9. The cost range of green hydrogen is mostly between 2.2 and 8.2 € per kg of hydrogen in the literature (see Fig. 9).

There are several reasons for the wide range among the calculated hydrogen production costs in the literature, mainly coming from different assumptions regarding possible operating hours and fossil fuel or electricity costs. Both depend on the region of operation [26]. When comparing the costs of different hydrogen colors, it is also important to keep in mind that grey hydrogen is currently the main production method

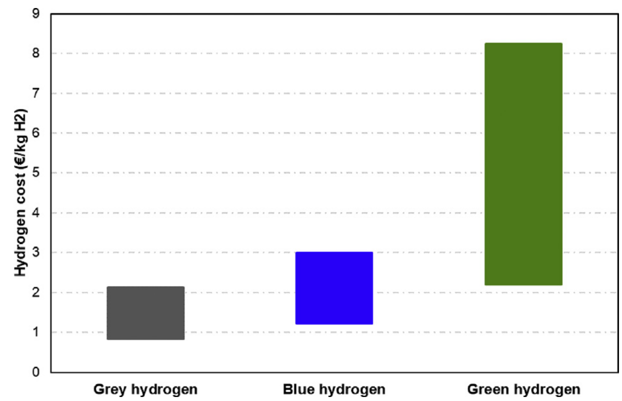

Fig. 9 – Reported cost of hydrogen production for different production pathways in the literature [7,30,43,44,80–83].

with plants in the GW range, whereas, for example, green hydrogen is still deployed with much smaller capacity, both on the side of the electrolyzer technologies as well as the respective renewable electricity generation. For blue hydrogen, both apply as the SMR technology is widely developed, whereas the technology to capture the carbon is still in the development phase with few installed projects so far. The cost of storing carbon is still a huge uncertainty.

In regions with low natural gas prices, grey hydrogen can be produced at 0.8 € per kg of hydrogen. The IEA [80] recorded the lowest prices for SMR in the middle east, the US and Russia, all below one € per kg of hydrogen. The highest prices were in Europe and China. The same applies to blue hydrogen [80]. The investment costs for coal gasification are higher than SMR, but fuel input is cheaper than natural gas [30], with a production cost range of 1.2–2 € per kg of hydrogen [43,65,83]. The production costs of biomass gasification are slightly higher, ranging from 1.6 to 3 € per kg of hydrogen [43,84].

Although currently fossil-based hydrogen production is the cheapest option, in the future, through technological learning and increasing electricity generation from RES, green hydrogen could become a viable option. According to IRENA [85], a combination of cost reductions in electricity generation and electrolysis due to increasing efficiency, as well as increasing number of full-last hours, could deliver up to 80% hydrogen cost reduction. It is expected that green hydrogen will be cheaper than blue hydrogen from 2030 onwards [86].

The key performance indicators for current and future electrolyzers are shown in Table 2.

In the case of green hydrogen, the two most significant components of the cost are the investment cost of the electrolyzer and electricity price. Currently, electricity price represents about 90% of the total operating costs. Current capital costs for alkaline electrolyzers are in the range of 500–1000 USD/kW and 700–1700 USD/kW for PEM electrolyzers.

Table 2 – Key performance indicators for Alkaline- and PEM Electrolysers [85].

	2020 - Alkaline	2020 - PEM	2050 - Alkaline	2050 - PEM
System efficiency (kWh/kg $_{H2}$)	50–78	50–83	<45	<45
Lifetime (1000 h)	60	50–80	100	100–120
Capital costs (USD/kWe), system size >10 MW	500–1000	700–1400	<200	<200

However, these costs are expected to decrease significantly. In 2050 capital costs for electrolyzers could be below 200 USD/kW [85].

Another factor that could contribute to green hydrogen becoming more economical are the recent price increase of natural gas as well as rising CO_2 costs. As can be seen in 10 for the hydrogen price, the data of the Netherlands hydrogen hub rose substantially since the beginning of 2021 for all four production methods analyzed [87]. Yellow hydrogen from either Alkaline or PEM electrolysis is currently also highly linked to natural gas prices as most of the electricity in the Netherlands is still produced from fossil fuels (52% gas and 27% coal [88]).

