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Levelized costs of low-carbon hydrogen production technologies

An analysis of the competitive position of bio-hydrogen

Peter Perey

Centre for Energy Economics Research (CEER)

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1. Introduction

1.1 Background

The production and deployment of low-carbon hydrogen is seen as one of the most promising routes in realising a successful energy transition to a carbon neutral energy system. Hydrogen strategies are developed on a national, European and global level. Public and private institutions jointly work on numerous projects to stimulate the uptake of production, deployment and trade in low-carbon hydrogen.

The most common low-carbon hydrogen technology that is stimulated and anticipated in these strategies is electrolysis based on the use of renewable electricity. Literature on both the current and projected production costs of this technology focuses on the costs of purified water and renewable electricity (both often dependent on availability of resources), capital costs, and the technical performance/efficiency of electrolysers. Actual production of hydrogen by electrolysis with renewable electricity is, however, very limited at the moment with very divergent projected cost ranges (Mulder, Perey and Moraga, 2019). Aside from the impact on costs, the actual availability of renewable electricity also creates uncertainty regarding the future feasible production levels of hydrogen by electrolysers. The continuously growing demand for (renewable) electricity (especially electric transport, heat pumps, electrification of industry) makes that electrolysers most likely have to compete for scarce available renewable electricity, resulting not only in high electricity prices but also in high prices for green certificates (Hulshof, Mulder and Perey, 2021; Li & Mulder, 2021).

A number of alternative production routes for low-carbon hydrogen exist that may not suffer from the same limitation in resource, and, therefore, it is useful to know how these compare to electrolysis in terms of unit costs. A commonly mentioned, but controversial production technology is steam methane reforming (SMR) in combination with carbon capturing and storage (CCS). Furthermore, there is the production route of "bio-hydrogen", i.e. hydrogen from the (supercritical)[1] gasification of bio-based raw materials.

This last mentioned route is, until now, hardly discussed in the public domain, while with a proper assessment of the availability and costs of bio-based raw materials a good cost comparison analysis can be conducted. Although the deployment of gasification technology for biomass is new, gasification itself is a proven and mature technology. A possible advantage of this route is that the operating hours of a gasification installation are primarily limited by only the supply of bio-based raw materials and the robustness of the chemical processes and not, as with sun and wind, by the weather. Consequently, this number of operating is potentially much higher leading to a better utilisation of the installation.

The use of biomass for energy production has led to an intense debate, though, with questioning whether this process is truly sustainable. Interesting as this discussion may be, particularly from a policy perspective, it is beyond the scope of this report as this publication primarily aims to contribute to the discussion of using bio-hydrogen in comparison with other hydrogen production technologies.

1.2 Research questions and method of research

In this research project, the focus is on comparing the levelized production costs of different low-carbon hydrogen production

[1] The term supercritical refers to the supercritical phase that the biomass will be in under high temperature and high pressure

technologies. The production technologies that are considered in this report include: steam methane reforming in combination with carbon capturing and storage, electrolysis with the use of renewable electricity, gasification of torrefied biomass, and the supercritical gasification in aqueous media of wet biomass flows.

For each of the production technologies, the levelized costs of hydrogen production will be estimated, based on information regarding the technical performance, operational costs, as well as energy and feedstock prices. This information is derived from publicly available literature or based on discussions with several industry experts. For each technology, the most relevant cost components are determined, after which the technologies are compared by constructing a merit order. To be able to explore the influence of adjusting assumptions on the future outlook, a thorough sensitivity analysis on both technical components as well as the energy and feedstock prices is conducted.

1.3 Outline of paper

The structure of this report is as follows. Section 2 briefly describes each of the technologies for low-carbon hydrogen production. In section 3, the method to estimate the levelized costs is introduced, and the underlying assumptions are given. In section 4 the results of the cost estimation are presented, while section 5 describes the outcomes of the sensitivity analysis. Finally, section 6 presents the conclusions.

2. Low-carbon hydrogen production technologies

2.1 Introduction

The costs of realising the ambitious European hydrogen plans depend on the hydrogen production technology used. Sections 2.2 till 2.5 briefly describe the four different low-carbon hydrogen production technologies that will be analysed in this paper. At the end of section 2, Figure 2.1 gives a schematic overview of the different production routes.

2.2 Steam methane reforming with carbon capturing and storage

Currently, the most commonly used method to make hydrogen in Europe is Steam Methane Reforming (SMR), using natural gas. By letting steam (H_2O) under high temperature react with methane coming from natural gas (CH_4), hydrogen (H_2) can be produced next to carbon monoxide (CO) or carbon dioxide (CO_2).[2]

If the carbon dioxide that is produced in the SMR process is emitted, this hydrogen production is called 'grey'. Grey hydrogen from the SMR process has been produced for many years in the Netherlands and is currently the only type of hydrogen being produced in considerable quantities. If the carbon produced in the process is captured and stored, the hydrogen is called 'blue'. This technology, carbon capturing and storage (CCS), is increasingly considered as a possibility to produce hydrogen with low carbon emissions. To obtain blue hydrogen, and thus to qualify as low-carbon hydrogen production, a significant amount of the carbon should be captured. For that

[2] Hence, the chemical process is: CH4 + H2O -> CO + 3 H2. Carbon dioxide (CO_2) is produced when the carbon monoxide (CO) reacts in an additional water-gas shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$.

purpose, here only technologies are considered where a minimum 90% capturing rate is achieved.

