



REPORT



Factors determining emission intensity of hydrogen production pathways in the Netherlands

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Management summary

There are several ways to produce hydrogen and even more to transport, store and utilize it. The 'hydrogen colours' can help to easily categorize the different production pathways, but this categorization can also neglect relevant aspects that are considered in future hydrogen production projects. This report aimed to specifically focus on the climate impact of hydrogen production: what are the main factors determining the climate impact of hydrogen value chains?; what measures can be taken to reduce climate impact?; and how can this overview be used to assess hydrogen production projects in the Netherlands?

By literature search, 22 peer-reviewed papers and 1 grey literature paper have been selected to perform the analysis presented in this report. This selection contained 132 life cycle assessment (LCA) case studies on hydrogen production and supply pathways.

Our analysis shows that the impact on global warming of different ways of producing hydrogen is not solely determined by the "colour" of hydrogen. For example, using electricity or hydrocarbons can both have similar impacts. We distinguished the key factors and mitigation measures for two fundamentally different categories of hydrogen production technologies: electrochemical and thermochemical technologies.

For electrochemical hydrogen production (for example via electrolysis), the most important consideration is what type of electricity is used. When producing hydrogen with electricity, it's important to consider the source of electricity. If the electricity comes from relatively clean sources like wind, hydropower or nuclear power, the impact is lower compared to solar and biomass electricity (medium impact) or fossil fuel-based sources like coal or gas (high impact). Reducing emissions from the electricity source helps lower the impact of hydrogen production. Other factors to consider are how efficiently electricity is used and at which structure the hydrogen production equipment is located. The materials used in the electrolyser have minimal impact on global warming.

For thermochemical hydrogen production, the primary energy source used is important. Coal has the highest emissions, followed by natural gas. Biomass or biomethane have lower emissions due to their biological origin. Capturing and storing carbon can further reduce emissions. The impact also depends on the upstream emissions, if natural gas or biomethane is used and the energy used for supporting equipment. Extracting natural gas with low emissions and using clean energy for supporting processes can help



reduce the impact. The emissions from biomass and biomethane processing and transportation vary depending on different factors.

It was seen that effective utilization of byproducts (e.g. oxygen, electricity, heat, etc.) could significantly impact the global warming potential of the produced hydrogen. Also, the climate impact of compression, long-distance shipping and small-scale tank storage can be considerable. The impact of large-scale underground hydrogen storage remains unclear from the papers that were researched.

Overall, our findings show that it is possible to achieve very low (less than $1 \text{ kg CO}_2/\text{kgH}_2$) or even negative emissions for hydrogen production in the Netherlands by using renewable energy sources, biological sources, or fossil sources with carbon capture and storage. However, to achieve this implementing appropriate measures and making use of situational opportunities are important. We believe the information in this paper, together with the formulated questions can guide project developers and policy makers to reduce the GWP of future hydrogen production initiatives in the Netherlands.



1

Introduction

Hydrogen has been receiving growing attention from policy makers, the energy sector and energy consumers as a low-carbon energy carrier. This is represented by multiple hydrogen strategies and roadmaps that have been published by the EU Commission and its member states; the Netherlands has gone a step ahead and recently published a new roadmap specifically for hydrogen [1]. In this strategy document, hydrogen production and consumption are described as one solution for the decarbonisation of all six Cluster Energy Strategies of the Dutch industrial clusters [2]. Hence, there is an ever-increasing consensus that clean hydrogen can play an important role in reducing Dutch CO₂ emissions towards zero by 2050.

In many of the publications on clean hydrogen, a distinction has been made between 'green' and 'blue' hydrogen, or 'low carbon' and 'renewable hydrogen'. The terms 'green hydrogen' and 'renewable hydrogen' are commonly used for hydrogen produced via electrolysis powered by renewable electricity. 'Blue hydrogen' generally refers to natural gas-based hydrogen production where a large share of the carbon emissions is captured and stored underground. 'Low carbon hydrogen' usually can mean any type of hydrogen produced under a pre-determined emission benchmark.

Green and renewable hydrogen are typically seen as favourable options because the process uses renewable energy, and the electrolysis process does not lead to direct emissions¹ of greenhouse gases. However, the production and supply of green hydrogen can lead to indirect emissions.

Several studies have tried to investigate the carbon impact of green hydrogen, and often it has been compared with the blue hydrogen supply pathways or other pathways as well. A widely used methodology to analyse the environmental impact of those pathways is the Life Cycle Assessment (LCA) methodology that calculates corresponding emissions of a product, process or service based on the energy and materials that are required across the industry value chain from cradle-to-grave [3]. There is a wide variety in the scope, geographical location and case-specific characteristics and assumptions in the LCA literature. A general critique of LCA is that it provides generic insights for products or processes while outcomes for specific projects might vary widely, which is also identified in studies analysing green and blue hydrogen production pathways [4].

¹ See emission scope 1, 2 and 3 definitions by the Greenhouse Gas Protocol



Therefore, this paper aims to provide an overview and understanding of the most relevant factors to consider when assessing green and blue hydrogen production initiatives on their carbon intensity, specifically in the Dutch context. This will be done by analysing existing literature that performs LCA on electrochemical and thermochemical hydrogen production pathways. Insights from the literature will be used to:

- ⊕ Shed clarity on the most relevant factors determining the greenhouse gas emissions of electrochemical and thermochemical-based hydrogen production and supply pathways;
- ⊕ Assess the generic factors and identify relevant measures and decisions that can be influential in lowering the emission impact of electrochemical or thermochemical-based hydrogen;
- ⊕ Show how the generic insights from literature can be utilized in the Dutch context by providing an overview that can serve as a guideline to identify the relevant measures and factors on the emission impact of hydrogen production projects;
- ⊕ Identify the knowledge gaps in comparing the emission intensity of different hydrogen supply pathways for further research.

The study is organized as follows: Chapter 2 starts with an overview and methodology used to assess scientific literature on the subject of Life cycle analysis of various hydrogen production pathways. Chapter 3 provides an overview of the most relevant factors and insights from the literature on determining the carbon intensity of different hydrogen supply pathways in the Netherlands. Chapter 4 shows how the generic insights from literature can be used for specific projects. Chapter 5 discusses the results and provides knowledge gaps for further research and Chapter 6 offers conclusions to the report.



2

Reviewed literature

The scientific database Web of Science was used to find scientific studies which undertook an LCA of hydrogen production pathways. Several search terms were used to arrive at an overarching set of relevant studies on the topic. Some of the keywords (used in combination with keyword search terms 'AND' or 'OR') include 'hydrogen', 'hydrogen production', 'life cycle assessment', 'life cycle analysis', 'electrolysis', 'steam methane reforming', 'auto-thermal reforming', etc. The search terms led to a set of around 300 studies. A filtering mechanism was employed to identify the most relevant studies in line with the goals of the literature review. Firstly, we selected studies which were published after 2015 to identify the most recent state-of-the-science on hydrogen and to account for updates into emission factors across various LCA databases. Secondly, we read the titles of the studies, looked at the keywords and excluded the studies where hydrogen or LCA were not central topics. Thirdly, we read through the abstracts to further filter out studies which were not relevant to our scope. At this stage, we excluded several studies that were focused on the application of hydrogen in the mobility sector; these studies used a well-to-wheels perspective and as a result, were focused more on fuel cell technologies instead of the hydrogen production and supply pathways. Another area of filtering was the functional unit used to report the Life Cycle Impact (that is, Greenhouse Gas (GHG) emissions or Global Warming Potential (GWP)) of hydrogen supply pathways). Two types of functional units were used in the literature – weight-based (CO₂ eq per kg of H₂) or energy-based (CO₂ eq per MJ H₂). In the interest of ensuring comparability of results across literature, only papers in which the GHG/GWP results could clearly be translated into weight-based functional units were included.² Lastly, we read the abstracts of the shortlisted studies to arrive at the most relevant studies after applying the aforementioned filtering logic.

² We assumed 120,1 MJ per kg of hydrogen

After the process of filtering and selecting, we arrived at 22 scientific papers and 1 report from grey literature that we found relevant to the scope and purpose of this study. 21 of the 23 studies used case studies as a way to compare two or more hydrogen supply pathways or production technologies; 2 studies were focused on one case each. As a result, the literature review covered 132 case studies across 23 papers (see the overview in Appendix A). Figure 1 depicts the studies and case studies that were included in our literature review, along with the authors, and the year of publication.



Figure 1: Overview of studies and their contribution to the total amount of case studies. The numbers after the author's name and year indicate the number of case studies reported in the study/paper.

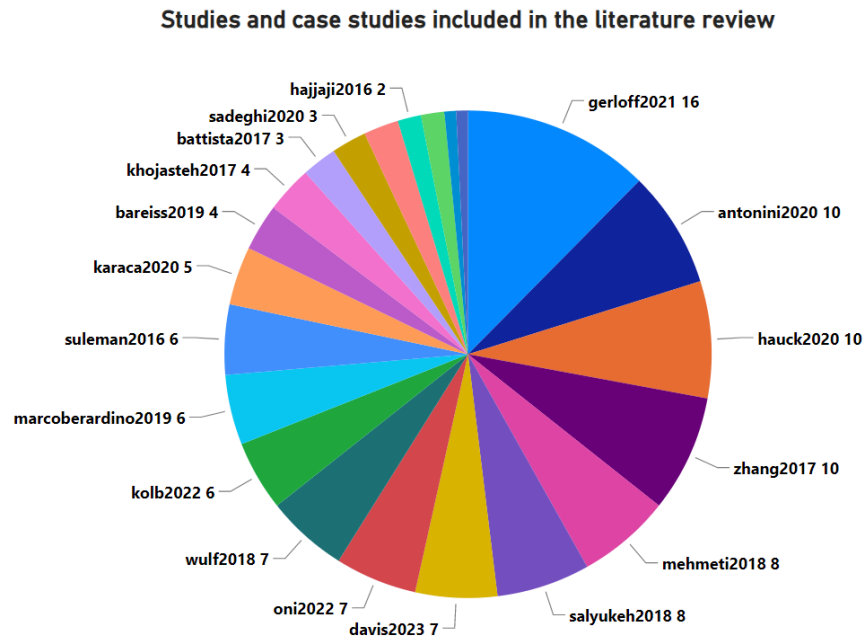


Figure 2: Distribution of publication years of the included case studies

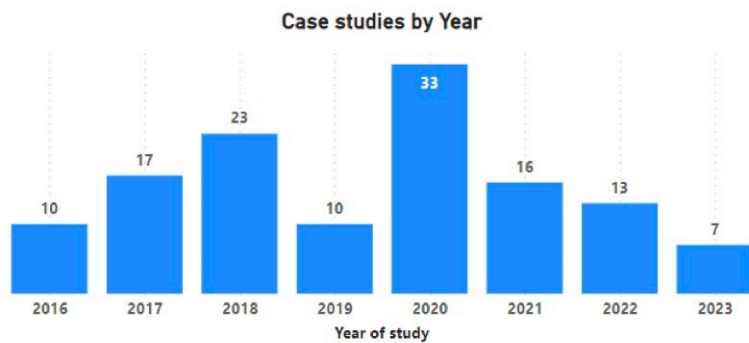
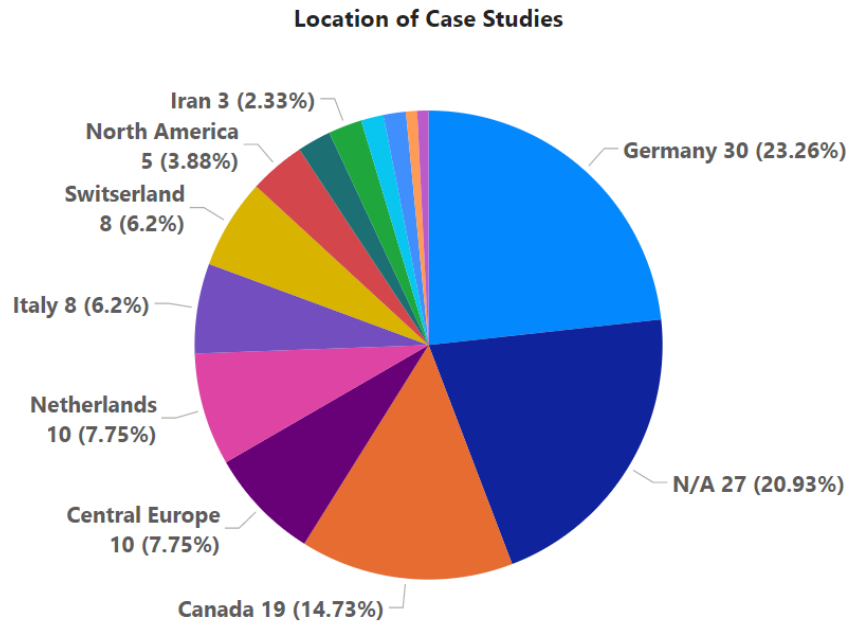


Figure 2 shows the distribution of studies across the years of publication. As can be seen, 2020 had the maximum number of studies (33) dedicated to the LCA of hydrogen pathways while the fewest studies were from 2016 and 2019 (10 each). 2023 is a promising year for research on this topic since 7 of the studies we shortlisted were already published in the first two months of the year.





Figure 3: Locations considered for the case studies involved in this literature review



There was a distinct trend observed in the location of the case studies, as shown in Figure 3. Of the total, 79% of the case studies were based in either Europe or North America; 21% did not state the location of the case study. Of the studies that mentioned their location, 71 studies were based in Europe while 24 were based in North America. In Europe, most case studies were located in Germany followed by the Netherlands and Central Europe (each with 10 cases). Switzerland and Italy had 8 case studies each and Denmark had 3 case studies. Of the 24 case studies in North America, 19 were based in Canada while 5 remaining did not mention the specific location. In four case studies, the hydrogen was produced abroad (in Chile, Canada and Morocco) and was imported to consumption centres in Germany.