Costs of hydrogen production are very dependent on the investment costs of the hydrogen production facility, the cost of raw materials or electricity used and on the operating hours of the hydrogen production technology. The cost of electricity is dependent on the production method and will decrease only if surplus electricity from renewable energy is used. This, however, results in a lower number of full-load hours per year, which increases the overall cost. For the following calculations, we included grey, blue and green hydrogen (Alkaline and PEM Electrolysis).

Including all the mentioned impact parameters, hydrogen costs are calculated as:

$$C_{H_2} = \frac{IC \cdot \alpha + C_{o\&m}}{T} + \frac{C_{f/e}}{\eta} \qquad (\notin/\mathrm{kWh}) \tag{12}$$

with

IC… specific investment costs of the hydrogen production facility, €/kW.

α… capital recovery factor.

$C_{o\&m}$… operating and maintenance costs, €/kW.

T… operating hours per year, h/year.

$c_{f/e}$… cost of fuel or electricity, €/MWh.

η… conversion efficiency.

The structure of hydrogen production costs from different technologies is shown in Fig. 11 with the input data from.

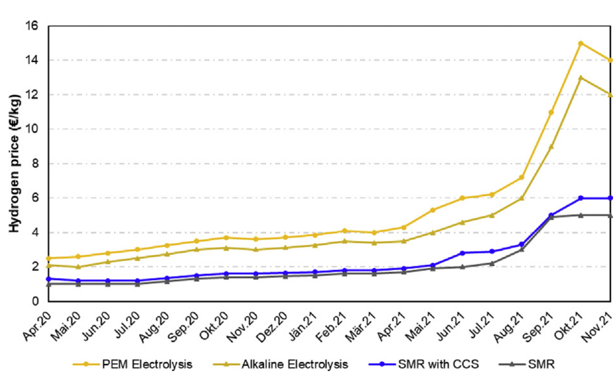

Fig. 10 – Hydrogen price development of the technologies PEM and Alkaline Electrolysis (yellow hydrogen), Steam methane reforming (SMR) with carbon capture and storage (CCS) (blue hydrogen) and SMR (grey hydrogen) based on the production costs including capital expenditure for the Netherlands production hub: Data from Platts Hydrogen Assessment. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3. It can be clearly seen that SMR is, to date, the most economic hydrogen production method due to its low investment costs of the reformer technology.

However, in the future, due to technological learning, substantial cost reductions of electrolyzer technology are expected. Furthermore, the electricity costs will further decrease with a high number of renewables in the electricity system, whereas fossil fuel costs will increase due to higher CO_2 costs. Since SMR is already a fully mature technology, no further learning effects are to be expected. In the future, it will be essential to increase the full load hours of the electrolyzers, especially for green hydrogen production and to utilize low electricity prices. Those cost developments of green and low carbon hydrogen have been further discussed by Schmidt et al. [89], Ajanovic and Haas [90], Böhm et al. [91] and Brändle et al. [92]. They conclude that high learning effects can be expected for electrolyzers and that green hydrogen might become viable in the near future.

Environmental aspects of hydrogen

The main issue when discussing different production methods of hydrogen is the corresponding CO_2 emissions hence the climate impact. Several studies conduct a life cycle assessment to properly define the emission impacts of hydrogen production, such as Howarth et al. [11] for grey and blue hydrogen, Lotrič et al. [93] and Zhao et al. [63] for electrolysis technologies and Ozbilen et al. [94], Parra et al. [95], Valente et al. [96], Sanchez et al. [74] and Longden et al. [30] for various methods. Al-Qahtani et al. [97] further extend the life cycle assessment with an evaluation of other environmental problems that occur in production and Frank et al. [98] focus on emissions that occur during transmission, distribution and dispensing of the produced hydrogen.

We focus in this section on the comparison of grey, blue, yellow and green hydrogen. Our analysis is limited to the main production process, including emission from fuel/electricity inputs (Eq. (13)) and does not consider further steps like purification, pressurization, transport and storage. Newborough

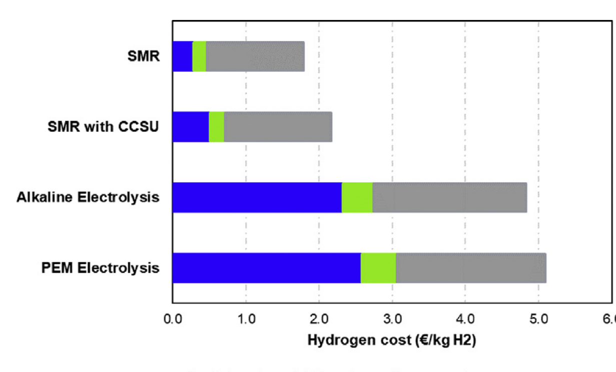

Fig. 11 – Hydrogen production costs of grey (SMR), blue (SMR with CCUS) and green hydrogen (PEM and Alkaline Electrolysis). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3 – Input data for the calculation of hydrogen production costs in Fig. 11.