2.3 Electrolysis with renewable electricity

A different technology for the production of hydrogen is electrolysis, where electricity is used to split water (H_2O) into hydrogen (H_2) and oxygen (O_2).[3] Although this technology is mature, it is not widely deployed as large scale production technology with less than five percent of global production (IRENA, 2018). Nevertheless, most of the plans and ambitions related to hydrogen involve the use of large-scale electrolysis.[4]

At present, electrolysis production technologies that have been industrialized include alkaline water electrolysis (AEL) and proton exchange membrane electrolysis (PEM). I would replace this by something like "There are other technologies, such as Solid-Oxide Electrolysis (SOE), but these are as yet less advanced and future developments are more uncertain. Based on expected future techno-economic developments and suitability for combination with renewable electricity production, this report considers the PEM production technology.[5]

As said, besides water, the electrolysis process consumes electricity, a secondary energy carrier that can be produced in several ways. To be able to ensure that hydrogen production through electrolysis has low-carbon emissions, the producer has to be able to show that the electricity used is generated with renewable sources. However, often consumers of electricity cannot distinguish electricity

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[3] The chemical process: 2H2O -> 2H2 + O2.
[4] See for example: European Commission, 2020; EZK, 2019; BMU, 2016; 0
[5] For a discussion on different electrolysis techniques, see: Anwar et al., 2021; Bessarabov et al., 2017 and Ruth et al., 2017

generated by a renewable source from electricity generated by other (non-renewable) sources as all sources are connected to the same grid.

To solve this information asymmetry, the electrolysis producer has two options. First, the electrolysis plant can be directly coupled to a renewable source, like a wind park, instead of the electricity grid. An advantage of this method is that the renewable source is undebatable, with the disadvantage that the operating hours of the electrolyser are automatically limited by the intermittent supply of the renewable source. The second option is to connect the electrolyser to the grid and use Guarantees-of-Origin to ensure that electricity from renewable sources is used. Given that the electrolyser minimizes costs by operating a maximum number of hours, this report considers the second option, where the electrolyser is connected to the grid. We therefore assume an average electricity price bought on the electricity market, including Guarantees-of-Origin.

2.4 Combined torrefaction and gasification of biomass

Another route for the production route of low-carbon hydrogen is the use of (dry) biomass for thermal gasification, which is a partial oxidation[6] process that converts biomass into a gaseous mixture of hydrogen, carbon monoxide, methane and carbon dioxide. This mixture can either be directly used (for example in a CHP-plant), or upgraded to hydrogen or synthetic natural gas (methanation).[7]

Typically, the biomass inputs used in thermal gasification are forestry products, grasses and residual wastes, which are relatively dry biomass inputs. Since each input of biomass has its own characteristics

[6] Partial oxidation is a chemical reaction that occurs when a fuel-air mixture is partially combusted in a reformer, creating a hydrogen-rich syngas.
[7] For more information on the use of thermal gasification for methane production, see: Moraga, Mulder & Perey (2019)

as methane yield and percentage dry matter, the biomass feedstock composition heavily influences the thermal gasification process. To stabilize the process, the biomass feedstock for the gasifier should be as homogeneous as possible. To obtain this and still be able to operate with (slightly) different biomass inputs, the biomass can be torrefied before gasification.

This process is called torrefaction, which converts lower energy density heterogeneous biomass streams to a higher energy density homogenous bio feedstock.[8] The conventional feedstock used in this process is cellulose feedstock, which includes woody biomass and grasses (Hoang et al., 2020). The torrefied biomass can be transported in a more cost-efficient manner, due to its higher energy density. It can be transported to be used in a gasifier, or other applications. In this report, combined torrefaction and gasification (CTG) is regarded as integrated, therefore no transport costs for the torrefied biomass to the gasifier are considered. Instead, the transport costs of the biomass are taken into account in the feedstock price of the biomass.

2.5 Supercritical gasification of sewage sludge

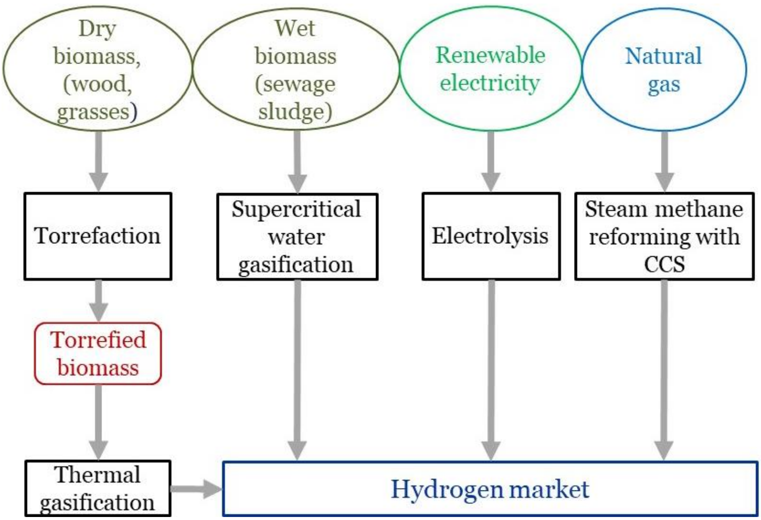
The fourth and final production process that is analysed in this report, is the production of hydrogen from wet biomass flows through supercritical water gasification (SWG). SWG is gasification under high temperatures and pressures, where the water (and the biomass solved therein) will transit to the supercritical phase. In this supercritical phase, the biomass splits into a mixture of methane, hydrogen and carbon dioxide.[9] An advantage of SWG, compared to CTG, is that there

[8] For more information on torrefaction, see: http://torrgas.nl/
[9] For more information on supercritical water gasification, see: https://www.gasunie.nl/en/expertise/green-gas/supercritical-water-gasification

is no need for drying the biomass as this process allows conversion even with wet material (Lepage et al., 2021).[10]

This makes that a broader range of material flows qualify as feedstocks to be used in SWG processes, even those that for other processes cannot be upgraded from the level of waste. As an example, in this report the usage of sewage sludge for a SWG installation is analysed. Typically, such a SWG plant would be placed next to a water treatment plant, thus avoiding transportation costs of the feedstock. It may come at the possible expense of having a sub-optimal plant size from the perspective of economies of scale.