Within this study, we define a hydrogen supply pathway as the collection of stages to supply hydrogen to a potential offtaker. Starting from the production of hydrogen, the supply pathway consists of compression, purification, storage and transport to the site of the end user.





Figure 4: Stages of the hydrogen supply pathways included in the case studies. Note: upstream emissions of the electricity and/or the fuel source are taken into account in the hydrogen production stage.

| | Within scope | | | | | Out of our scope |
|--------------------------------------------|---------------------|-------------|--------------|-------------|-------------|------------------|
| Lifecycle stage | Hydrogen Production | Compression | Purification | Storage | Transport | End Use |
| No. of case studies that include the stage | 132 (100%) | 70 (53%) | 68 (52%) | 27 (20%) | 34 (26%) | N/A |

As shown in Figure 4, the scope of the studies varied widely in terms of the stages of the hydrogen supply pathway included in the LCA. All 132 case studies included the production stage, but the remaining stages were not always included in the LCA. Compression and Purification were included in more than half of the case studies, but storage and transport were included only in around a fifth of the cases. We excluded the end-use part of the supply pathway in our analysis to retain focus on the production and supply of the hydrogen irrespective of its end-use.

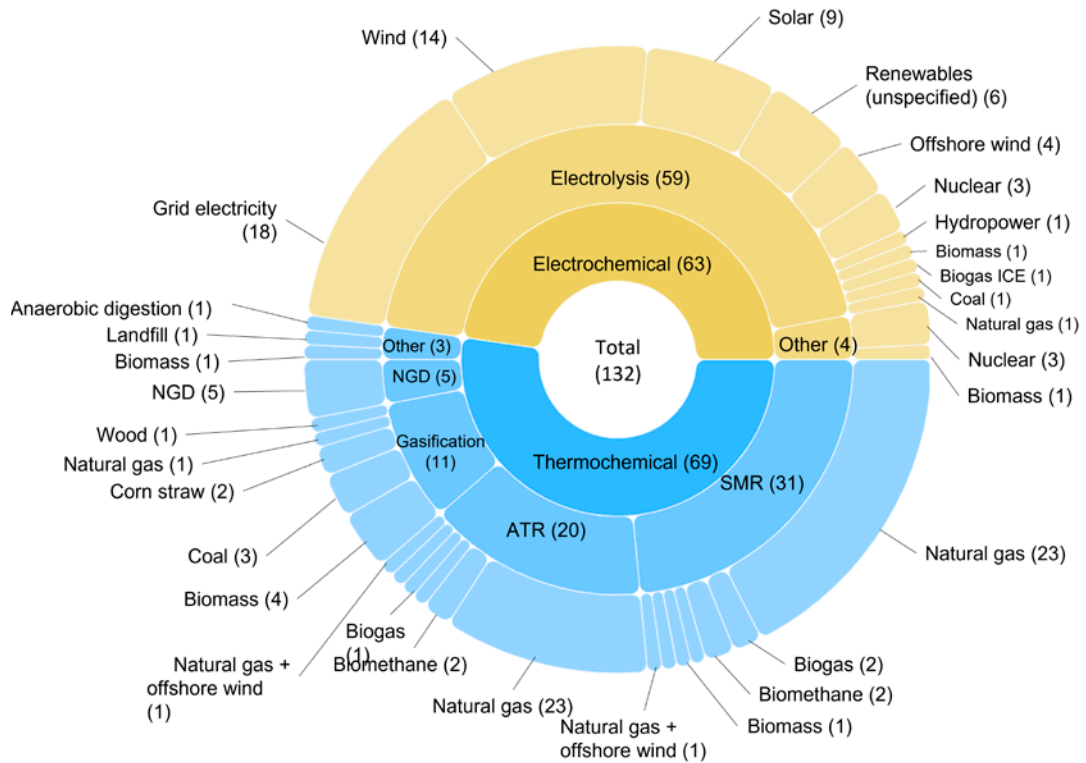
All of the studies used the guidelines for defining the Goal and Scope as part of the LCA, as defined by the ISO in Environmental management – Life Cycle Assessment – Principles and Framework, (2006) [5]. Within this framework, the authors of the studies have made methodological choices in defining the system boundaries (for example, by including in full or only partially, steps such as raw material extraction, infrastructure, transport of materials, and emissions). As a result, while all studies follow the conventions of LCA, the system boundaries were found to be highly case-specific, leading to variance in the GHG/GWP reported for the case studies. This, of course, has implications in terms of whether we can make a case-to-case comparison of the results and in exploring the underlying factors that have a significant impact on the GHG/GWP of the different hydrogen supply pathways.

Technologies and fuel sources covered in the literature: Several technologies can be used to produce hydrogen. This study uses the technology classification as per Valente et al. [6]: thermochemical and electrochemical production processes. 69 cases deployed a thermochemical process, comprising 52% of the total cases studied while electrochemical processes were used in 63 cases (47% of the total).





Figure 5: Overview of case studies by the technology and energy sources used for hydrogen production



Electrochemical Technology

Electrolysis was the predominant technology used for electrochemical hydrogen production; only 4 case studies used a non-electrolytic method to produce hydrogen. The non-electrolytic methods include 3-, 4-, 5- step Cu-Cl cycles with nuclear energy and dark fermentation of biomass using a microbial electrolysis cell. In terms of the energy sources for electricity, grid electricity was used in the largest number of cases (28% of electrochemical cases), followed by wind (22%) and solar (14%). 4 cases specifically mention offshore wind as the energy source and have been classified separately as such a distinction allows for further insights into the impact of energy sources on GHG/GWP. 6 case studies mentioned renewables as the source of electricity without specifying the technology. A small proportion of studies used electricity produced from nuclear energy or coal to conduct electrolysis.





Thermochemical Technology

Steam Methane Reforming (SMR) was the predominant technology used in 31 cases, almost half of all Thermochemical cases. Autothermal Reforming (ATR) was applied in 20 cases while Gasification was used in 11 cases. SMR and ATR were used predominantly with natural gas as a fuel source (75% and 70% cases respectively). Other fuel sources that were used with SMR and ATR included biogas/biomethane or biomass. Gasification technology was applied across diverse fuel sources – evenly distributed across different types of biomass, coal, corn straw and wood chips. Less frequently used technologies include Natural Gas Decomposition (NGD) and landfill waste or other biomass digestion.

The inclusion of Carbon Capture and Storage (CCS) as part of the hydrogen production under thermochemical processes has implications for the overall GHG/GWP. 26 out of 69 cases included CCS while 43 studies did not include CCS in the production process.



3

Emission intensity



Emission intensity factors of hydrogen supply

In this chapter, the main insights on factors that impact the emission intensity of hydrogen production will be discussed in general, and more specifically for the most commonly used and considered thermochemical and electrochemical processes.



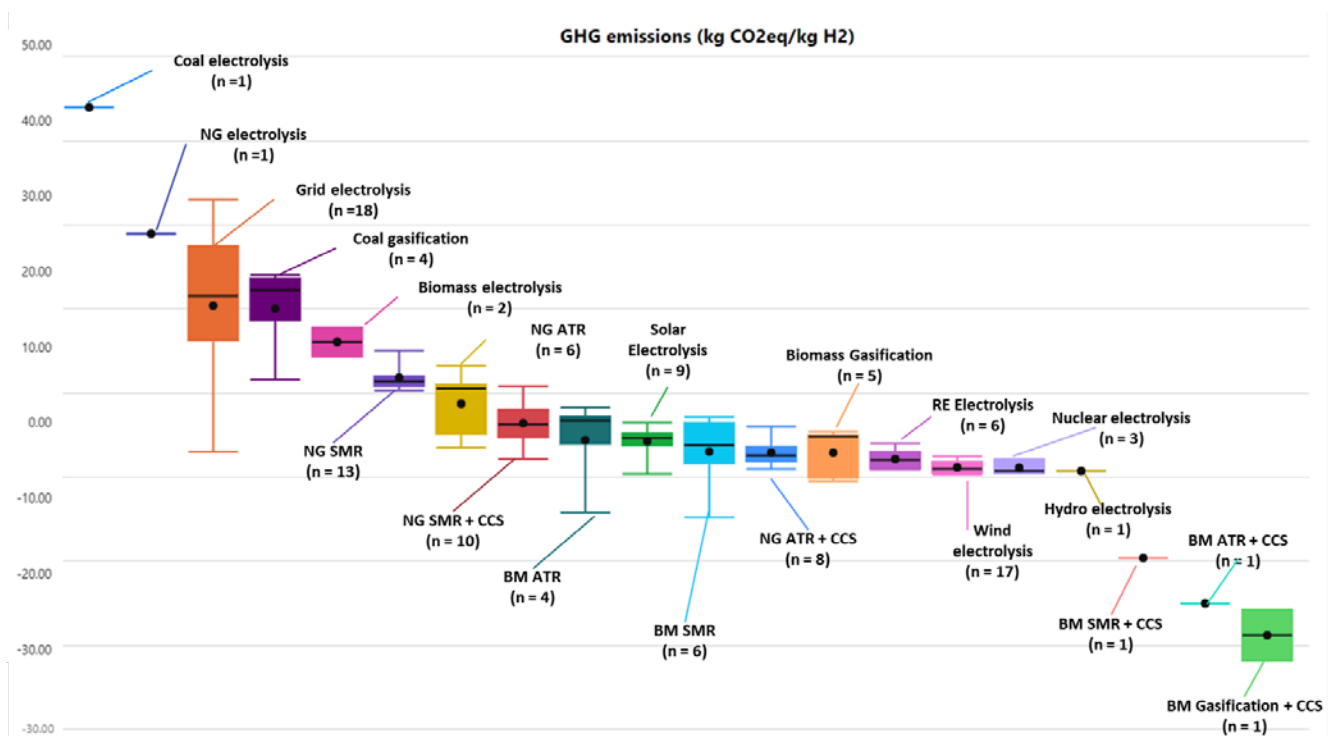
3.1 Overview of main production pathways and determinant factors

Figure 6 shows an overview of the GHG emission intensities (kg CO₂eq/kg H₂) that were reported by the case studies in the selected literature. The GHG emission intensities are categorized by the used technology and the primary energy source used in order to categorize the production pathway that the GHG emission intensity considers. The number (n) of included cases per category is shown. Very specific, or innovative pathways³ have been omitted in this overview for the sake of visibility. Moreover, it should be considered that the reported GHG emission intensities are not corrected based on the different scopes and other factors (like different purity, pressure or supply chain assumptions between the cases).

³ Such as: natural gas decomposition (NGD); syngas chemical looping (SCL); chemical looping reforming (CLR); biomass derived liquid reforming; dark fermentation-microbial electrolysis cell; nuclear 3/4/5 step Cu-Cl cycles; or autothermal catalytic membrane reactor.



Figure 6: Overview of emission impact bandwidths categorized by technology and primary energy source used. Note: This figure illustrates an overview of the different values reported in LCA studies on GHG emissions for hydrogen supply. The averages are not statistically representative and are not meant to be used to compare the different technologies, but the ranges of reported GWPs are useful for comparison and the differences between high and low values are relevant for analysis.





The following background information of the presented bandwidths should be understood:

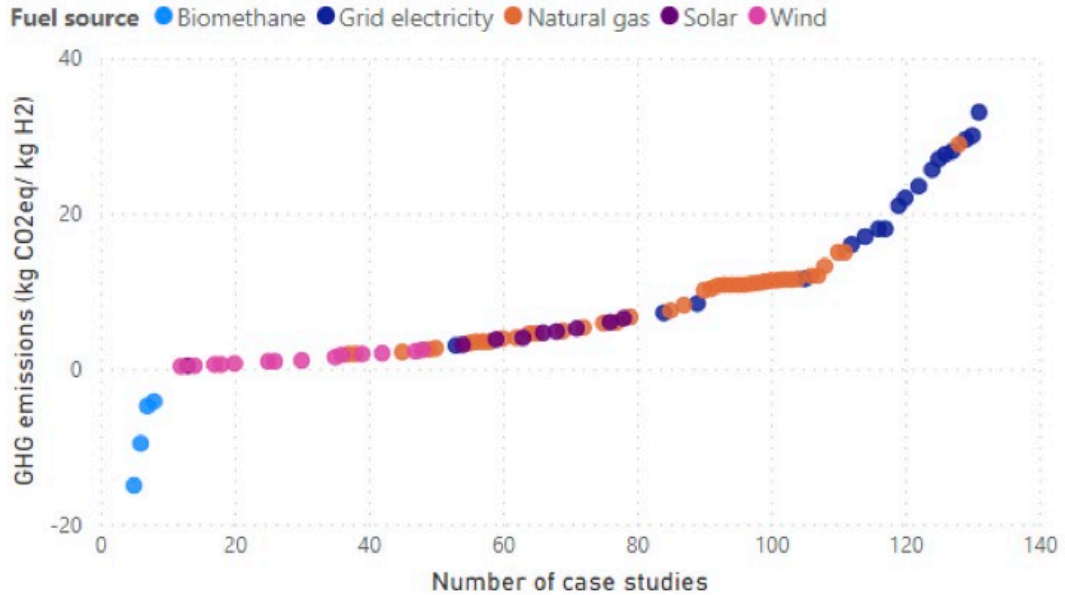
- ⊕ The large range of GWP for electrolysis using grid electricity is not surprising since the electricity grid consists of a mix of energy sources. The degree to which coal and natural gas contribute to the grid mix determines the carbon intensity of electrolysis using electricity from the grid.
- ⊕ The GWP of Steam Methane Reforming (SMR) and Autothermal Reforming (ATR) using natural gas is reported consistently in a large number of cases.
- ⊕ For hydrogen production technologies using biomass as the primary energy source, relatively large differences in GWP values are reported due to the broad range of biomass sources and handling technologies. Antonini et al. [7] show lower values for SMR and ATR using biomethane than the other studies (Battista et al., 2017; Di Marcoberardino et al., 2019; Hajjaji et al., 2016; Wulf & Kaltschmitt, 2018). We discuss this further in section 2.4.1
- ⊕ Although the 17 case studies on electrolysis with electricity from wind turbines seemingly show comparable absolute values in the figure, the third quartile of the case studies (1.8 CO₂eq/kg H₂) report three times higher emissions than the first quartile (0.55 CO₂eq/kg H₂).