	SMR	SMR with CCUS	Alkaline Electrolysis	PEM Electrolysis
Investment costs (€/kW)	1000	1778	2600	2900
Operation and maintenance costs (€/kW)	47	53	39	44
Efficiency (LHV)	76	69	64	66
Operating hours	8322	8322	3000	3000
Energy price (€/kWh)	0.03	0.03	0.04	0.04

and Cooley [6] highlighted that including the same quality and pressure of hydrogen is essential for a complete comparison. Our focus, however, is to give a general overview of emissions that occur in the respective production processes. We do consider fugitive methane emissions in line with [11] and a methane leakage rate of 2.54% [58]. As electricity input for yellow hydrogen production, we consider the EU Electricity mix according to the IEA [99], with emission of 0.354 kg $CO_{2\ eq}$ per kWh $_{PE}$ and power plant efficiency of 39% for coal and 0.201 kg $CO_{2\ eq}$ per kWh $_{PE}$ and power plant efficiency of 43% for natural gas. For green hydrogen, we assume a generation mix of wind, PV and hydro.

$$CO_{2\ eq\ TOTAL} = CO_{2\ eq\ FUEL} + CO_{2\ eq\ PRODUCTION} + CO_{2\ eq\ CCSU} \tag{13}$$

$CO_{2\ eq\ FUEL}$ are emissions that occur in the production of electricity and in the extraction and transportation of natural gas, $CO_{2\ eq\ PRODUCTION}$ are emissions that result from the production of hydrogen either in steam methane reforming or in the electrolyzer and $CO_{2\ eq\ CCSU}$ are emissions that result from the process of capturing the emissions for blue hydrogen production.

As shown in Fig. 12, only hydrogen produced by renewable electricity such as hydro, wind and PV has really low greenhouse gas emissions and hence a positive ecological performance. When also including fugitive methane emissions in the calculation [11], the greenhouse gas emissions for grey and also blue hydrogen are high. Upstream methane emissions can add up to 5.2 kg $CO_{2\ eq}$ per kg $_{H2}$ to the grey or blue hydrogen production process, according to IEA [66] but might be higher according to other authors, e.g., Ref. [58]. Bauer et al. [10] further investigate methane emission rates, applying different methane leakage rates from 0.2% up to 8%, thus showing a range from 11 to nearly 30 kg $CO_{2\ eq}$ per kg $_{H2}$ for

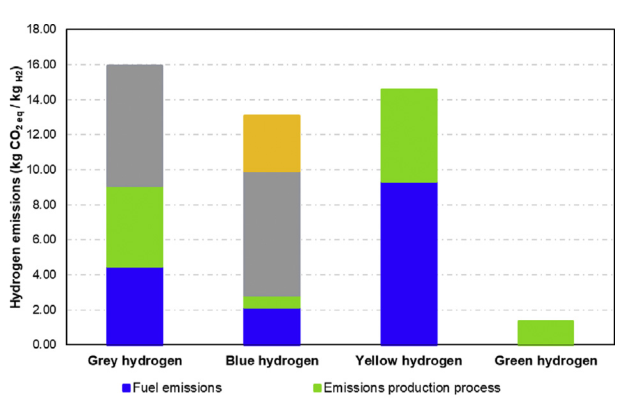

Fig. 12 – Hydrogen emissions for various production methods.