Figure 2.1 Overview of low-carbon hydrogen production routes



[10] It is important to note, however, that to reach the temperatures of the supercritical gasification, additional energy is required.

3. Estimating levelized costs of hydrogen production

3.1 Introduction

To be able to compare the economic feasibility of the different low-carbon hydrogen production technologies, this report estimates the levelized costs for the four discussed in section 2. In section 3.2 it is described how the method of levelized costs is used to make the estimations. Section 3.3 will show the assumptions made on plant performance and costs, while section 3.4 gives the prices used of the different inputs and outputs.

3.2 Method

In order to assess the economic outlook for the various ways of producing hydrogen, the levelized costs of hydrogen are estimated. These levelized costs equal the minimum price of hydrogen necessary for the various technologies to be profitable. This required price is the financial compensation needed per unit of output to cover the present value of all the costs over the lifetime of the hydrogen plants. The formula for calculating levelized costs of hydrogen (LCOH) is:

$$LCOH = \frac{PV(net\ costs)}{PV(hydrogen\ production)},$$

where the net costs equal all the costs minus the benefits of any by-products other than to hydrogen. One can think of potential benefits for heat, oxygen, green CO_2 or biochar. Although these products will generate benefits, there are also costs to commercialize them. For many of the by-products there is insufficient information on the costs and benefits of commercialization. Therefore, the default assumption is that benefits of by-products are 0, unless enough information to provide reliable estimate.

The levelized costs calculation of all production technologies depends primarily on the input parameters for technical performance, costs and prices. These parameters are difficult to precisely estimate as technical developments can have profound impact on the value of these parameters. Besides the uncertainty of technical developments, input prices are hard to precisely predict, due to the strong influence of global developments which come with their own uncertainties . To make the outcomes of the LCOH calculations more robust, it is useful to perform a sensitivity analysis on those parameters that have the potential to change. This sensitivity analysis will allow us to estimate a range for the LCOH with more reliability than the sole outcome of the base case.

First, the assumptions made on the parameter values for the base case are shown in sections 3.3 and 3.4. The results for the base case calculations are shown in section 4, and finally the range of results from the sensitivity analysis is given in section 5.

3.3 Assumptions on plant performance and costs in base case

For the base case estimation of the LCOH, inputs for the plant performance and costs are taken from literature. The assumptions for SMR with CCS and electrolysis production are displayed in Table 3.1, and the assumptions for the bio-hydrogen production technologies, CTG and SWG, are displayed in Table 3.2.

As can be seen, the economic lifetime for SMR with CCS is assumed to be 25 years, opposed to 20 years for the other technologies. The input capacity of a SMR plant is by far the largest and SWG the smallest, with electrolysis and CTG in between. It is notable that the economically optimal size of the hydrogen technologies is also influenced by the feedstock availability. As stated in section 2.3, this report considers a grid connected electrolyser with Guarantees-of-

Origin for renewable hydrogen production. Given this assumption, the availability of electricity is no limitation in this report. This is in contrast to the case of electrolysers directly connected to renewable generation without a connection to the grid, where the availability of renewable electricity determines the ability to produce hydrogen.

For CTG, not all inputs are likely to be economically available for the large scale hydrogen production, as for example the entire Dutch annual verge grass consumption is needed to feed one plant of 120 MW.[11] Also, the input of some biomass feedstock types automatically nullifies the possible advantage of a more robust production as those streams are typically only available for limited moments in the year. In theory, one could think of storage of biomass, but this is only feasible for biomass that is not emitting harmful substances. Because of this, this report analyses the biomass feedstock that is most suitable for a stable hydrogen production, being A wood.

The feedstock availability is also a considerable disadvantage for the SWG process, which needs with the assumed size in this report (20 MW of dry matter) the sewage sludge input of one large city of over 2 million inhabitants, based on roughly 30 kg of dry material per person per annum (Al-Mosuli et al., 2011). This would mean that there are no significant opportunities in scaling to be expected for this plant type.

The bio-hydrogen technologies experience significantly higher capital and operating costs than SMR with CCS and electrolysis. One must note that there are large fluctuating estimates for both the current and expected future capital expenditures for PEM-electrolysers over the years (Saba et al., 2018). In this report, an initial capital

[11] See: https://www.rvo.nl/subsidies-regelingen/projecten/winning-van-hoogwaardige-vezels-uit-bermgras-voor-productie-van-biocomposieten#:~:text=In%20Nederland%20wordt%20jaarlijks%20ca,voeren%20en%20te%20laten%20verwerken.

expenditure of 1250 €/kW is assumed, with a stack replacement cost of 30% needed after 10 years. Especially the operating costs reported for SWG are high compared to the others, mainly due to the need to prevent plugging and corrosion problems. These needs may be overcome in time through technological progress, but up to now there is not clear evidence on to what extent this will really happen. In terms of overall energy efficiency, the electrolyser is performing best, followed by SMR with CCS, SWG and CTG. Moreover, CTG needs an additional input of oxygen, where other technologies do not.