Apart from the overview of reported emission intensities, the 23 papers were studied carefully on their scoping decisions and results. It is noticeable that although the papers contain different scopes (e.g. geography, value chain scope, functional unit) and sometimes report different GWP values, there is a consensus on the factors that are most impactful in the overall GWP. 15 out of the 23 papers report clearly on the main contributors to the overall GWP of the case studies and conclude the primary energy source (e.g. natural gas, coal, electricity) is the most significant emission impact factor. Only in case studies consisting of thermochemical processes (mainly ATR) with very high CCS capture rates, the electricity used for the ancillary processes is the main global warming impact driver instead of the primary energy source [7], [8]. To illustrate the impact of the primary energy source on the overall emissions in the production of hydrogen, we ordered the case studies with the most investigated types of primary energy sources (grid electricity, natural gas, wind electricity, solar electricity and biomethane). Figure 7 clearly shows that the hydrogen production case studies using grid electricity typically lead to the highest emissions, followed by natural gas (with some exceptions where CCS is applied); solar electricity; wind electricity; and biomethane respectively. A similar trend was seen in a literature review consisting of hydrogen production LCAs in the period between 2009 and 2015 [9].



Figure 7: Ordered GWP of case studies and marked by primary energy source (every dot represents one case study)

Fuel source, Number of case studies and GHG emissions (kg CO₂eq/ kg H₂)

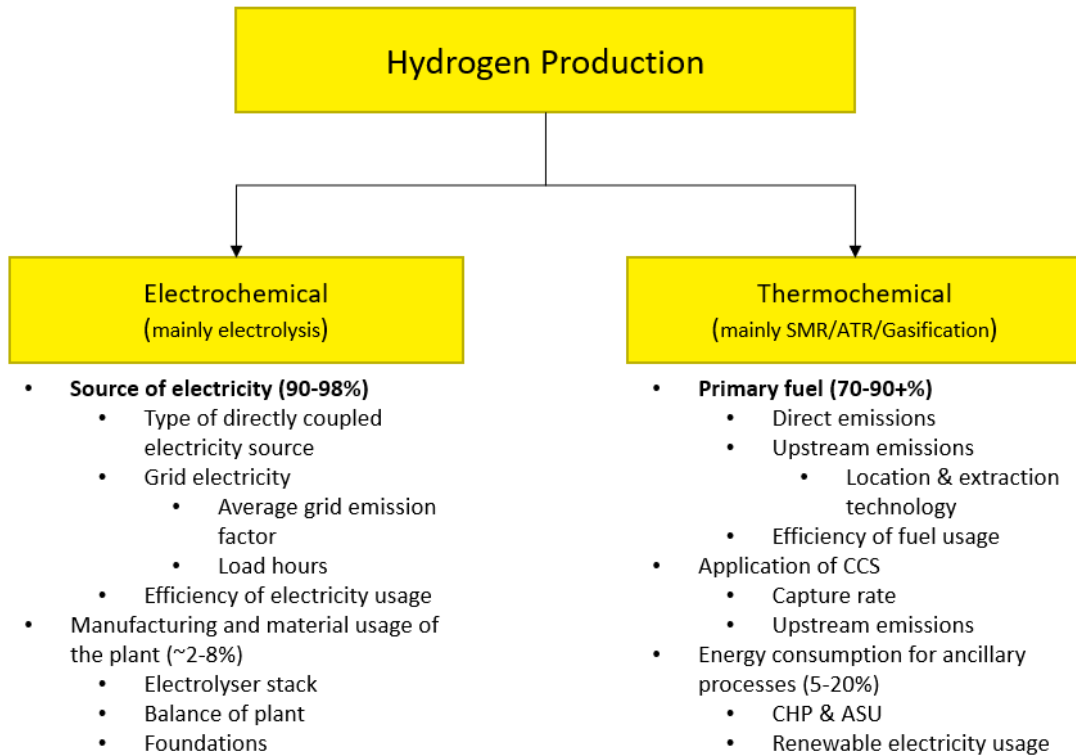


The primary energy source typically contributed 90-98% of the emission impact of electrochemical hydrogen production processes [10], [11] and 75-90+% to the emission impact of thermochemical processes without applying CCS [7], [10], [12], [13]. The other factor impacting the life cycle emissions of electrochemical hydrogen production processes is the manufacturing of the electrolyser [14], [15]. For thermochemical hydrogen production processes, the other factors are the application of CCS and the electricity consumption of ancillary equipment within the process (see Figure 8). In the next sections, the emission impact factors for both electrochemical and thermochemical processes are described in greater detail.





Figure 8: Overview of main factors determining GWP of electrochemical and thermochemical hydrogen production



3.2 Factors determining the emission intensity of electrochemical hydrogen production

3.2.1 Source of electricity

In the previous chapter, it was highlighted that the LCA literature on electrochemical hydrogen production suggests that the source of electricity contributes to 90-98% of the overall GWP ([14] (96%); [16] (92-98%), [10] (90%), [11] (70-98%)). It was also seen that using grid electricity in most of the cases typically leads to more GHG emissions than solar or wind electricity only. This can be explained by looking further into the emission intensity of each electricity source individually (see Figure 9 for an overview):





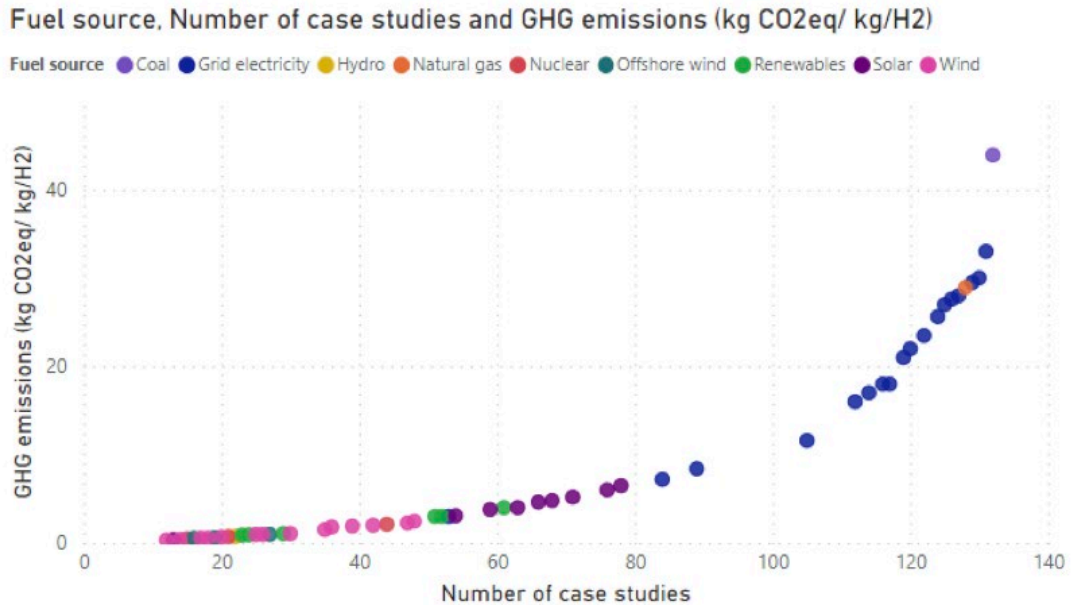
4 A significantly different value of 0.37 CO₂eq/kg H₂ was reported in [32]

- ⊕ for electrolysis using coal-based electricity 44 kg CO₂eq/kg H₂ was reported [17];
- ⊕ for electrolysis using natural gas-based electricity 29 CO₂eq/kg H₂ was reported [17];
- ⊕ for electrolysis using biomass-based electricity 14-18 CO₂eq/kg H₂ was reported [8], [17];
- ⊕ for electrolysis using solar electricity typically 3-6 CO₂eq/kg H₂ was reported [10]–[12], [17], [18];⁴
- ⊕ for electrolysis using wind electricity 0.39-2.26 CO₂eq/kg H₂ was reported [4], [10], [11], [15]–[19];
- ⊕ for electrolysis using nuclear electricity 0.48-2.11 CO₂eq/kg H₂ was reported ([17], [20]); and
- ⊕ for electrolysis using hydropower 0.72 CO₂eq/kg H₂ was reported [17].

Therefore, electrolysis using grid mixes containing a relatively higher share of coal and natural gas-based result in high carbon emission intensity (e.g. Germany in [21] but a grid mix containing a lot of hydropower results in lower carbon emission intensities (e.g. Switzerland in [11]).



Figure 9: Overview reported GWP of electrolysis categorized by the used electricity source (every dot represents one case study)

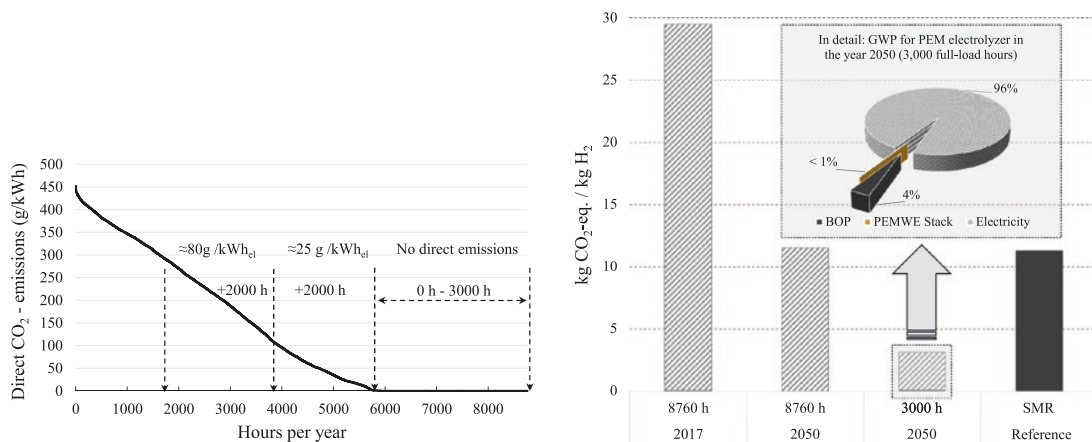




Especially for electrolysis running on grid electricity with higher shares of coal and natural gas, the load hours of the electrolyser become more relevant [14]. The left side of Figure 10 shows that the carbon intensity of the electricity grid mix can differ over time (high when coal and natural gas are used to satisfy demand, low when renewables are sufficient to satisfy demand). If electrolysers are running only during the hours when the grid electricity is generated via low-emission sources, the carbon emissions of electrolysis using grid electricity can be reduced significantly (see right side of Figure 10). Hence, if electrolysers are using grid electricity, the load hours in relation to the hourly electricity grid mix are an important factor impacting the GWP.



Figure 10: Impact of load hours on the GWP of electrolysis using grid electricity with significant shares of natural gas and coal [14] Note: this source assumes a 2050 electricity grid mix still using fossil sources. The left figure only shows direct emissions of electricity generation (2050) and the right figure direct and indirect emissions of hydrogen production (in 2050 8760 hours using 40% natural gas-based electricity and in 2017 using 54% of fossil sources including coal as well).



Since the electricity source was seen as the significant contributor to the GWP of hydrogen production by electrolysis, the amount of electricity used to produce one kg of hydrogen (i.e. the efficiency) is a factor of consideration in the reported GWP. Noticeably this has just been specifically concluded in two sources [4], [11]. Therefore, future research should indicate the relevance of this factor more extensively.



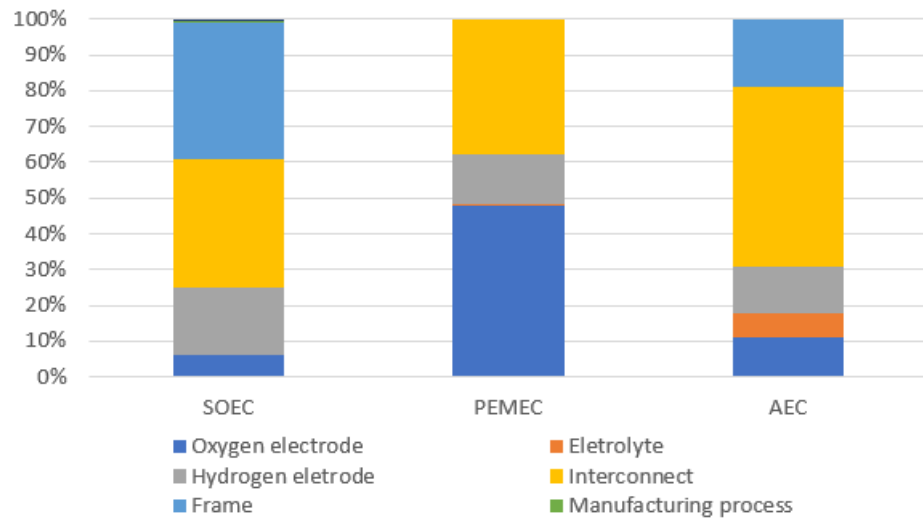


3.2.2 Manufacturing and material use of the electrolyser

The manufacturing of the electrolyser and the materials required are the remaining, small contributors to GWP (~2-8%) of electrochemical hydrogen production (See Figure 8) [14], [15]. Going beyond the electrolyser stack itself, the balance-of-plant, foundations and steel construction elements contain significantly more mass of materials than the materials for the electrolyser stacks and contribute more significantly to the GWP [14], [15]. To illustrate, Bareiß et al. show that the electrolyser stack itself contributes less than 1% to the overall GWP of 1 kg of hydrogen production, while the balance of plant and foundations contribute 4% [14]. Zooming in on the impact of the stack components, Zhao et al. ([16]) show the contribution of each component to the GWP of the stacks of the different electrolyser technologies (see Figure 11).