grey hydrogen production. Parkinson et al. [100] also highlight this problem in their comprehensive study on the carbon footprints of various hydrogen production methods. Some studies, especially earlier publications (e.g. Refs. [95,101,102]), do not take fugitive methane emissions into account and conclude that yellow hydrogen from the EU-electricity mix has higher emissions than from converting fossil fuels. When considering the US electricity mix, Siddiqui and Dincer [103] even find higher emissions than for grey hydrogen from coal gasification (28.6 vs. 23.7 kg $CO_{2\ eq}$ per kg $_{H2}$). Other authors, however, acknowledge that coal gasification is the production method with the highest carbon footprint, nearly double of SMR [43]. Nevertheless, it highlights the importance of a high renewable electricity mix. The EU is in the process of further increasing the share of renewables in the electricity mix. According to the European Environment Agency [104], the emission intensity of the EU-27 electricity generation decreased from 334 g $CO_{2\ eq}$ per kWh $_{ele}$ in 2010 to 253 g $CO_{2\ eq}$ per kWh $_{ele}$ in 2019 (231 $CO_{2\ eq}$ per kWh $_{ele}$ in 2020 due to COVID). This will also make yellow hydrogen production in Europe more environmentally friendly. There is still a substantial difference in primary energy sources used for electricity generation among countries, as Fig. 13 shows. Outside of the EU, both China and the US rely heavily on fossil fuel, with the difference that coal is the dominant source in China, leading to higher specific emissions. Two positive examples are Norway and Iceland having nearly all their electricity generated by renewable sources, due to favorable topography.

Some countries rely heavily upon and also build in the future on nuclear energy, hence this will also be depicted in hydrogen production. Parra et al. [95] and Ozturk and Dincer [27] describe the impact on human health due to the high ionizing radiation of nuclear power. Valente et al. [105] also include emissions from uranium mining in their life cycle analysis for pink hydrogen production. They find that high-temperature electrolysis is the most suitable option for pink hydrogen production and conclude in general that the emission and acidification impact is lesser than with grey hydrogen production, the energy performance is not very satisfactory [105].

Blue hydrogen has been promoted heavily as bridging technology for the path to a renewable energy system, but in the recent literature, concerns regarding emissions have been expressed, especially in Europe and Australia [76]. In the study by Howarth and Jacobson [11], they find that using blue hydrogen only emits 18–25% less greenhouse gas emissions than grey hydrogen and still has 20% higher emissions than using natural gas or coal for heat. This is mainly due to the fugitive methane emissions when extracting and transporting natural gas and from additional energy inputs needed for

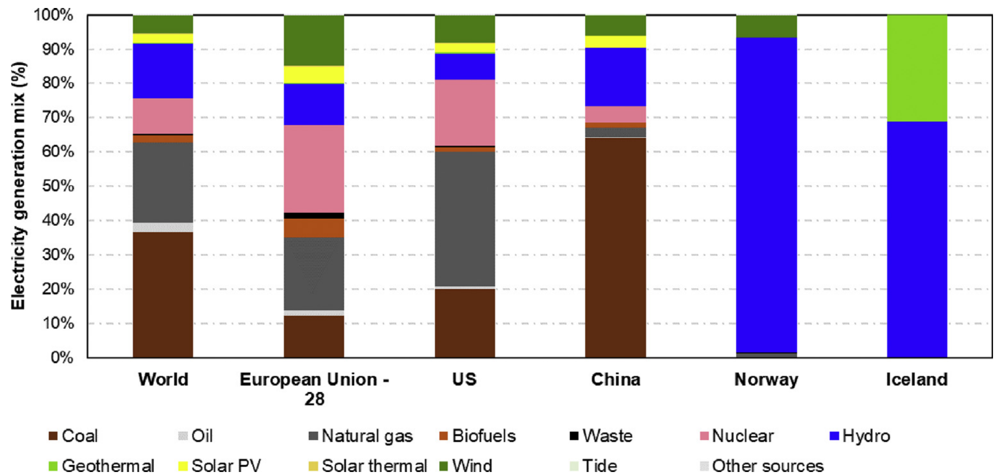

Fig. 13 – Electricity generation mix in 2020 (own compilation based on [89]).

powering the carbon capture. They strongly recommend switching to green hydrogen right away, otherwise, the shift to green technologies will be delayed. Further, they note that the Hydrogen Council is especially promoting blue hydrogen and hydrogen in general, which helps their stakeholders from the oil and gas industry to generate even more profits as more natural gas inputs are required to create the same quantity of heat [11].