Table 3.1 Base case assumptions on plant performance and costs of SMR with CCS and electrolysis, in 2021 €

Assumptions	SMR with CCS	Electrolysis	Sources
lifetime plant (years)	25	20	Chardonnet et al. (2017); Collodi et al. (2017) Guerra et al. (2020); IRENA (2019)
Energy input capacity (MW)	430	100	
operating hours/year	8322	8000	
initial capital expenditure (€/kw)	1000	1250	
additional stack replacement costs after 10 years (€/kw)	-	375	
Yearly OPEX (%/CAPEX)	3	1.5	
water use (L/kg)	4.7	15	
efficiency production plant (MWh H_2/MWh energy input)	69%	75%	
CO_2 emissions (kg/kg H_2)	0.99	-	
CO_2 captured (kg/kg H_2)	8.9	-	

Note: the operating hours for SMR with CCS are corresponding to 90% of total hours per year; the stack replacement costs for electrolysis are 30% of initial capital expenditure costs

Table 3.2 Base case assumptions on plant performance and costs of CTG and SWG, in 2021 €

Assumptions	CTG[12]	SWG	Sources
lifetime plant (years)	20	20	
Biomass input capacity (MW)	120	20	
operating hours/year	8000	8000	
initial capital expenditure (€/kw)	2000	2800	Al-Mosuli et al. (2011); Chen et al. (2020); Gasafi et al. (2008); Porcu et al. (2019); Sara et al. (2016); Salkuyeh et al. (2018); Wang et al. (2019)
additional capital expenditure pre-treatment (€/kw)	350	-	
yearly OPEX (%/CAPEX)	4	14	
Water use (L/kg H_2)	0.01	-	
oxygen use (kg/kg H_2)	4.46	-	
electricity use (MW)	12.4	13	
efficiency production plant (MWh H_2/MWh energy input)	46%	81%	
CO_2 production (kg/kg H_2)	14.35	12.25	
Biochar production (kg/kg H_2)	1.52	-	

Note: some of the inputs reported are based on data that is provided by private industrial parties. However, all the inputs are compared with publicly available information and adjusted if necessary

One by-product of hydrogen production through the CTG of biomass is biochar, which is a stable solid that is rich in carbon. Biochar can endure in soil for long periods of time and can be used as a soil amendment. Finally, the bio-hydrogen technologies also produce respectively considerable amounts of CO_2 per unit of hydrogen. However, since the feedstock of these technologies is biomass, they are excluded from the ETS system, meaning there are no additional costs involved (in contrast with the case of SMR).[13]

[12] Note that the performance slightly differs for different biomass inputs. We show the numbers for A wood here.
[13] One should note that it is necessary to prove that the biomass used in the process is sustainable to be exempted from the ETS system

3.4 Assumptions on prices in the base case

To be able to estimate the LCOH of the different technologies, it is necessary to make credible assumptions for inputs like electricity, natural gas, biomass, water and oxygen as well as the price or costs of the by-products that are produced, being CO_2 and biochar. All the assumed values for the different prices are displayed in Table 3.3 together with their sources, and discussed in the sections below.

Table 3.3 Base case assumptions on the prices for different inputs and outputs, in 2021 €

Product	Value	Source
Electricity (€/MWh)	60	Eurostat; IRENA (2020)
Natural gas (€/MWh)	25	Eurostat; IEA (2021)
Biomass - A wood (€/ton)	60	de Jong et al. (2015); de Wit & Faaij (2010); Kuppens et al. (2015); Trippe (2013)
Biomass - sewage sludge (€/ton)	0	Default option
Demineralised water (€/L)	0.0025	Industrial suppliers
Oxygen (€/ton)	80	Hurskainen, M. (2017); Poláková & Variny (2021)
CO_2 allowances (€/ton)	70	Ember
CO_2 storage costs (€/ton)	45	Van der Spek et al. (2019)
Green CO_2 (€/ton)	0	Default option
Biochar (€/ton)	200	Jin et al., (2019); Thengane et al. (2021); Vochozka et al. (2016)

3.4.1 Energy and biomass feedstock prices

Energy and biomass feedstock prices are a particularly essential component for the estimation of the LCOH. Since it is known that the assumptions on these costs have a significant impact on the LCOH, the effect of all these prices on the estimated LCOH is shown in section 5. For the base case, the best estimate for an average price based on historical data, projections and literature is taken.

The 2021 European electricity prices are reaching record high levels following high natural gas prices. Given the anticipated higher penetration of renewable electricity, this relation is expected to reduce in the future. Simultaneously, the levelized costs of energy (LCOE) of renewable electricity will become a more decisive input for the electricity prices. Given that not all hours of the year renewables will be the price-setting technology, an average electricity price of 60 €/MWh is assumed, which is somewhat above the anticipated future LCOE of renewable electricity production (IRENA, 2020). This includes the costs for the Guarantees-of-Origin, which are crucial in order to be able to call the hydrogen produced low-carbon or 'green' (Weeda & Niessink, 2020).

As said above, the natural gas prices are relatively high in 2021 as compared to the long year average. This is due to a combination of steeply growing demand and supply shortages. A series of events in the global supply chain of natural gas have caused this imbalance, leading to an increase in the natural gas prices in all markets. However, long-term forward prices indicate the gas price will be much lower than current ones and closer to the historical levels, resulting in an outlook where prices will not remain as high in the future (IEA, 2021). Therefore, an average base case price of 25 €/MWh for natural gas is assumed.