Figure 11: Contribution in % of each component to the GWP (kg CO₂eq/kg H₂) per m³ of stack for solid oxide electrolysis (SOEC), polymer electrolyte membrane electrolysis (PEMEC) and alkaline electrolysis (AEC). Retrieved from [16]. and indirect emissions of hydrogen production (in 2050 8760 hours using 40% natural gas based electricity and in 2017 using 54% of fossil sources including coal as well).





5 See [15] for small-scale electrolysis at HRS; see [14] for electrolysis in general; and see NSE 4 for offshore structures such as platforms and artificial islands.

To conclude, the overall impact of material use and manufacturing of the electrolyser is small. It is more relevant to focus on the materials used in the foundations and balance-of-plant of the electrolyser than on the stacks itself.⁵ In general, we see the materials for structures could matter more for small scale electrolysis; offshore structures; or electrolysers with lower utilization rates, although compared to the impact of the source of electricity, it is typically not the main contributor. Note that these conclusions are based on our focus on the GWP, and not on other environmental measures such as material usage, acidification, eutrophication, photo ozone creation, particulate matter and human toxicity [10], [16].

3.3 Factors determining the emission intensity of thermochemical hydrogen production

3.3.1 Primary energy source

Similar to the electrochemical process, the primary energy source is the main GWP contributor for thermochemical hydrogen production processes (gasification, SMR and ATR) if fossil sources are used and no CCS is applied. All the papers that specify the contribution of the primary fossil energy source agree that direct emissions of using coal in gasification [10], [12] and natural gas in SMR and ATR [7], [10], [12], [13] contribute to approximately 75-90% to the total life cycle emissions of hydrogen production.⁶ If the upstream emissions of extracting the primary energy source are also taken into account, the contribution is reported to be even higher than 90% [7], [22]. For natural gas, upstream emissions contribute to 10-16% (or: 0.72-1.7 kg CO₂eq/kg H₂)⁷ of the overall hydrogen production life cycle emissions [7], [12], [22] while for coal, upstream emissions only contribute to a tiny share in the range of 1-3% (or: <0.5 CO₂eq/kg H₂) [12].⁸ For example, Hauck [4] assumed 0.72 kg CO₂eq/kg H₂ upstream emissions by using Dutch natural gas from electrified production platforms, which is over 50% less than Oni et al. [22] and Antonini et al. [7] that looked to Canada and Central Europe, respectively. Moreover, small differences between SMR and ATR are reported in the amount of natural gas consumed per kg of hydrogen produced ([22], [23], for example, 0.18 MJ NG/kg H₂ for SMR and 0.15 MJ NG/kg H₂ for ATR [22]). On the contrary, ATR typically uses more electricity than SMR.

As the direct emissions from fossil sources are significant, (partial) replacement of fossil sources by biogenic sources can significantly reduce the overall emissions. Several papers investigated the options of using biomass for gasification [10], [23], [24], biomethane for SMR [8], [10], [25], [26] and biomethane for ATR [7], [8], [25]. We observed some differences in the results, commonly due to the differences in biomass used or differences in processing the biomass.

6 Although we mentioned that coal gasification has a significantly higher GWP (mainly 21-24 CO₂eq/kg H₂) than natural gas reforming (mainly 10-13 CO₂eq/kg H₂), the contribution of the primary energy source to the total emissions seems relatively the same

7 Note: Hauck [4], the only study that specifically used natural gas from Dutch electrified natural gas extraction platforms, reported upstream emissions of only 0.72 CO₂eq/kg H₂

8 Appendix C provides additional information on the GWP impact of upstream natural gas emissions. Coal extraction can involve methane emissions as well, depending on (the lack of) taken measures.

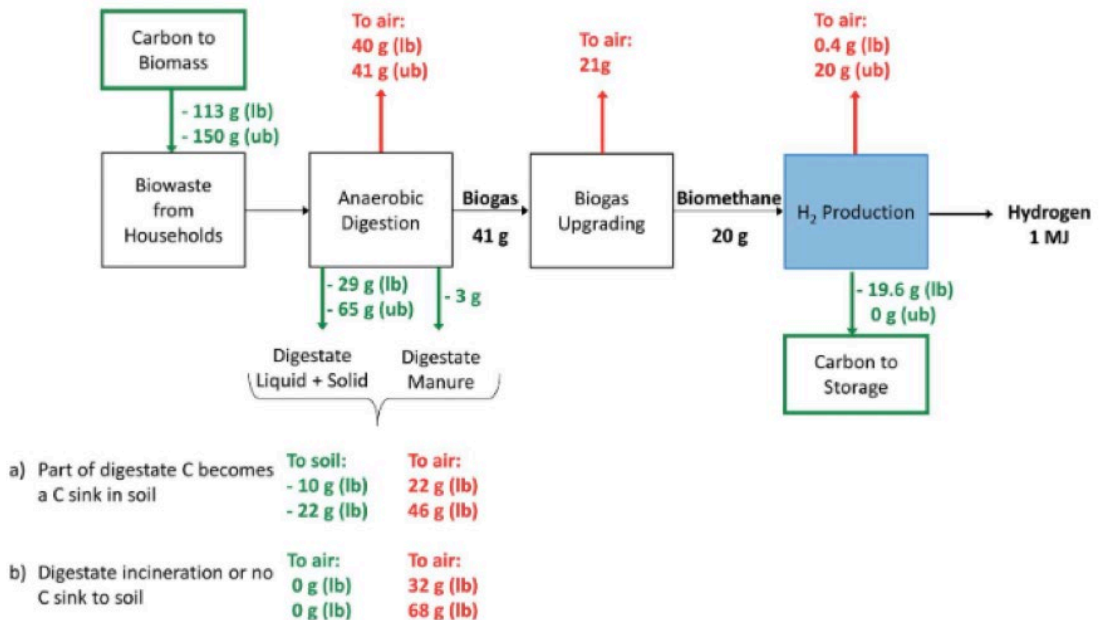


Biomass for gasification process: In all three studies, the handling and processing of the biomass were considered and described: Wulf & Kaltschmitt [10] used wood consisting of forest residues from German spruces that were shredded and transported over 50km; Salkuyeh et al. [23] did not specify the type of biomass but included processing, storage, handling and transportation into the system boundary; Li et al. [24] describe the process of handling and transporting wheat straw in China very carefully, including emissions evolving during these broad ranges of activities. The results indicate that wood gasification leads to additional electricity-related emissions (for biomass pre-treatment) compared to coal, however the overall emissions decrease due to the carbon-neutrality of the direct emissions [10]. In Salkuyeh et al. [23] the direct emissions are also eliminated due to the carbon-neutral nature of the biomass. Since electricity is also produced via CHP during the biomass handling process and credits are given for this, the study reports negative emissions for this hydrogen supply pathway. In Li et al. [24] significantly less emissions (2.6 times) are seen for using biomass compared to fossil gasification, although emissions result from the use of fertilizers and electricity. Hence, the exact impact of the biomass gasification pathway is hard to digest from these sources, but it is clear that the decisions in the biomass handling and supply pathway can have a considerable impact on the hydrogen production GWP, and that, in general, use of biomass reduces the emission impact of gasification compared to the use of fossil sources.

Biomethane for SMR and ATR processes: Similar insights are observed as for biomass in gasification processes. The studies consider different biomass to biomethane pathways, but all papers conclude a considerable decrease in GWP when using biomethane compared to natural gas [7], [8], [10], [25], [26], although using biomethane is slightly less energy efficient than natural gas [7]. A major difference is seen between Antonini et al. [7] and the other sources due to the credits that lead to significant negative emissions (-4.2 to -4.7 CO₂eq/kg H₂) when using biomethane for hydrogen production even without applying CCS. This is a result of the assumption that digestate, which is a by-product of anaerobic digestion of municipal waste, is used as fertilizer and therefore acts as carbon sink (see Figure 12). On the other hand, Wulf & Kaltschmitt [10] consider significant emissions during the supply of biomethane for SMR (4.55 kg CO₂eq/kg H₂) still representing 88% of the total life cycle emissions.



Figure 12: (Example) carbon balance of the hydrogen production chain based on biowaste as considered in [7]. The digestate is used as a) fertilizer or b) incinerated; lb= lower bound; ub= upper bound, values differ at reformer if CCS is used (lb) or not (ub), and if low (lb) or high (ub) carbon uptake into the soil is assumed.



3.3.2 Application of carbon capture and storage

As direct emissions contribute to the major share of the GWP of thermo-chemical processes, these emissions can be reduced by applying Carbon Capture and Storage (CCS) at the cost of some additional energy usage to capture, transport and store the carbon.

In the SMR process, CO₂ can be captured at two locations, leading to 50-70% of emission reduction if CO₂ is only separated from the synthesis gas stream after the water gas shift reaction (pre-combustion) or around 80-90% if CO₂ is also captured from the furnace flue gas stream (post-combustion) [7], [22]. In the ATR process, all direct CO₂ emissions are from the combustion of the PSA-tail gas in the fired heater. High capture rates of 85-98% can be reached by applying pre-combustion only [4], [7], [27]. When CCS is applied, additional energy is required to separate, compress, transport and sequester the CO₂. Both Oni et al. [22] and Davis et al. [27] assume that the CO₂ is captured and transported over an 84 km pipeline, which results in additional electricity usage. If SMR is used without CCS, 0.96 kWh of electricity per kg of produced hydrogen is required. If SMR with 52% capture was applied, the electricity usage increased to 1.32 kWh per kg of hydrogen; and if SMR with 85% capture





was applied, the electricity requirement increased significantly to 4.42 kWh per kg of hydrogen. ATR without CCS consumed 2.35 kWh/kg of hydrogen and with 91% captured 3.59 kWh/kg of hydrogen [22], [27]. Hence, if higher capture rates are desired ATR becomes relatively more efficient compared to SMR. Other studies do not offer specific values on additional energy usage due to the application of CCS, because it has not been reported specifically or it is not directly traceable due to the assumption that electricity is obtained via a Combined Heat and Power (CHP) installation [4], [7], [23], [28]. However, all studies clearly conclude that:

- ⊕ SMR with 50-60% capture rates can reduce the overall GWP of the produced hydrogen by around 25-50% compared with not applying CCS [7], [22], [27];
- ⊕ SMR with 80-90% capture rates can reduce the overall GWP of the produced hydrogen by around 40-60% compared with not applying CCS [7], [22], [27];
- ⊕ ATR with 91-96% capture rates can reduce the overall GWP of the produced hydrogen by around 55-75% compared with not applying CCS [4], [7], [23], [28].

Three notes should be made interpreting the numbers above. Firstly, Salkuyeh et al. [23], [28] show a lower overall GWP reduction (5% for SMR with capture after water gas shift reaction; 45% for ATR with carbon capture) since these studies assume that the CO₂ has to be liquified which demands more energy than compressed transport. Hauck [4] shows a relatively strong reduction for SMR with CCS (80%) because a relatively high capture rate of 95% was assumed. Antonini et al. [7] also investigated the impact of applying vacuum pressure swing adsorption (VPSA) instead of pressure swing adsorption (PSA) for separating the CO₂ from the synthesis gas stream. It was argued that VPSA can achieve high capture rates (>97%) at lower GWP impact than PSA because the electricity consumption for PSA increases relatively more (i.e. exponentially) than VPSA when higher CO₂ recovery rates are aimed to be achieved.

Applying CCS on SMR or ATR using biomethane instead of natural gas leads to a similar impact. The main difference is that instead of direct fossil emissions being eliminated, biogenic direct emissions are taken out of the GHG emission cycle and therefore can be considered negative emissions [7].

Next to the major considered methane-based thermochemical hydrogen production pathways (SMR and ATR), some other options have been reviewed in our literature selection:



The first is natural gas decomposition (NGD). This process uses a fluidized bed reactor with an internal cyclone that helps to separate the solid carbon from the produced hydrogen and unconverted natural gas. After this process, the remaining CO₂ is captured by a PSA process leading to a capture rate of 90%. Initially, the GWP of hydrogen produced by this process is already just 4-4.89 CO₂eq/kg H₂ (as a part of the carbon (61%) is leaving the process in a solid state per definition, and therefore not contributing to GHG emissions). Applying CCS on the remaining CO₂ streams via PSA leads to a GWP of 3.3-4 CO₂eq/kg H₂ [22], [27].

The second and third alternative options discussed are syngas chemical looping (SCL) and chemical looping reforming (CLR). Both processes use a chemical looping gasification process in which multiple reactions are performed to obtain pure streams for both hydrogen and CO₂. The difference is that SCL contains an autothermal reformer and in CLR the natural gas is directly fed into the chemical looping unit. Applying carbon capture leads to a reduction in GWP from 11.7 to -0.9 CO₂eq/kg H₂ for SCL and 8.7 to 0.1 CO₂eq/kg H₂ for CLR [28]. Note that this is the only study that investigated these two options, using an alternative setup by using electricity from a CHP installation. We discuss the implications this has on the results in greater detail in section 3.3.3 as this also impacts the results for the SMR and ATR pathways.