In addition, the question of the classification of green hydrogen is still unresolved. There is no universal definition to date, but the EU project CertifHy is developing hydrogen certification schemes in Europe. Their threshold for low carbon hydrogen is below 36.4 g $CO_{2\ eq}$ per MJ $_{H2}$ (assumed emissions for grey hydrogen production are 94 g $CO_{2\ eq}$ per MJ $_{H2}$) [106]. Green hydrogen is further defined by TÜV SÜD as 75% greenhouse gas reduction compared to the mentioned baseline [107]. An overview of the ongoing definition discussion is provided by Ref. [108].

On the technical side of green hydrogen production, Gerloff [16] finds that in the future, the solid oxide electrolyzer cell (SOEC) with a high share of wind and solar electricity production has the highest potential for being a fully green production method up to the year 2030. From then on, PEM electrolysis is expected to be more environmentally friendly. The study does not consider any production costs, only considering the environmental aspect of different technologies [16]. Zhao et al. [63] further recommend a reduction of metal inputs (e.g., stainless steel and nickel for SOEC, platinum and iridium for PEM and nickel for alkaline) for all three electrolysis technologies in order to further reduce their impact on the environment.

Discussing environmental issues, water consumption is an aspect that is often overlooked. Usually, water consumption is associated with green hydrogen but also grey- and blue hydrogen production consumes a significant amount of water, and in some cases even more than electrolysis. In the case of electrolysis, pure water consumption is in the range of 10–15 L per kg of hydrogen output [44,97]. However, when comparing embodied water based on a life cycle inventory, the water consumption for steam reforming could be about 24 L per kg of H_2. In the case of coal gasification, water consumption could be even higher, about 38 L per kg of H_2 [97].

The water requirement for hydrogen production could be challenging in some world regions. For example, the regions that have a high solar potential, such as deserts, are usually coping with water scarcity and desalination plants would require further substantial energy inputs. This problem could be intensified due to climate change, and could be a barrier to hydrogen production.

Status quo and outlook of installed hydrogen production capacity

Grey hydrogen with steam methane reforming amounts with about 300 GW is the biggest production capacity worldwide [6]. In recent years some of those capacities were equipped with carbon capture, utilization and storage (CCUS) technology or new blue hydrogen production facilities were built. However, the total number is still quite low, with 27 CCUS projects worldwide. Only three of them are explicitly used for hydrogen production (Air products SMR, Quest, ACTL Sturgeon) [109]. Turquoise hydrogen is, to date, not being produced on a commercial scale, with some technical challenges such as blockages from carbon deposits and emissions from the necessary process heat [1]. The first pilot project in the United States might be operational in 2022 [110]. Most developments happened in terms of additional electrolysis capacity, see Fig. 14. A total of 280 MW are installed as of 2020, nearly doubling the capacity from five years ago.

Sizes of plants also got bigger over the years, as can also be seen in Fig. 14. Around 2010, plants were even smaller with newly installed capacities in the kilowatt scale. The largest worldwide operating production capacity is a 25 Alkaline electrolysis plant in Peru for nitrate production, which has been in operation since 1965. Recently, the second largest plant, a 20 MW polymer electrolyte membrane electrolyzer at the Air Liquide hydrogen production facility in Béancour, Canada started operation [111]. It increases the production capacity of Air Liquide by 50% and is mainly powered by

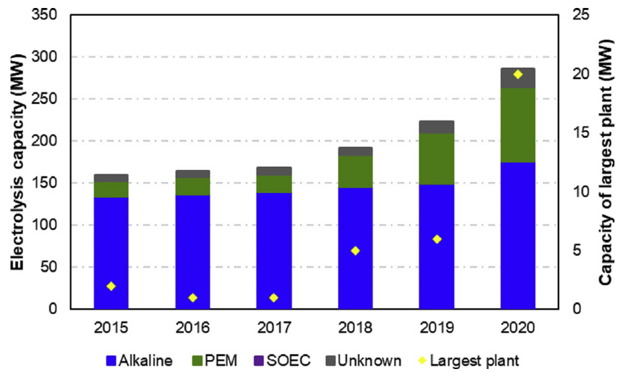

Fig. 14 – Worldwide installed electrolysis capacity (own compilation based on [1]).

hydropower. In Fukushima, Japan a 10 MW alkaline electrolyzer is also in operation since 2020 [85]. The largest European production capacities are located in Germany (Wesseling [112] and Energiepark Mainz [113]) and in Austria. In Austria, the 6 MW electrolyzer for industrial purposes in iron and steel production was launched in 2019 at the Voestalpine industrial in Linz [114].