Biomass feedstock price estimates are very different for different feedstock types. Often the use of biomass for energy production processes is argued to be a solution for waste streams that otherwise would be neglected. Because of this reasoning, the biomass feedstock then is often assumed to be abundantly available for a low or sometimes negative price. However, each stream of biomass feedstock is often also useful in other profitable processes as production of animal feed and chemicals. If these alternative applications make use of the similar feedstocks, the assumed availability for a low price becomes doubtful (Hoang et al, 2020). For the case of A wood, this effect can already be observed, and has resulted in reported biomass prices around 60 €/ton.

Still, for some biomass streams it is indeed the case that there are very limited options for further processing, leaving the producers of these streams with a burden. In these cases, amongst which sewage sludge, a negative price for taking over this burden of having to properly dispose such a waste stream is likely to remain. However, this negative price is a reflection that the burden does not disappear, and the responsibility of properly managing these streams now lies with the buyer of the biomass. In the specific case of sewage sludge, the operator of a SWG system will have to deal with all the harmful chemicals in the sludge, such as for example resulting from medicine use, which can induce extra costs.

Although the wastewater treatment plant operator may be willing to pay a certain price for not having this obligation anymore, this obligation also imposes a cost on the SWG operator. Generally, any waste stream used in a production process can at some point in time become a resource. As soon as it does, the gate fee may disappear or even turn into a price. This is more likely for some than for other, nevertheless, to accommodate for this our central assumption is a price of 0 €/ton.

3.4.2 Water and oxygen price

Water and oxygen are two other inputs that are needed for the production of hydrogen. Water is used by all the four technologies, with electrolysis as the highest water consuming technology with 15 L of demineralised water per kg of hydrogen produced (Chardonnet et al., 2017). From industrial suppliers a demineralised water price of 0.0025 €/L is obtained.[14]

Oxygen is only used by CTG. The oxygen market is a mature global market, with many suppliers. Industrial oxygen prices that were obtained were mostly based on the costs of the use of Air Separation Units (ASU) and were in the range of 80 €/ton (Hurskainen, 2017; Poláková & Variny , 2021). On the contrary, electrolysis produces oxygen as a by-product, indicating a potential extra revenue stream. However, to make it profitable for an electrolysis operator to invest in the capturing and storage installation for oxygen the oxygen price should at least be 730 €/ton (Squadrito et al., 2021). Since the current observed oxygen price is significantly below this threshold, we do not take extra revenues from oxygen production into account.

3.4.3 Carbon costs and prices

As mentioned above, SMR production plants are operating under the EU-ETS, meaning allowances have to be bought to compensate for the emission of CO_2. It is noteworthy that the CO_2 allowance price has significantly increased the last years, from a mere 5 €/ton to a current price of 70 €/ton, adding roughly 30% to the costs of grey hydrogen production.

[14] See, for example: https://www.uswatersystems.com/blog/de-ionization-101

When a CCS installation is included in the process, costs for allowances are avoided, but, without usage of the captured CO_2, these are replaced with the costs of transporting and storing the captured CO_2. On top of the capturing costs, also costs of transporting and storage are incurred, which are in the range of 15-45 €/ton (Van der Spek et al., 2019). As for the foreseeable future a low utilization of the large-scale storage of CO_2 is expected, the upper value of 45 is taken in the base case. The influence of a cost reduction in carbon storage is analysed in section 5.

However, CO_2 is not only a harmful greenhouse gas when emitted into the air but also a productive input into various economic applications. These applications particularly include the production of e.g. urea (fertilizer), carbonated beer & soft drinks and decaffeinated coffee as well as cooling in the form of dry ice for e.g. the transport of perishable food and vaccines.[15] Typically, CO2 suppliers procure CO2 from industrial emitters (i.e. the actual CO2 producers) and sell and transport the CO2 to end-users. CO2 is generally produced by capturing CO2 in the production of hydrogen (SMR) and ethanol . CO2 in these processes is typically a by-product which would otherwise be emitted into the atmosphere.

Market prices for CO2 consumption are not transparent. It appears unlikely that the wholesale price that the CO2 suppliers pay to the producers are meaningful in the sense that they exceed the cost of CO2 separation or capture and (on-site) storage. The current level of production is a fraction of what could theoretically be produced from existing installations that emit CO2 as a by-product. This means that

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[15] Total global consumption of CO2 amounted to 230mT of CO2 in 2015, and has grown in the past years (IEA, 2019). Europe accounts for about 10% of global consumption (IHS Markit, 2021). This is very small in comparison with total European CO2 emissions of about 2,500mT in 2019 (EEA, 2021).

wholesale prices in excess of the separation/capture costs are unsustainable, as this provides an incentive for existing emitters that are not yet capturing CO2 to install capturing installations. For the near future, it not expected that the demand for CO2 will increase to the extent that sources with higher costs are required. Therefore, it will be assumed that the price for CO2 reflects the costs of the capturing equipment and does not provide a meaningful source of profit for any of the types of hydrogen plants.

3.4.4 Char price

Biochar is a product that has the potential to be widely used in sustainable agriculture as there is numerous evidence of a positive impact of biochar one the conditions of soil, water and plants (Zimmermann et al. 2011). However, the supply of biochar is reported to be small and therefore market price estimates are in the wide range of 120-600 €/ton of delivered biochar (Thengane et al., 2021 & Vochozka et al., 2016). The revenues that can be realized by the producer are lower than this market price, as the costs for the transportation to the consumer also have to be compensated. Furthermore, the current market price is heavily influenced by the small number of suppliers and is likely to decrease with more competition due to an increased supply. In the base case, a biochar benefit for the CTG operator of 200 €/ton is assumed, close to the value assumed by Jin et al. (2021). In section 5, it will be shown what happens when the char price is increased to 350 €/ton.