Next to the methane-based thermochemical processes, Salkuyeh et al. [23] also investigated the impact of CCS on two biomass gasification using a fluidized bed gasifier (FB gasification) or an entrained flow gasifier (EF gasification). Note that this study assumes that the electricity used in the process is generated by a CHP. Like the processes discussed previously, here CCS lowers the GWP of the produced hydrogen (-0.1 to -21.9 and -0.5 to -15.8 CO₂eq/kg H₂ for FB and EF gasification respectively). Although the overall GWP decreases, also for these pathways, applying CCS comes with the (relatively small) cost of more biomass and electricity usage to produce the same volume of hydrogen [23]. Typically, the EF and FB gasification pathways come with higher total energy usage (fossil and/or non-fossil) than the methane-based processes [23].

⁹ As discussed in the section on CCS, due to the decrease in direct emissions and increase of electricity usage, the GWP contribution of electricity consumption increases if CCS is applied.

¹⁰ The compressors and PSA's are also fuelled (partially) by fossil fuels or syngas streams, or syngas streams are used to fuel the CHP. It becomes not directly clear from the sources what the GWP impact of these decisions are.

3.3.3 Energy consumption for ancillary processes

The studies that specify the contribution of different emission impact categories conclude that electricity consumption for ancillary processes (without CCS)⁹ typically contributes to less than 5% to the overall GWP for SMR (or: <0.52 kg CO₂eq/kg H₂) [4], [10], [12], [22] and 11-20% for ATR (or 0.36-2.52 kg CO₂eq/kg H₂) [4], [22]. Typically, electricity is, or can be, used in these processes for general ancillary processes, compression and purification (PSA).¹⁰ The major reason that ATR consumes more electricity than SMR is that an air separation unit (ASU) is used to obtain oxygen that is required in the reactor [4], [22].



11 Unspecified for [21] as the coal gasification route is only included for comparison purposes in this paper.

Some studies involve a local CHP unit in the hydrogen production setup, which effects the results as a fuel other than electricity is consumed to produce steam and power simultaneously inside the plant. All case studies considering coal or biomass gasification include CHP as a part of the hydrogen production facility [11], [12], [23], [24].¹¹ For SMR and ATR, this is the case in several studies (at least [7], [10], [11], [23], [28]). CHP units can typically be integrated efficiently if both heat and power are required, which is the case in the considered hydrogen production pathways: The steam is used in the reactors and electricity for specific types of ancillary equipment, but also the carbon capture appliances. Hence, if case studies consider CHP units, additional electricity usage results in more natural gas consumption per produced kg of hydrogen.

Alternatively, some case studies (mainly gasification related) consider that more electricity is generated than consumed, and therefore exported to the grid. If this is the case, credits for the supplied electricity are applied under different assumptions. Wulf & Kaltschmitt [10] and Sadeghi [12] assume a credit covering the average emission factor of the electricity grid, leading to a credit of 1-2 kg CO₂eq/kg H₂ for hydrogen produced by coal gasification. Salkuyeh et al. [23] consider credits for electricity exported during the biomass EF and FB gasification processes and in [28] during the SCL and CLR processes using natural gas, both resulting in GWP results close to zero due to credits related to avoided electricity delivered by natural gas-fuelled CHP. The impact of these credits will disappear if carbon-neutral/renewable electricity grid mixes would be assumed/achieved.

A final consideration is to use renewable electricity in the ancillary processes. There was only one study in our literature selection that looked into this specifically (considering Dutch offshore wind). The impact on SMR (with or without CCS) was seen to be relatively limited due to the relatively low electricity usage considered in this study [4]. The impact on ATR, especially on the case applying CCS was significant due to the relatively high electricity usage considered in this study, decreasing the GWP from 2.16 to 0.96 kg CO₂eq/kg H₂ [4].

Hence, the strategic decision to design thermochemical hydrogen production plants including a CHP unit and/or the use of renewable electricity is one of importance for the overall GHG emissions, but the options are not compared specifically with each other in literature yet to the best knowledge of the authors.



3.4 Hydrogen production emissions in relation to the other chain elements

¹² This is partially a result of selecting papers with the functional unit per kg of hydrogen. Studies including transport and storage are often focussed on specific hydrogen applications (such as mobility or industry) and therefore use the functional unit relevant for the end product (e.g. per km driven, per ton of ammonia).

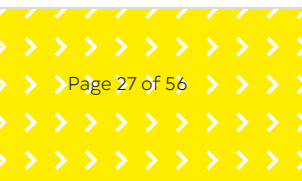
Figure 4 showed that most of the case studies do not include the transport and storage of hydrogen in their scope.¹² Thereby, based on the characteristics of the technology and the degree to which certain supply chain elements are taken into account in the case studies, we notice that emissions related to compression and transportation might be production technology-agnostic, as compression and transportation have been done relatively equally independent of which production technology is used. Purification is usually more applicable to the thermochemical processes, as in most of these processes, first, syngas is produced which is purified further using PSA. Electrochemical processes, mainly considering electrolysis, are known for the high purity of the hydrogen output and therefore, do not usually require any additional purification steps. Electrochemical processes that use renewables are often characterized by the variable generation of solar and wind, therefore, storage might be required in this supply chain.

Table 1: Overview relation of other hydrogen supply chain elements to production technology

| Compression | Technology-agnostic | Applied to all production technologies |
|--------------------|----------------------------|---------------------------------------------------------|
| Purification | Technology-dependent | Usually applied to Thermochemical |
| Storage | Technology-dependent | Usually applied to vRES-based H ₂ production |
| Transportation | Technology-agnostic | Applied to all production technologies |

There were just a few (mostly small-scale applications) that considered storage for electrochemical hydrogen supply [10], [15], [18], [19], [27].

The emission impact of the energy requirements for compression and purification are typically not separated in most of the papers and therefore it is not always specified what the exact contribution of these elements is. However, chapter 3.3.3 made clear that the energy consumption for ancillary processes is relatively modest.





If we consider the scope of the whole hydrogen supply chain, in most of the cases, the impact of storage and transport on the total GWP is modest compared to the production stage, although this is highly situation dependent. Therefore, we highlight some examples from our literature selection in which transport and/or storage contributed quite significantly to the overall hydrogen chains' GWP: Wulf & Kaltschmitt [10] showed that if hydrogen is transported at 500 bars, the required compression and conditioning has an impact but still in the modest range of around 1 kg CO₂eq/kg H₂, and the overall transport and storage emission contribution in Germany was in the range of 1.21-2.46 kg CO₂eq/kg H₂. Burkhardt et al. [15] consider a local wind-based hydrogen supply chain for mobility; here, the compressed tank storage had a considerable impact of 27% (see Table 2) on the overall emissions, mainly due to the required concrete foundation and steel for the construction of the tank. Local electrolysis that supplies its hydrogen via a pipeline leads to significantly lower emissions and another distribution along the chain, according to Ghandehariun and Kumar [19]. This example shows that, at least for decentralized wind-based hydrogen supply, considerations for end-use, storage and material required for foundations (next to the factors described earlier) can result in different outcomes. Ghandehariun and Kumar [19] assume that the produced hydrogen can be balanced and used somewhere along the (relatively long) 400 km pipeline. Therefore, the impact of hydrogen transport by pipeline seems relatively modest. It is not clear from the studies how the potentially-required large-scale underground hydrogen storage would impact the GWP of renewable hydrogen supply.



Table 2: GWP impact and distribution of two decentral wind-based hydrogen chains with different chain considerations and assumptions

| Type of chain | Decentralized wind-based hydrogen supply chain for mobility | Decentralized wind-based hydrogen transported via pipeline |
|----------------------------------------------------------|-------------------------------------------------------------|------------------------------------------------------------|
| Source | [15] | [19] |
| Total GWP in kg CO ₂ eq/kg H ₂ (%) | 1.92 (100%) | 0.68 (100%) |
| Wind | 0.79 (41%) | 0.44 (65%) |
| Electrolyser | 0.36 (19%) | 0.04 (7%) |
| Compressor | 0.23 (12%) | 0.15 (22%) |
| Storage | 0.52 (27%) | N/A |
| Transport | N/A | 0.05 (8%) |
| Dispenser | 0.02 (1%) | N/A |

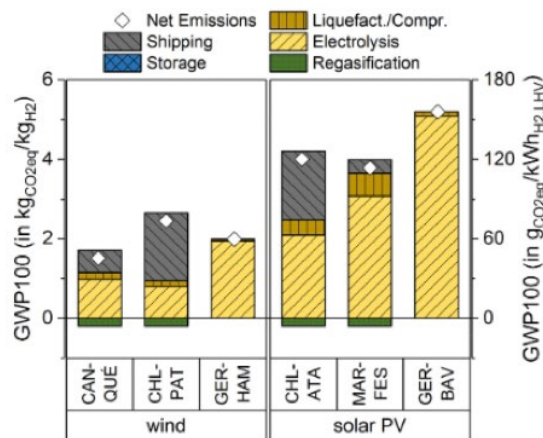


13 In the papers' discussion of results it is mentioned that the GWP of German wind is relatively high and import GWP is relatively low compared to earlier published literature [18]. We recognize this as well.

Another consideration with respect to transport and storage is if hydrogen is imported over long distances via ships. Kolb et al. [18] investigated wind- and solar- based imported (liquified) hydrogen specifically to Germany (see Figure 13).¹³ The results show that, based on the distance, fuel emissions of heavy fuel oils (HFO) can contribute from 0.5 to 2 kg CO₂eq/kg H₂. These can be reduced significantly if renewable or low-carbon fuels, such as liquid hydrogen (LH₂) would be used. On the other hand, using grid electricity for the liquification process can increase the GWP for the import cases from Chile and Morocco by 8 to 10 kg CO₂eq/kg H₂. Using (fossil) grid electricity for the liquification process seems illogical for the purpose of producing renewable hydrogen to reduce greenhouse emissions, however, from an economic perspective it can make sense to do so if there are no criteria for 'renewable' hydrogen to be converted and transported with renewable energy and fuels.



Figure 13: Cradle-to-gate GWP of produced and imported (liquified) and domestic hydrogen to Germany, as presented by ([18]). CAN= Canada, CHL= Chili, GER= Germany, MAR= Morocco.



A final, but crucial, consideration is the integration of the process or chain with alternative or adjacent processes. Some case studies apply credits if it is assumed that the by-products are used in processes not directly linked to the supply of hydrogen and therefore, lead to lower emissions. This is, of course, only the case if these by-products really can decrease emissions of other processes. If these processes would already be decarbonized in another way, it does not make sense to apply credits for these by-products anymore. Another reason why credits can be applied is when biologically captured emissions from the air are returned to the soil and therefore operates as net negative 'emission sink'. We summarized the examples and impact of the cases we have seen in our literature selection in Table 3.





It can be seen that multiple credits are applied by a considered replacement of a (partially) fossil alternative, which can be interpreted as useful if this is applicable for the case of interest and no better decarbonization alternatives are available in the short term. The credits for the biomass by-products were only seen in Antonini et al.[7], from our literature analysis did not become clear why this assumption was made in this case and not in the other BM reforming case studies. Therefore, further research is required to understand the circumstances of applying these credits.



Table 3 Overview of the impact of by-products on the GWP of hydrogen

| By-products used for credits | Hydrogen technology applied | Sources | Reduction in GWP of supplied hydrogen (In kg CO ₂ eq/kg H ₂) |
|-----------------------------------------------------------------------------------|------------------------------------------------|------------|-------------------------------------------------------------------------------------|
| Fertilizing soil with digestate stream from biomass | Anaerobic digestion for BM reforming (SMR/ATR) | [7] | 12.5 (incl. range 7-18) |
| Steam production (unspecified) | NG/BM SMR | [10] | 0.1-1 |
| Heat output replaces combustion of natural gas* | NG reforming (SMR/ATR) | [4] | Unknown but very significant |
| Replacing average grid electricity | Coal gasification | [10], [12] | 1-2 |
| Accounting part of direct emissions equivalent to energy of delivered electricity | Gasification | [23] | 0.6-2 |
| Replacing electricity supplied by natural gas CHP | Biomass (EF and FB) gasification | [28] | Unknown but significant (>20) |
| Replacing purely produced oxygen* | Electrolysis | [4] | 1 |
| Replacing average grid electricity | Regasification LH ₂ | [18] | 0.2 |

* Note that in [4] credits for by-products are only included for indicative purposes. Multiple specific limitations of the approach are mentioned. More recent investigations reported in [29].





3.5 **Conclusion on the most significant impact factors and measures**

To conclude, we have seen that typically the most impactful factor on the emissions related to hydrogen production is the primary energy source, but also the combination of factors matters. It is seen that different 'hydrogen colours' can lead to a similar GWP, but also differences in GWP are seen between pathways falling under the same 'hydrogen colour'. Hence, the colour of hydrogen is not directly related to its climate impact performance. In order to discuss the more specific emissions factors related to hydrogen production further, we have divided the broad range of hydrogen production technologies into electrochemical and thermochemical processes, due to the fundamental differences between those technologies.

It was seen that for the GWP of electrochemical hydrogen production, the source of electricity deserves the main attention rather than the materials and manufacturing of the assets specifically related to the production of hydrogen (such as electrolyser, balance-of-plant, etc.). A tremendous emission impact can result if coal or natural gas power (or grid mixes) are used while a relatively low GWP is achieved when relatively clean sources such as wind, hydro- and nuclear power are directly coupled to an electrochemical process (and solar to a lesser extent). Biomass-based electricity performs in-between but was less investigated in the selected literature. Due to the large impact of these sources, it makes sense to look further into LCAs performed for these specific electricity generation processes in order to reduce the emission impact of the produced hydrogen via electrochemical processes. Next to that, the efficiency of electricity usage is an aspect that matters, which can be achieved by the improvement of electrolyser technologies. Moreover, materials and operation of local storage to balance intermittent production can impact the results. Large-scale underground hydrogen storage has not been investigated by the identified papers.