Another 48,500 MW are planned worldwide until 2040, according to the IEA [115], with the largest projects in Australia (Asian Renewable Energy Hub, Murchison), Italy (Silver Frog) and the Netherlands (North H2 green hydrogen) with planned capacities ranging from 12,000 to 3000 MW. Spain also has various projects with up to 400 MW in the pipeline and announced a $10 billion investment to support green hydrogen over the next ten years [116]. The location of the country is perfect for photovoltaics and wind generation. In various other countries, there are additional projects underway.

Table 4 gives an overview of selected hydrogen electrolyzer projects in operation, construction and in planning. Adding additional electrolyzer capacity will lead to overall cost reductions due to economies of scale and technological learning.

It is often discussed whether enough electricity for green hydrogen production will be available in the EU. A recent study by Kakoulaki et al. [121] calculates the electricity generation potential in the EU, accounting for 10,000 TW h/yr. When compared to the current production of 819 TW h in 2019, there would be enough renewable electricity available according to the authors.

Hydrogen applications and fuel cell vehicles

To date, hydrogen is mostly used as a chemical substance; nevertheless, there are other main applications for hydrogen. According to the International Energy Agency (IEA) [122], the main applications are to store additional electricity generated by renewables either to convert it back into electricity (very high losses) or to use it in industrial processes, to inject it into natural gas grids or to use it in the transport sector in fuel cell vehicles [122], see Fig. 15.

Especially challenging is the transport sector, which is almost completely based on fossil fuels. Largest amount of GHG emissions from the transport sector are caused by road transport dominated by passenger internal combustion engine (ICE) vehicles powered by fossil fuels. In the last few years, huge effort has been put into the electrification of mobility. This process is supported worldwide by a very broad portfolio of policy measures. Although the total number of electric vehicles (EV) has been rapidly increasing since 2010, reaching more than 7 million in 2019, e-mobility is still facing many challenges [123]. The majority of these EVs are charged by grid electricity. Although a very small number of EVs is currently powered by hydrogen, see Fig. 16, there are very high expectations of hydrogen and fuel cell vehicles (FCV) in the future. One of the first hydrogen applications in the transport sector is in passenger cars. However, these vehicles are mostly used in the US, Japan, Korea and Germany. In most other countries, fuel cell vehicles are still used in the scope of different demonstration projects.

Table 4 – Selected electrolysis plants in operation and in planning worldwide [1,111,117–120].

Project and country	Capacity (MW)	Use	Status	Start
Cachimayo Plant, Peru	25	Nitrate (fertilisers, explosives)	Operating	1965
Air Liquide Becancour, Canada	20	Industry, Mobility	Operating	2020
Refhyne, Germany	10	Refinery	Operating	2021
Fukushima Hydrogen Energy Research Field, Japan	10	Power, Mobility, Chemicals	Operating	2020
H2Future, Austria	6	Iron, blast furnace	Operating	2019
Energiepark Mainz, Germany	6	Industry, Mobility	Operating	2015
Plant Svartsengi, Iceland	6	Methanol	Operating	2011
H&R Ölwerke Schindler	5	Refinery	Operating	2018
Hybrit (Luleå)	4,5	Iron, direct reduction	Operating	2021
Green Lab Skive, Denmark	100	Methanol	Under construction	2024
HySenergy, Denmark	100	Refining	Under construction	2030
Puertollano Green Hydrogen Plant, Spain	830	Ammonia	Under construction	2027
Emsland hub (GETH2)	2000	Gas grid, Industry	In planning	2030
NorthH 2 green hydrogen, the Netherlands	3000	Grid injection, Industry	In planning	2027
Silver Frog, Italy	10,000	Grid injection, Mobility, Industry	In planning	2030
Asian Renewable Energy Hub, Australia	12,000	Export	In planning	2027