4. Results

4.1 Introduction

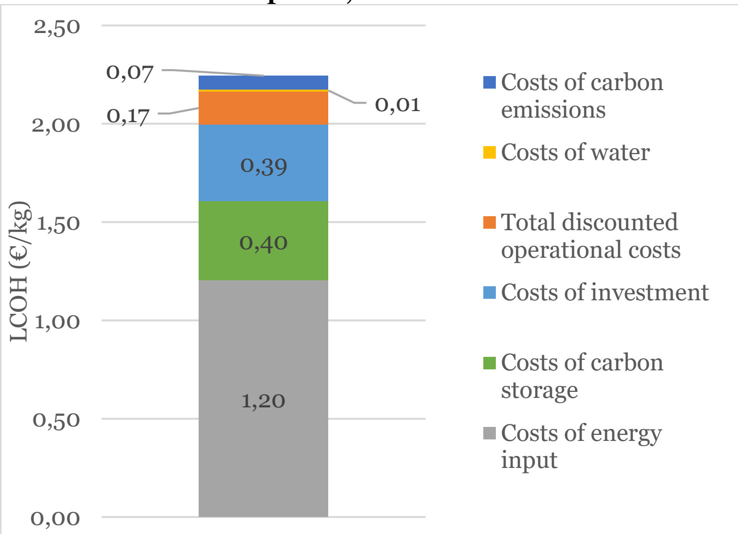
The levelized costs of hydrogen production consist of several components, including investment and operational costs, input costs for energy, water, biomass and oxygen as well as costs of carbon. In sections 4.2 till 4.5 the breakdown of these cost components for the LCOH of the four different technologies in the base case are discussed. Section 4.6 will compare the four technologies.

4.2 Steam methane reforming with carbon capturing and storage

The breakdown of the LCOH for this technology is shown in Figure 4.1. The base case estimate for the LCOH of this technology is 2.24 €/kg with the cost of natural gas being the major cost component, being more than half of total costs. Other important components are the costs of carbon dioxide transportation and storage and the investment costs. The operational costs as well as the costs of water for steam production and the compensation for residual carbon dioxide emissions are relatively small.

The ratio of the costs of carbon storage and emissions are also dependent on the capturing rate of the CCS installation. With a lower capturing rate, more costs of emissions are accompanied with lower costs of storage. In the base case, the ETS allowance price is higher than the storage costs of carbon. If this difference is large enough to absorb the extra installation costs of CCS, the SMR plant has an automatic incentive to obtain an higher capturing rate, up to the point where the extra costs of CCS and the extra costs of allowances are equal.

Figure 4.1 Breakdown of the LCOH for SMR with CCS, base case assumptions, in 2021 €



Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3

4.3 Electrolysis with renewable electricity

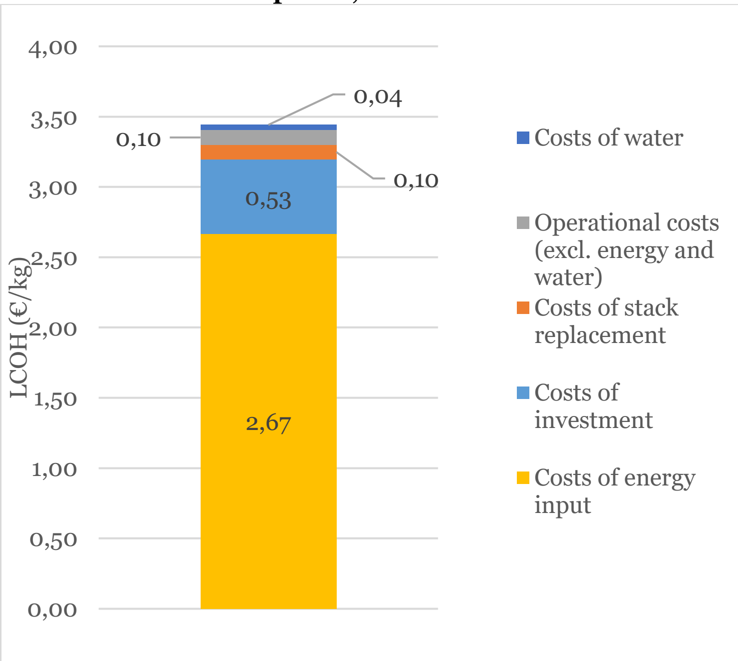
The breakdown of the estimated base case LCOH through electrolysis is depicted in Figure 4.2. As is the case with the SMR with CCS technology, the majority of the total LCOH (3.44 €/kg) turns out to be the costs of the energy input. The investment, operational and water costs combined only make up less than 25 percent of the total LCOH. This large importance of the electricity costs for the total LCOH, makes that the estimation for electrolysis is very sensitive for the assumed electricity price. This effect is also shown in the sensitivity analysis in section 5. It must be mentioned that this large importance of electricity costs is partly due to the cost minimizing assumption of 8000 operating hours a year, in combination with a grid connection. If a lower utilisation of the electrolyser is considered, for example to reflect the connection to renewable power generation, the share of electricity costs is lower. However, it will still determine the majority of the LCOH for electrolysis. This is based on the fact that if the Full Load Hours (FLH) of the electrolyser are changed, the electricity and water costs per kg of hydrogen do not change. Only the investment and (related) operational costs per kg of hydrogen increase proportionally to the decrease in FLH. For example, with half of the operating hours (4000 per year), the investment and operational costs per kg of hydrogen double. In this example, the electricity costs still make up for more than 60% of the LCOH.[16]

An implication of this result is that it is hardly possible to increase the competitiveness of electrolysis produced hydrogen through a reduction of capital expenditures. This is somewhat in contrast to often stated predictions for electrolysis technology, where cost reductions in capital expenditures for the electrolyser are attributed a large role in diminishing the LCOH.[17] It should be mentioned that the majority of the competitiveness of electrolysis is not determined by the capital expenditure, but rather by the (renewable) energy price. Only in the case with structural heavy reduced renewable electricity prices, a reduction of capital expenditures can play a role in the competitiveness.