For the GWP of thermochemical hydrogen production processes, the type of the main feedstock is, together with the application of CCS, the most impactful factor contributing to the GWP. If natural gas, biomethane or biomass is used, upstream emissions are relevant to identify and take actions on, for coal this is less applicable. The more emission reduction becomes relevant, the more other technologies (such as ATR and several specific gasification technologies) than the traditional SMR technology become relevant due to their higher direct emission capture potential. Also, emission impact can be further optimized by integrating VPSA, renewable electricity and/or delivering useful by-products to the regional energy system in order to reduce emissions that otherwise could not have been reduced.



Relevant questions to indicate the GWP of hydrogen production projects in the Netherlands

Based on the insights we obtained from the LCA literature, we have identified the most relevant questions to ask in order to indicate the direct and indirect GHG impact/GWP of a hydrogen production project (see Table 4). The relevance of the question is visualized with stars to represent the potential impact on the GWP of hydrogen production. These questions, together with the answers in this paper, can guide discussions on the wide variety of options and measures that can be taken to reduce the GWP of hydrogen production, rather than falling back on semantic and simplified arguments about what 'hydrogen colour' a certain project belongs to, and which colours should be qualified as 'good' and 'bad'.

To illustrate, we discuss the questions and results that can help to assess some greenfield hydrogen production activity that is, or could be, considered in the Netherlands:



Table 4: Overview of relevant questions to indicate the GWP of hydrogen production projects (potential impact: 1 star: the answer to the question has 0-2 kg CO₂eq/kg H₂ maximum absolute impact on the GWP result; 2 stars 2-10 kg CO₂eq/kg H₂; 3 stars >10 kg CO₂eq/kg H₂. A half star means that it is more to the upper or lower side of the range). Note that this represents the 'potential' impact, the actual impact depends on the answer given.

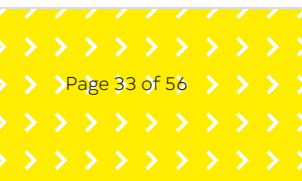
| Category | Question | Potential impact |
|-----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Is a thermochemical or electrochemical production process used? | How much electricity is required to produce one kg of hydrogen? | ★ |
| | What source(s) of electricity is used? | ★★★★ |
| | If a directly coupled source is used: <ul style="list-style-type: none"> Which type of source is used? Is the source additional or is electricity used that could reduce more emissions elsewhere? What measures are taken to reduce the life cycle emissions of the electricity source used? | ★★★★ |
| | If grid electricity is used: <ul style="list-style-type: none"> What is the emission factor of grid electricity? Do the running hours of the production unit match with the generation of renewable sources? | |
| | On what type of structure is the electrolyser located? | ★ |
| | How, and using which materials, is the electrolyser manufactured? | ★ |



| Category | Question | Potential impact |
|------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Is a thermochemical or electrochemical production process used? | What primary energy source is used? | ★★★★ |
| | What are the upstream emissions of the energy source? (mainly relevant for natural gas, biomass, biomethane and residual gases) | |
| | How much energy is used to produce one kg of hydrogen? | ★ |
| | Is CCS applied? | ★★ |
| | <ul style="list-style-type: none"> What is the capture rate of direct emissions? How is the CO₂ transported and stored? | |
| | What does the conversion process look like? | ★★ |
| | <ul style="list-style-type: none"> What type of technology is used? (e.g. SMR, ATR, Gasification, other technology) What energy is used for ancillary processes? (e.g. CHP, grid power, renewable power) | |
| Questions on how production is integrated into the energy system | Which by-products of the certain related processes are utilized? | ★★★★ |
| | Do these by-products reduce emissions of activities that otherwise will likely remain? And for what time? | |
| | To what degree is the hydrogen compressed? | ★ |
| | Via what means and over what distance is the hydrogen transported? | ★ |
| | To what degree is small-scale (e.g. compressed) hydrogen storage in tanks performed? | ★ |

In the Netherlands, electrolysis is often identified as the technology to produce hydrogen in a sustainable manner (+50 projects in the Netherlands as of January 2023). We have seen that if (partially) grid electricity is used, this can significantly increase the GWP of the produced hydrogen, such that even a higher GWP results than via the traditional SMR with natural gas pathway. The climate impact of using electricity from the grid mix can significantly be reduced if grid electricity is only used when wind and solar are the major sources to satisfy electricity demand. In the current (2023) Dutch electricity mix this implies that the load hours of the electrolyser will have to be significantly reduced.¹⁴ Directly coupled electrolysis to wind, nuclear or hydropower reported the lowest emission impact (0.33-1.90 kg CO₂eq/kg H₂). The most promising options to reduce emissions even further is to reduce the life cycle emissions of the electricity source, improve the efficiency of the electrolyser or to effectively utilize the by-products such as oxygen and heat.

¹⁴ The requirements for additionality and hourly correlation (after 2030), described in the intended final version of the RED II Delegated Act (describes the criteria that electric power must fulfil to legally call hydrogen 'renewable', see Appendix B) are expected to overcome that electrolysers connected to the grid will operate such that no additional emissions will be caused.





Another consideration for renewable hydrogen by electrolysis in the Netherlands is that it is likely that the demand can not be met by domestic electrolysis of renewables only. Therefore, projects considering imported hydrogen produced by electrolysis can be expected as well (e.g. OCI terminal, ACE terminal, Air Products-Gunvor terminal, H₂A consortium). In literature, it was seen that GWP related to transport was relatively low for hydrogen transported with pipelines or ships using low carbon fuels (~0.05-0.1 kg CO₂eq/kg H₂) [18]. However, as long as fossil fuels are used for international transport by ships, the impact of emissions related to the transport of imported hydrogen is considerable (~0.5 to 2 kg CO₂eq/kg H₂, but highly dependent on distance and fuel type) [18].

Also, new thermochemical hydrogen production facilities are considered in the Netherlands, such as hydrogen from biological sources (e.g. Hynoca, H₂ub Laren, Cleanup Gas, Brigh₂, GH₂), hydrogen from non-biological and biological waste (e.g. FUREC), and hydrogen using refinery residual gases (e.g. H-vision). For the first category (biological without CCS) we have seen -0.5-5.39 kg CO₂eq/kg H₂ being reported for biomass gasification and -4.8-8.3 kg CO₂eq/kg H₂ being reported for biomethane reforming. The wide variety of fuels, ways to obtain and process biomass, and options to obtain credits make it rather difficult to provide simple guidelines to quickly assess the emission impact of such projects. For these projects, the questions on the upstream emissions and use of by-products are of the most importance.

Moreover, we have seen that thermochemical hydrogen production with fossil sources can be done with a relatively low GWP as well. ATR is more effective in capturing up to 98% of the direct emissions compared to 80-90% with SMR. By this measure alone ATR using natural gas can produce hydrogen with a GWP of 1.9-6 kg CO₂eq/kg H₂. One study investigated ATR using natural gas from Dutch electrified platforms, resulting in a contribution of upstream natural gas emissions of only 0.72 kg CO₂eq/kg H₂ (50% lower than the typical upstream emissions of non-Dutch natural gas considered in the other sources). If also Dutch offshore wind electricity would be used for the ancillary processes in the ATR plant, a GWP of 0.96 was reported for the produced hydrogen (Hauck, 2020). This falls in the range of reported values for directly coupled wind electrolysis. Also here, emission impact can be further reduced by effective utilization of by-products (e.g. heat) and (partial) inclusion of biogenic sources.



5.1 **Limitations of the research**

The first limitation of our research, inherent to our methodology, is that the selection of literature is not exhaustive. Life cycle analysis of hydrogen production is a widely investigated topic. We scanned the abstracts of the first 300 papers resulting based on our search terms although thousands of results were available. We acknowledge that there are more recent relevant papers on this topic, such as de Kleijne et al. [29]. However, based on the uniformity of the conclusions of the papers we think the same conclusions would be drawn if we would continue scanning papers and expanding our literature selection. A more extensive literature review could lead to more specific measures, technologies or types of credits.

Secondly, we noticed that the LCA was performed conforming to the scientific NEN standards. However, each paper had different ways to describe (or not describe) the exact scope, specific assumptions, and used databases and tools. The extensive calculations of the LCA studies include were not described in depth in 10–15-page scientific publications and therefore, the authors rely on the credibility of the peer-review process that all selected papers went through.

Although we selected papers published after 2016, it is not mentioned in every paper which LCA database and version was used. Therefore, some of the papers may use older, and probably outdated data.

Finally, as defined in the scope, this paper solely focusses on the life cycle GWP of different hydrogen supply pathways. Therefore, we did not report on other (rather important) environmental and social impacts of these pathways,¹⁵ such as scarce material usage, acidification, eutrophication, photo ozone creation, particulate matter and human toxicity. Also, we did not focus on broader system advantages that certain technologies can have in contributing to a sustainable society and planet. Therefore, conclusions based on the results of this paper only would be too limited to make statements such as 'most environmental' or 'most sustainable'.

¹⁵ LCA often considers a wider scope of environmental impact than GWP only.



5.2 Discussion of results

This paper can help to separate the most impactful factors of different hydrogen production pathways from the less impactful ones and the relation between them. Thereby, this paper contributes to the vast existing literature by providing an overview of the interrelation between factors affecting the impact of hydrogen production activities on global warming, rather than the 'black and white' hydrogen colour approach.¹⁶ Next to that, it can guide practitioners and the public to understand the relevant aspects of hydrogen production projects that cause or reduce its GWP.

The insights from LCA literature are important for the development of the policy, market regulation and subsidy landscape for hydrogen activities. An example is the European definition for renewable hydrogen (or actually 'Renewable Fuels of Non-Biological Origin', RFNBO) under RED III. Given the tremendous climate impact that electrolysis using (partially) fossil grid electricity can have, it is not completely not surprising that the Delegated Act requires from electrolysers using grid electricity that production needs to be matched on an hourly basis with the generation of renewable sources. The argument against is that this can delay scaling up the required technologies (e.g. electrolysis) to reduce emissions in the future. Related to the topic above, there is often discussed that as long as renewable electricity remains scarce it should be utilized for applications where it has the highest emission reduction potential Kleijne et al. 2022 [29]. These examples are illustrating that the pathway towards carbon neutrality and the total system integration are important aspects to consider while interpreting the provided results and insights on the GWP of hydrogen supply pathways. Therefore, LCA provides useful insights but is only one piece of the larger puzzle.

¹⁶ Noticably, very close before publishing this paper the International Energy Agency (IEA) published a paper arguing the similar drawbacks of using the colour approach: <https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity>

5.3 Considerations for further research

Based on our literature review four most important considerations for further research should be mentioned.

Firstly, consideration for future LCA research on hydrogen supply pathways is to take into account the intermittency with which the hydrogen is delivered. For example, electrolysis coupled to wind generation sources implies that the electrolyser follows the wind profile, while most hydrogen end users will not be able to consume hydrogen only when the wind blows. From our selection of papers, the impact of intermittency of the different hydrogen production pathways remained unclear and therefore we advise further research to take into account the way that is dealt with intermittency, such as oversizing or combining wind/solar farms, using batteries (see [30]) or including the potential impact of hydrogen storage as well.



Secondly, it has been noticed that most studies report relatively less information on the assumptions and upstream considerations for transporting and handling biomass and biomethane, while significant differences in impact were reported. Since it turned out to have a crucial impact on the results, it is advisable to clearly report the assumptions made in the biomass chain (see Figure 12 by [7] for a more informative example).

The same is seen for the reporting of specific credits provided for delivered by-products. In most cases, it has been mentioned what alternative is replaced, but it generally remains unclear what the assumed carbon intensity of this replaced product was and to what degree the delivered by-products affect the results. Moreover, further dedicated research is required to identify an exhaustive list of options and measures to optimize the GWP of hydrogen supply by the upstream handling approach of biomass and utilization options of specific by-products.

A final consideration for future research is to take into account the GWP of potential hydrogen leakages, or i.e. fugitive emissions. There seems to be a rising concern about the impact of these types of emissions along the hydrogen supply chains (e.g. [31]). The literature in our selection did not report on these types of emissions at all. Future research can investigate sensitivities of the impact of leakage and its GWP along the different technologies such that the impact of these can be estimated and mitigated better.



6

Conclusion

There are plenty of ways to produce hydrogen and even more to transport, store and utilize it. The 'hydrogen colours' can help to easily categorize the different production pathways, but this categorization can also neglect relevant aspects that are considered in future hydrogen production projects. This report aimed to specifically focus on the climate impact of hydrogen production.

We studied a selection of existing LCA literature to identify the main factors contributing to the GWP of hydrogen production. It was seen that typically the primary energy source contributed to 75-98% of the total climate change impact. Therefore, the primary energy source used can often provide a good indication, but since there are exceptions also this view is too limited.

Given the various specific choices and situational aspects that are related to the climate impact of hydrogen production, we found that a set of most relevant questions would be more helpful to identify the GWP of specific hydrogen production projects than guidelines, as specific exceptions and circumstances are always possible.

The question of whether electrochemical or thermochemical hydrogen production technology is used is not relevant for the GWP, but it is relevant to determine which questions are the most relevant to ask.