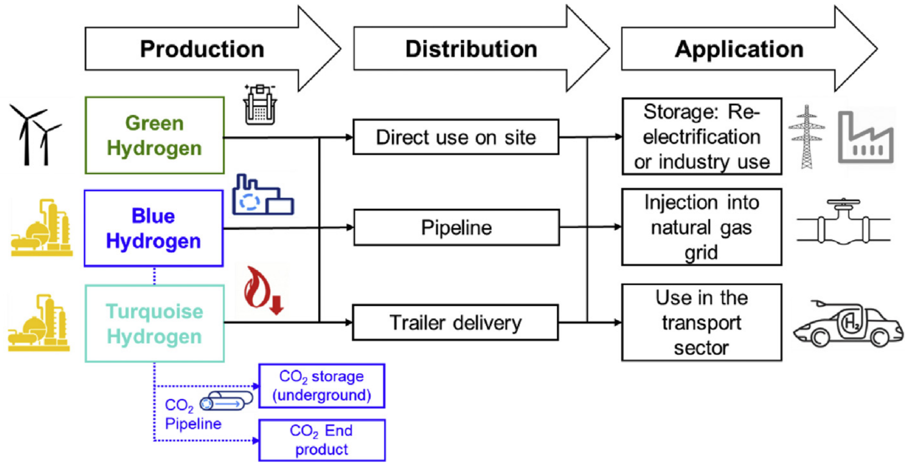

Fig. 15 – Hydrogen production and use in the future.

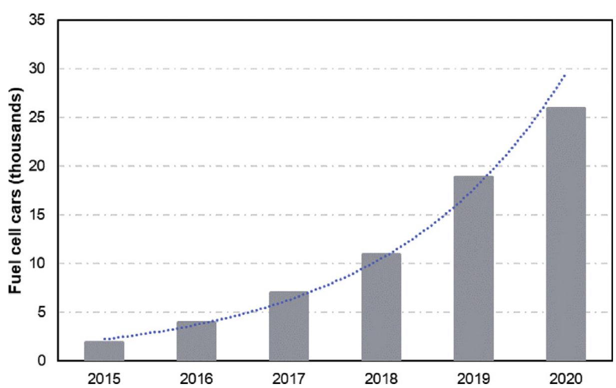

Fig. 16 – Stock of fuel cell vehicles [1,44,123–125].

To accelerate hydrogen, use in transport sector it is important to improve economic performance of hydrogen and fuel cells, as well as to develop the necessary infrastructure. This process could be significantly faster in the case of the increasing hydrogen use also in other energy or industry sectors.

Since emissions from the transport sector are continuously growing, of special interest is the possible use of hydrogen and fuel cell vehicles in the transport sector. In this paper, we have calculated the mobility costs of fuel cell vehicles in comparison to battery electric vehicles as well as conventional internal combustion engine vehicles. Total mobility costs per km driven are divided into capital costs (C_c), operation and maintenance costs ($C_{O\&M}$) and energy/fuel costs (C_e):

$$C_m \times = C_C + \times C_{O\&M} + \times C_e \tag{14}$$

In this paper, the focus is put on Well-to-Wheels (WTW) emission analyses. WTW analysis focuses on lifetime energy use and corresponding GHG emissions.

$$WTW = WTT + TTW \tag{15}$$

Tank-to-Wheel (TTW) describes the use of fuel in the vehicle and emissions during driving, and Well-to-Tank (WTT) describes emissions related to energy/fuel supply starting from primary energy sources (e.g. oil, coal, wind power, natural gas, etc.) up to the charging point or refueling station.

In the case of hydrogen use in the transport sector, besides hydrogen costs, very important are the capital costs of the fuel cell vehicles. The largest amount of the total mobility costs by all types of vehicles is caused by capital costs. The capital costs are currently especially high in the case of FCV, see Fig. 17.

Depending on the kind of electricity used in BEV or the color of hydrogen used in FCV, fuel costs could be lower or higher. However, the impact of energy costs is relatively low in comparison to the impact of capital costs. Yet, with the increasing number of electric vehicles, capital costs could be significantly reduced.

Although, hydrogen use in the transport sector is still not economically competitive with conventional vehicles, the major reason for their support through different policy measures is a possible benefit for the environment.

To contribute to significant reduction of emissions in the transport sector it is important to use low-carbon hydrogen in FCVs. The advantage of blue hydrogen is that the production process builds on already mature experience from grey hydrogen. However, CCS systems need to ensure an effective and durable storage of CO_2, which can cause additional infrastructure investments and may increase the total cost significantly.