[16] This is in line with the findings of Janssen et al. (2022), where it is shown that the relative importance of electricity costs to the electrolyser costs is high in the case of a LCOE of 50 €/MWh

[17] See for example: European Commission, 2020

Figure 4.2 Breakdown of the LCOH for electrolysis, base case assumptions, in 2021 €

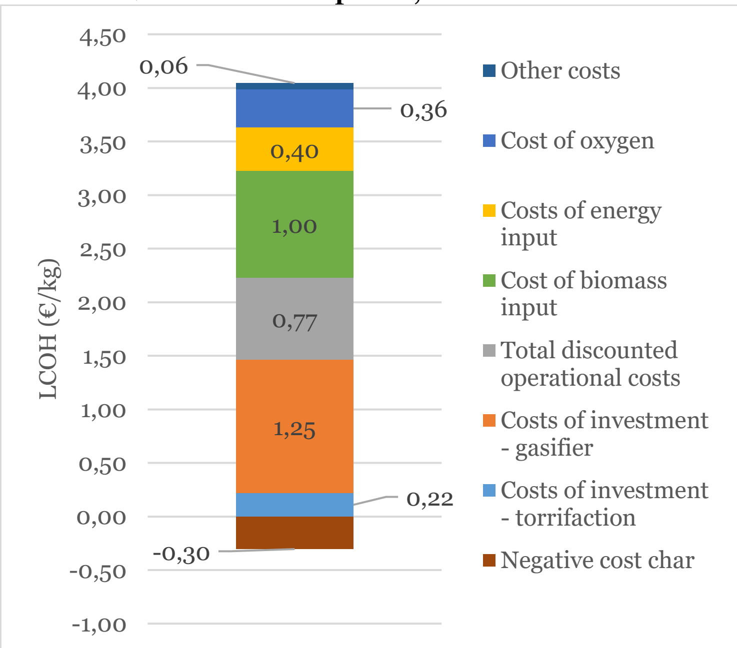


Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3

4.4 Combined torrefaction and gasification of biomass

Compared to the previous technologies, CTG of biomass has a different cost structure as shown in Figure 4.3. It is important to note that the influence of the investment and operational costs on the total costs are larger than for electrolysis and SMR with CCS, as they constitute more than half of the LCOH. Another component of importance are the biomass and energy input costs, making up almost a third of overall costs. This is a significant amount, but considerably less than is the case for the previous technologies. Furthermore, it can be seen that in the base case, the production of the by-product biochar creates a negative cost component of 0.30 €/kg. Altogether, the LCOH produced through CTG of biomass is 3.74 €/kg in the base case, making it more expensive than SMR with CCS and slightly above the value found for electrolysis.

Figure 4.3 Breakdown of the LCOH for CTG of biomass, base case assumptions, in 2021 €



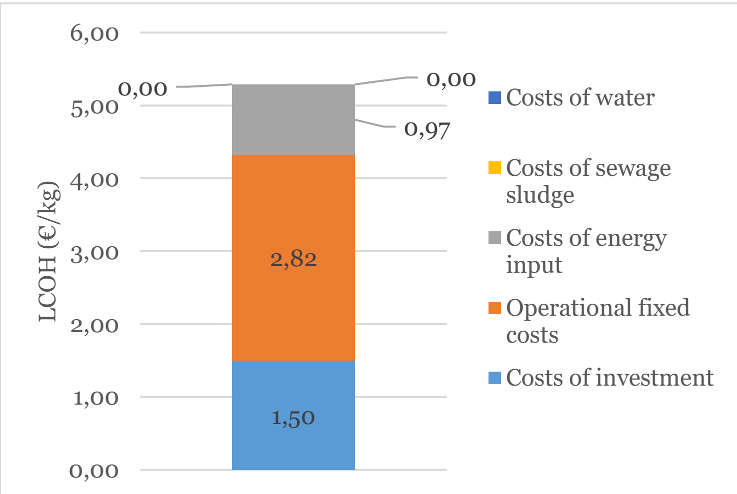
Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3

4.5 Supercritical gasification of sewage sludge

For the SWG of sewage sludge, the breakdown of costs is shown in Figure 4.4. In contrast to the other technologies, one can observe that the investment and operational costs are by far the most important cost components for the total LCOH of 5.32 €/kg. This is the result of the reportedly relatively high capital intensity of the sytem as well as the high operational costs. This also implies that the LCOH of this technology is more sensitive to adjustments of the investment and operational cost assumptions, which will be discussed in section 5. Since the costs of the sewage sludge are assumed to be 0 in the base case, it is also not reflected in the breakdown. If this (negative) cost price is different, it will automatically also influence the LCOH.