For electrochemical hydrogen production (e.g. via electrolysis) the most important consideration is what type of electricity is used. If grid electricity is used, the GWP very much depends on the carbon intensity of the grid mix and the degree to which the electrolyzers are operated during moments when high carbon intensity electricity generation capacities (such as coal and gas-fired power plants) are used. If a directly coupled electricity source is used, typically wind, nuclear and hydropower lead to the lowest climate impact, followed by solar, biomass, natural gas and coal respectively. Obviously, due to the relatively large impact of the electricity source, measures to decrease the emission impact of the electricity source will reduce the emission impact of hydrogen production as well. Other relevant aspects are the efficiency of electricity usage and in certain cases the structure at which the electrolyser is located. The materials used in the stack itself barely impact the GWP.



For thermochemical hydrogen production, the most relevant consideration is the primary energy source used, as direct emissions typically have the biggest emission impact. Coal typically has the highest direct emissions, followed by natural gas and for biomass or biomethane direct emissions are often considered near zero due to their biological origin. CCS can be applied to reduce direct emissions. The capture rate depends on which technology is used. If CCS is applied the remaining emissions relate typically to the upstream emissions of the primary energy source (especially for natural gas and biomass) and the energy usage for ancillary equipment. Dutch natural gas can be extracted by electrified platforms via relatively low emissions and also renewable energy can be considered to operate the ancillary and CCS processes. The upstream emissions of biomass and/or biomethane processing and transportation remain with a large variety of options, that can lead to considerable emissions, but also can serve as carbon sinks, dependent on decisions made and regional circumstances.

Both electrochemical and thermochemical hydrogen production was seen that effective utilization of by-products (e.g. oxygen, electricity, heat, etc.) could significantly impact the GWP of the produced hydrogen. To a lesser extent also the climate impact of compression, long-distance shipping and small-scale tank storage can be considerable. The impact of large-scale underground hydrogen storage remains unclear from the papers that were researched.

All in all, we saw that for most of the considered hydrogen production options in the Netherlands (electrochemical using wind, thermochemical using biological sources and thermochemical using fossil sources with CCS; thermochemical hydrogen using waste sources was not part of the investigation) the GWP could potentially very low ($<1 \text{ kg CO}_2\text{eq/kg H}_2$), or even negative emissions can be achieved as long as the right measures are taken and situational opportunities are utilized (see paragraphs above). We think the information in this paper, together with the formulated questions can guide project developers and policy makers to reduce the GWP of future hydrogen production initiatives in the Netherlands



7

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Case Studies Included in the Literature Review

| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ eq/FU) |
|--------------------------------------|-----------------------------------------|-------------------------------|-------------|----------------------|-----------------------------------------|
| Suleman et al., 2016 [32] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 11.9567 |
| | Electrochemical | Unspecified electrolysis | Wind | kg H ₂ | 0.325 |
| | Electrochemical | Unspecified electrolysis | Solar | kg H ₂ | 0.37 |
| | Electrochemical | Mercury cell electrolysis | Renewables | kg H ₂ | 1.051 |
| | Electrochemical | Membrane cell electrolysis | Renewables | kg H ₂ | 0.8872 |
| | Electrochemical | Diaphragm cell electrolysis | Renewables | kg H ₂ | 0.909 |
| Ghandehariun & Kumar, 2016 [19] | Electrochemical | Alkaline electrolysis | Wind | kg H ₂ | 0.68 |
| Khila et al., 2017 [33] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 11.2 |
| | Thermochemical | Steam Methane Reforming | Biogas | kg H ₂ | 5.59 |
| Burkhardt et al., 2016 [15] | Electrochemical | Alkaline electrolysis | Wind | kg H ₂ | 1.9008 |
| Khøjasteh Salkuyeh et al., 2017 [28] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 11.5 |
| | Thermochemical | Steam Methane Reforming + CCS | Natural gas | kg H ₂ | 3.5 |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|-------------------------|-----------------------------------------|-----------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------|
| Zhang et al., 2017 [11] | Thermochemical | Autothermal Reforming | Natural gas | kg H ₂ | 10.8 |
| | Thermochemical | Autothermal Reforming + CCS | Natural gas | kg H ₂ | 1.9 |
| | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ (350+ bar, 99.997% purity) | 15.0125 |
| | Thermochemical | Gasification | Coal | kg H ₂ (350+ bar, 99.997% purity) | 24.02 |
| | Electrochemical | PEM electrolysis | Wind | kg H ₂ (350+ bar, 99.997% purity) | 0.9608 |
| | Electrochemical | PEM electrolysis | Solar | kg H ₂ (350+ bar, 99.997% purity) | 4.804 |
| | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ (350+ bar, 99.997% purity) | 7.206 |
| | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ (350+ bar, 99.997% purity) | 30.025 |
| | Electrochemical | Alkaline electrolysis | Wind | kg H ₂ (350+ bar, 99.997% purity) | 1.8015 |
| | Electrochemical | Alkaline electrolysis | Solar | kg H ₂ (350+ bar, 99.997% purity) | 6.005 |
| | Electrochemical | Alkaline electrolysis | Grid electricity | kg H ₂ (350+ bar, 99.997% purity) | 8.407 |
| Electrochemical | Alkaline electrolysis | Grid electricity | kg H ₂ (350+ bar, 99.997% purity) | 33.0275 | |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|-------------------------------|-----------------------------------------|--------------------------------------|------------------|------------------------------------------------|----------------------------------------|
| Battista et al., 2017 [8] | Thermochemical | Steam Methane Reforming | Biogas | kg H ₂ (1.5 bar, 40 dC, 99% purity) | 6.7278 |
| | Thermochemical | Autothermal Reforming | Biogas | kg H ₂ (1.5 bar, 40 dC, 99% purity) | 6.6722 |
| | Electrochemical | Unspecified electrolysis | ICE via biogas | kg H ₂ (1.5 bar, 40 dC, 99% purity) | 17.7926 |
| Wulf & Kaltschmitt, 2018 [10] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 11.98 |
| | Thermochemical | Steam Methane Reforming | Biomass | kg H ₂ | 7.12 |
| | Thermochemical | Gasification | Coal | kg H ₂ | 23.48 |
| | Thermochemical | Gasification | Wood | kg H ₂ | 4.8 |
| | Electrochemical | PEM electrolysis | Wind | kg H ₂ | 1.06 |
| | Electrochemical | Alkaline electrolysis | Wind | kg H ₂ | 0.95 |
| | Electrochemical | High Temperature electrolysis | Solar | kg H ₂ | 6.49 |
| Mehmeti et al., 2018 [17] | Electrochemical | High Temperature + SOEC electrolysis | Grid electricity | kg H ₂ | 25.64 |
| | Electrochemical | High Temperature + SOEC electrolysis | Coal | kg H ₂ | 43.95 |
| | Electrochemical | High Temperature + SOEC electrolysis | Natural gas | kg H ₂ | 28.93 |
| | Electrochemical | High Temperature + SOEC electrolysis | Nuclear | kg H ₂ | 2.11 |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|-------------------------------------|-----------------------------------------|----------------------------------------|-------------|-------------------------------------------------|----------------------------------------|
| | Electrochemical | High Temperature + SOEC electrolysis | Wind | kg H ₂ | 2.26 |
| | Electrochemical | High Temperature + SOEC electrolysis | Solar | kg H ₂ | 4.63 |
| | Electrochemical | High Temperature + SOEC electrolysis | Biomass | kg H ₂ | 14.36 |
| | Electrochemical | High Temperature + SOEC electrolysis | Hydro | kg H ₂ | 0.72 |
| Salkuyeh et al., 2018 [23] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 11.5 |
| | Thermochemical | Steam Methane Reforming + CCS | Natural gas | kg H ₂ | 3.5 |
| | Thermochemical | Autothermal Reforming | Natural gas | kg H ₂ | 10.8 |
| | Thermochemical | Autothermal Reforming + CCS | Natural gas | kg H ₂ | 1.9 |
| | Thermochemical | Gasification - Biomass - FEB | Biomass | kg H ₂ | -0.5 |
| | Thermochemical | Gasification - Biomass - FEB + CC | Biomass | kg H ₂ | -15.8 |
| | Thermochemical | Gasification - Biomass - EF | Biomass | kg H ₂ | -0.1 |
| | Thermochemical | Gasification - Biomass - EF + CC | Biomass | kg H ₂ | -21.8 |
| Di Marcoberardino et al., 2019 [25] | Thermochemical | Steam Methane Reforming | Landfill | kg H ₂ (20 bar, 15°C, 99.99% purity) | 2 |
| | Thermochemical | Autothermal Reforming | Landfill | kg H ₂ (20 bar, 15°C, 99.99% purity) | 8.3 |
| | Thermochemical | Autothermal catalytic membrane reactor | Landfill | kg H ₂ (20 bar, 15°C, 99.99% purity) | 2.1 |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|---------------------------|-----------------------------------------|----------------------------------------|---------------------|-------------------------------------------------|----------------------------------------|
| | Thermochemical | Steam Methane Reforming | Anaerobic digestion | kg H ₂ (20 bar, 15°C, 99.99% purity) | 1.5 |
| | Thermochemical | Autothermal Reforming | Anaerobic digestion | kg H ₂ (20 bar, 15°C, 99.99% purity) | 6.8 |
| | Thermochemical | Autothermal catalytic membrane reactor | Anaerobic digestion | kg H ₂ (20 bar, 15°C, 99.99% purity) | 2 |
| Bareiß et al., 2019 [14] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 11.4 |
| | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ | 29.5 |
| | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ | 11.6 |
| Zhao et al., 2020 [16] | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ | 3 |
| | Electrochemical | Alkaline electrolysis | Wind | kg H ₂ | 0.55 |
| | Electrochemical | PEM electrolysis | Wind | kg H ₂ | 0.55 |
| Sadeghi et al., 2020 [12] | Electrochemical | SOEC electrolysis | Wind | kg H ₂ | 0.39 |
| | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 10.3 |
| | Thermochemical | Gasification - Coal | Coal | kg H ₂ | 11.59 |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|---------------------------|-----------------------------------------|-------------------------------|----------------------|---------------------------------------------|----------------------------------------|
| Karaca et al., 2020 [20] | Electrochemical | Alkaline electrolysis | Solar | kg H ₂ | 3.08 |
| | Electrochemical | Unspecified electrolysis | Nuclear | kg H ₂ | 0.7071 |
| | Electrochemical | High Temperature electrolysis | Nuclear | kg H ₂ | 0.4768 |
| | Electrochemical | 3 step Cu-Cl cycles | Nuclear | kg H ₂ | 1.32 |
| | Electrochemical | 4 step Cu-Cl cycles | Nuclear | kg H ₂ | 1.201 |
| | Electrochemical | 5 step Cu-Cl cycles | Nuclear | kg H ₂ | 1.346 |
| Li et al., 2020 [24] | Thermochemical | Gasification | Biomass - Corn Straw | kg H ₂ | 5.39 |
| | Thermochemical | Gasification + MTR | Biomass - Corn Straw | kg H ₂ | 4.96 |
| Antonini et al., 2020 [7] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ (200 bar, >99.97% purity) | 10.6889 |
| | Thermochemical | Autothermal Reforming | Natural gas | kg H ₂ (200 bar, >99.97% purity) | 10.9291 |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) | |
|-----------------|-----------------------------------------|-------------------------------------|----------------------------------|---------------------------------------------|----------------------------------------|---------|
| | Thermochemical | Steam Methane Reforming + ccs (55%) | Natural gas | kg H ₂ (200 bar, >99.97% purity) | 5.8849 | |
| | Thermochemical | Steam Methane Reforming + ccs (70%) | Natural gas | kg H ₂ (200 bar, >99.97% purity) | 4.5638 | |
| | Thermochemical | Autothermal Reforming + ccs (85%) | Natural gas | kg H ₂ (200 bar, >99.97% purity) | 3.4829 | |
| | Thermochemical | Autothermal Reforming + ccs (98%) | Natural gas | kg H ₂ (200 bar, >99.97% purity) | 2.6422 | |
| | Thermochemical | Steam Methane Reforming | Biomethane | kg H ₂ (200 bar, >99.97% purity) | -4.804 | |
| | Thermochemical | Autothermal Reforming | Biomethane | kg H ₂ (200 bar, >99.97% purity) | -4.2035 | |
| | Thermochemical | Steam Methane Reforming + ccs (70%) | Biomethane | kg H ₂ (200 bar, >99.97% purity) | -9.608 | |
| | Thermochemical | Autothermal Reforming + ccs (98%) | Biomethane | kg H ₂ (200 bar, >99.97% purity) | -15.0125 | |
| | Hauck, 2020 [4] | Electrochemical | Alkaline electrolysis | Offshore wind | kg H ₂ (68 bar) | 0.9608 |
| | | Electrochemical | Alkaline electrolysis (offshore) | Offshore wind | kg H ₂ (68 bar) | 0.54045 |
| Electrochemical | | Alkaline electrolysis | Grid electricity | kg H ₂ (68 bar) | 27.623 | |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|--------------------|-----------------------------------------------|--------------------------------------------------------|-----------------------------|----------------------------|----------------------------------------|
| Gerloff, 2021 [21] | Electrochemical | PEM electrolysis (offshore) | Offshore wind | kg H ₂ (68 bar) | 0.6005 |
| | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ (68 bar) | 10.809 |
| | Thermochemical | Steam Methane Reforming + CCS (95%) | Natural gas | kg H ₂ (68 bar) | 2.1618 |
| | Thermochemical | Autothermal Reforming | Natural gas | kg H ₂ (68 bar) | 13.211 |
| | Thermochemical | Autothermal Reforming + CCS (100%) | Natural gas | kg H ₂ (68 bar) | 6.005 |
| | Thermochemical | Steam Methane Reforming + CCS (95%) | Natural gas + offshore wind | kg H ₂ (68 bar) | 2.1618 |
| | Thermochemical | Autothermal Reforming + CCS (100%) | Natural gas + offshore wind | kg H ₂ (68 bar) | 0.9608 |
| | Thermochemical | Steam Methane Reforming + CCS (95%) + reuse byproducts | Natural gas | kg H ₂ (68 bar) | -504.42 |
| | Thermochemical | Autothermal Reforming + CCS (100%) + reuse byproducts | Natural gas | kg H ₂ (68 bar) | -228.19 |
| | Electrochemical | Alkaline electrolysis + reuse byproducts | Offshore wind | kg H ₂ (68 bar) | 0 |
| | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 15 |
| | Thermochemical | Gasification - Coal | Coal | kg H ₂ | 21 |
| | Thermochemical | Biomass derived liquid reforming | Biomass | kg H ₂ | 8 |
| Electrochemical | Dark fermentation-microbial electrolysis cell | Biomass | kg H ₂ | 17 | |



| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|----------------------|-----------------------------------------|-------------------------|-------------------|----------------------|----------------------------------------|
| On et al., 2022 [22] | Electrochemical | Alkaline electrolysis | Renewables | kg H ₂ | 3 |
| | Electrochemical | PEM electrolysis | Renewables | kg H ₂ | 3 |
| | Electrochemical | SOEC electrolysis | Renewables | kg H ₂ | 4 |
| | Electrochemical | Alkaline electrolysis | Grid electricity | kg H ₂ | 27 |
| | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ | 28 |
| | Electrochemical | SOEC electrolysis | Grid electricity | kg H ₂ | 23.5 |
| | Electrochemical | Alkaline electrolysis | Grid electricity | kg H ₂ | 21 |
| | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ | 22 |
| | Electrochemical | SOEC electrolysis | Grid electricity | kg H ₂ | 18 |
| | Electrochemical | Alkaline electrolysis | Grid electricity | kg H ₂ | 17 |
| | Electrochemical | PEM electrolysis | Grid electricity | kg H ₂ | 18 |
| | Electrochemical | SOEC electrolysis | Grid electricity | kg H ₂ | 16 |
| | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 11.35 |
| | Thermochemical | Autothermal Reforming | Natural gas | kg H ₂ | 11.01 |
| Thermochemical | Natural Gas Decarbonisation | Natural gas | kg H ₂ | 4.89 | |
| Thermochemical | Steam Methane Reforming + CCS (52%) | Natural gas | kg H ₂ | 8.2 | |

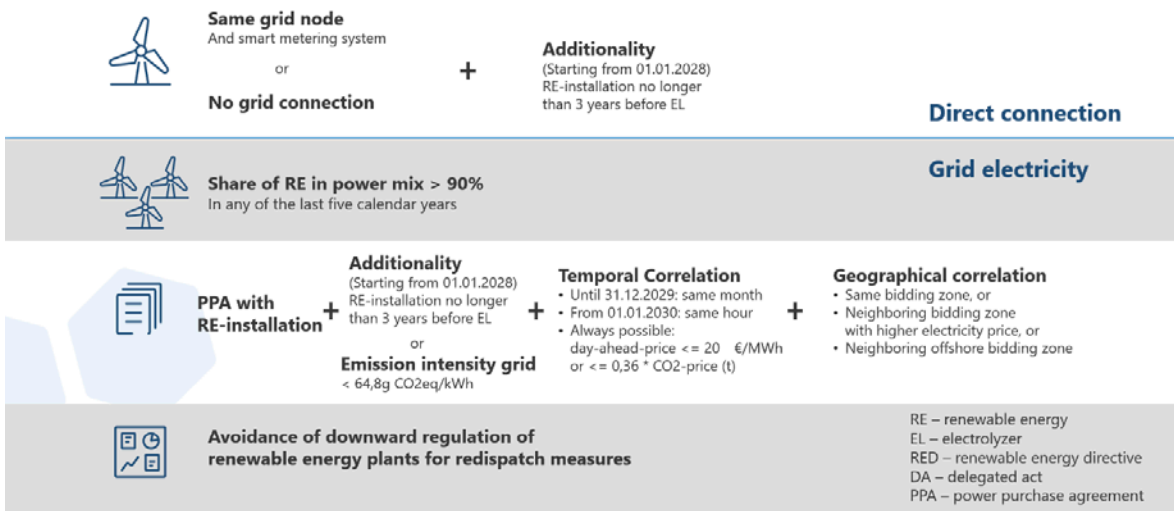


| Study and Year | Classification of Production technology | Production Technology | Fuel source | Functional unit (FU) | GHG emission (kg CO ₂ e/FU) |
|-------------------------|-----------------------------------------|---------------------------------------|-------------|----------------------|----------------------------------------|
| Kolb et al., 2022 [18] | Thermochemical | Steam Methane Reforming + CCS (85%) | Natural gas | kg H ₂ | 6.66 |
| | Thermochemical | Autothermal Reforming + CCS | Natural gas | kg H ₂ | 3.91 |
| | Thermochemical | Natural Gas Decarbonisation + CCS | Natural gas | kg H ₂ | 4.54 |
| | Electrochemical | PEM electrolysis | Wind | kg H ₂ | 2 |
| | Electrochemical | PEM electrolysis | Wind | kg H ₂ | 1.505 |
| | Electrochemical | PEM electrolysis | Wind | kg H ₂ | 2.457 |
| | Electrochemical | PEM electrolysis | Solar | kg H ₂ | 5.195 |
| | Electrochemical | PEM electrolysis | Solar | kg H ₂ | 3.787 |
| | Electrochemical | PEM electrolysis | Solar | kg H ₂ | 4 |
| Davis et al., 2023 [27] | Thermochemical | Steam Methane Reforming | Natural gas | kg H ₂ | 10.8 |
| | Thermochemical | Steam Methane Reforming + CCS (52%) | Natural gas | kg H ₂ | 7.5 |
| | Thermochemical | Steam Methane Reforming + CCS (85%) | Natural gas | kg H ₂ | 5.3 |
| | Thermochemical | Autothermal Reforming | Natural gas | kg H ₂ | 10.1 |
| | Thermochemical | Autothermal Reforming + CCS (91%) | Natural gas | kg H ₂ | 2.5 |
| | Thermochemical | Natural gas decomposition | Natural gas | kg H ₂ | 4 |
| | Thermochemical | Natural gas decomposition + CCS (90%) | Natural gas | kg H ₂ | 3.3 |

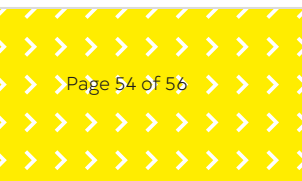


EU RFNBO definition by intended final proposal RED II Delegated Act

Options for the production of 'green' hydrogen according to RED II DA (13.02.2023)



Retrieved from: FFE





Appendix C

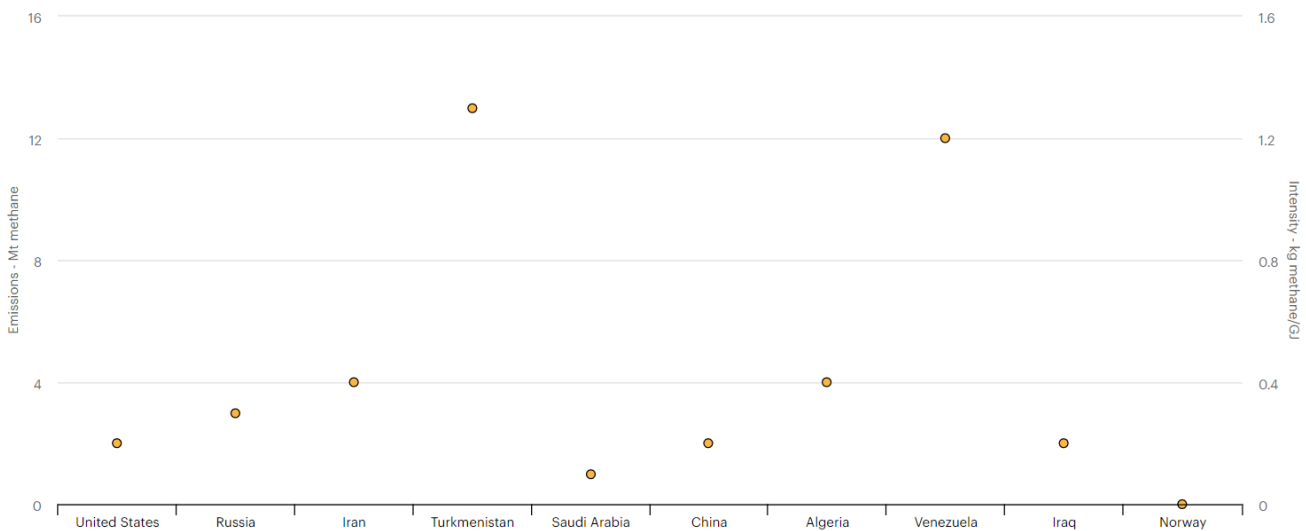


Impact of upstream natural gas extraction emissions

It often is mentioned that upstream natural gas extraction emissions differ significantly around the world due to variations by reserve type, technologies used for extraction and processing and the transportation distances [34]. See Figure 14 indicatively for oil and natural gas). These emissions can strongly impact the GHG effect because methane emissions have a higher GWP than CO₂.



Figure 14: Oil and gas methane intensity of production in selected countries, 2022. Retrieved from: <https://www.iea.org/reports/global-methane-tracker-2023/strategies-to-reduce-emissions-from-oil-and-gas-operations#abstract>



¹⁷ For the medium supply chain impact emissions of 13.4 gCO₂eq/MJ was considered based on HHV.

Based on the low, medium¹⁷ and high upstream emissions of natural gas, DNV [34] investigated its impact on thermochemical hydrogen production using CCS. In Figure 15 it is shown that the difference of the upstream natural gas emissions can have significant impact.

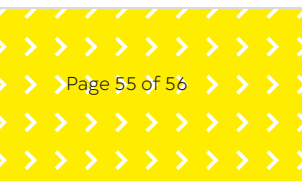
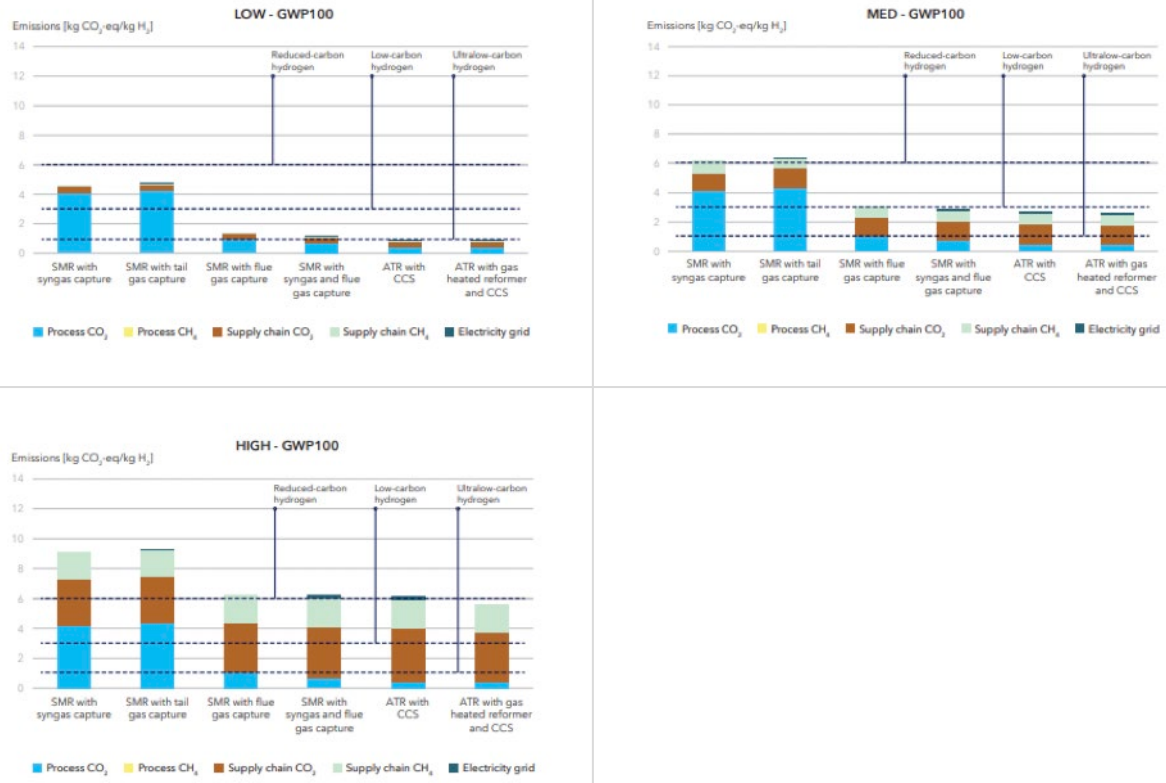




Figure 15: Emissions thermochemical hydrogen production with low, medium and high upstream emissions of the natural gas supply chain



The conversion of natural gas to hydrogen involves energy losses and performing carbon capture and storage requires energy as well. This means that using natural gas with very high upstream supply chain emissions could lead to situations that hydrogen production with carbon capture and storage (using partially fossil electricity) could lead to slightly less, or under more extreme assumptions even higher GWP than without [35]. Moreover, under these circumstances burning natural gas with high upstream emissions directly has a lower global warming impact than using this type of natural gas to produce hydrogen.

In short, taking into account assumptions (in research) and mitigation measures (in practice) related to upstream natural gas emissions for thermochemical hydrogen production is of importance for its GWP.