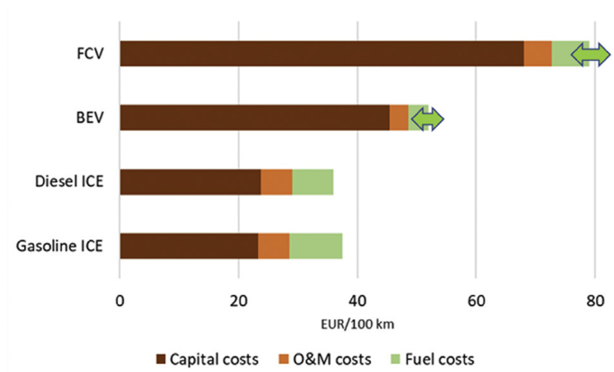

Fig. 17 – Mobility costs (own figure based on [126,127]).

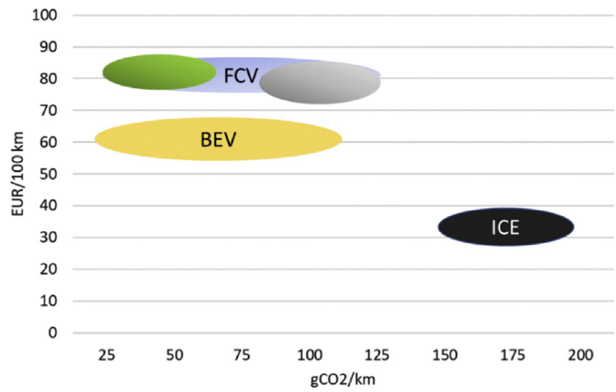

Fig. 18 – Mobility costs vs. emissions per km driven (own figure based on [126,127]).

The best option from an environmental point of view is the use of green hydrogen. Fig. 18 shows the range of emissions and corresponding mobility costs with different types of passenger cars.

Conclusions and outlook

While fundamentally a very broad range of „colors“ (options and paths to produce hydrogen) exists, only few may finally be proper for a sustainable energy system. The major open questions are: (i) What are the potentials and the overall costs of the different options? (ii) Will firstly the hydrogen infrastructure be built relying in a first step on mainly blue hydrogen or should the focus immediately be put on low carbon green hydrogen? (iii) What are the (embedded) GHG emissions of the different production paths? (iv) What are the overall costs of the different options? (v) To what extent can these options be produced in different countries? Especially for countries in the Northern hemisphere (e.g., northern Europe), the potentials from PV may be limited, but there could be the option of hydrogen imports.

The most important future options and the corresponding caveats are: (i) To produce green low carbon hydrogen via PV plants in the countries with a high number of sunshine hours and to transfer the hydrogen to northern countries; The caveat in the case is, whether it is really justified to transport hydrogen from emerging countries with own electricity generation mainly from fossil fuels to the rich countries? (ii) To produce green hydrogen by off-shore wind power plants, which still have a huge potential worldwide and to rely on an international exchange; (iii) depending on the CO_2-price, it might even become economically feasible to generate hydrogen from hydropower plants. The caveat is that in this case, the hydro-electricity is no more available for the normal electricity supply.

The major conclusion of this analysis is, that most important is to introduce an international market for hydrogen. With this hydrogen market, hydrogen could be produced in countries or regions that have preferable conditions for renewable electricity production, hence the lowest production cost. Having a worldwide traded commodity also simplifies the organization of supply and demand for hydrogen. As a first step, this could be done for different production technologies, see Fig. 10. Yet, ideally, in the mid-term, it would make sense to strive for one hydrogen market having the full external cost of all colors of hydrogen included.

In order to include all external costs of hydrogen production, further research is needed, especially on the difference between green and yellow hydrogen and a strong emphasis should be put on greening the electricity mix worldwide. Some other lower carbon hydrogen production methods need further research, especially on upstream emissions of natural gas and its influence on the overall emissions of blue and turquoise hydrogen. This paper presents an analysis of all major productions methods including their technical, economic and environmental advantages and disadvantages.

Finally, the major open question remaining is whether – including all external costs of all energy carriers, hydrogen of any color may become economically competitive in any sector of the energy system. The future success of hydrogen is very dependent on technological development and resulting cost reductions, as well as on future priorities and corresponding policy framework.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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