Compared to the CTG, it is noteworthy that the costs of the external energy input are higher. This is due to the fact that to transit to the supercritical phase, more external energy input (besides the biomass input) is needed.[18]

Figure 4.4 Breakdown of the LCOH for SWG of sewage sludge, base case assumptions, in 2021 €



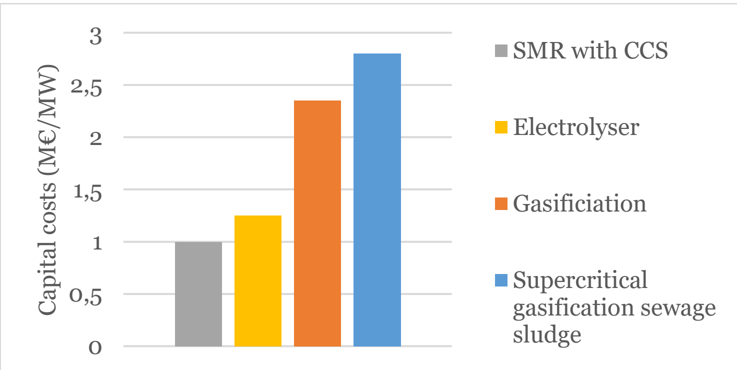
Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3

[18] Following from assumptions on the external energy input based on literature and experts, as stated in Table 3.3

4.6 Comparison

In the analysis of the breakdown of costs of the different technologies, it becomes apparent that different cost structures are in place. One of the cost components that varies most across the different technologies is the capital expenditure (needed) per kg of hydrogen produced. This variation in capital intensity is depicted in Figure 4.5, which shows the capital costs per installed MW of each technology in millions of euros. As can be expected from the breakdown of costs presented above, the capital intensity of both CTG and SWG is significantly higher compared to SMR with CCS and electrolysis.

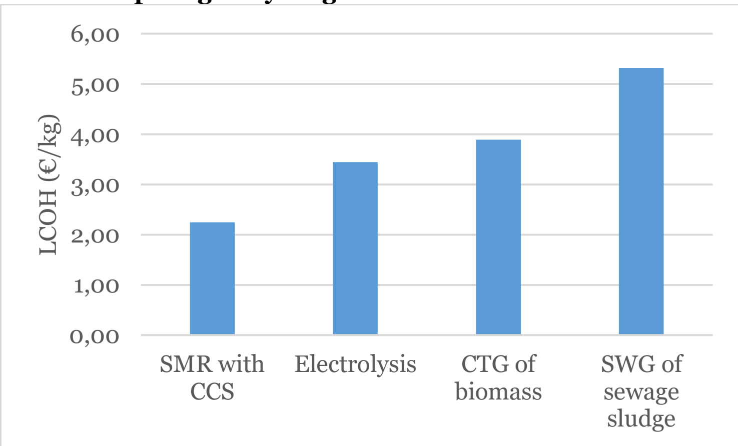
Figure 4.4 Capital costs per MW installed capacity, all technologies, base case assumptions, in million 2021 €



Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3

The merit-order of low-carbon hydrogen production based on the LCOH is shown in Figure 4.6. It can be seen that with the base case assumptions, SMR with CCS is the most competitive source of low-carbon hydrogen production, followed by electrolysis, CTG and SWG, ranging from 2.23 to 5.37 €/kg. In section 5, it is shown how assuming different inputs and parameters changes this estimation.

Figure 4.4 Merit-order of low-carbon hydrogen production, all technologies, base case assumptions, in 2021€ per kg of hydrogen



Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3

5. Sensitivity analysis

5.1 Introduction

As explained above, the estimation of the LCOH for the technologies is depending on variable assumptions on parameters and costs. To make the estimates more robust for different future scenarios, it is useful to perform a sensitivity analysis for multiple assumptions. This enables the comparison of the technologies under dynamic circumstances and helps to determine the most economic efficient low-carbon hydrogen production process for alternative scenarios. In section 5.2, it is shown what the effect of improved plant performance and lower capital and operational cost is on the LCOH. In section 5.3, the relation between the LCOH and energy and feedstock prices are depicted for all the technologies.

5.2 Sensitivity to plant performance and costs

For the sensitivity analysis of the plant performance and costs, an innovative scenario is constructed for each of the four technologies. The assumptions that correspond to this scenario are given in Table 5.1

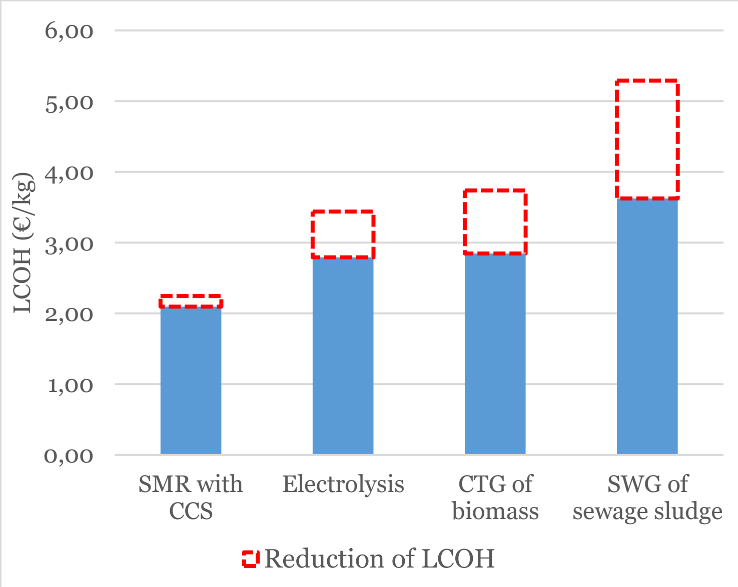
Table 5.1 Assumptions on plant performance and costs in an innovative scenario, in 2021 €

Assumptions	SMR with CCS	Electrolysis	CTG	SWG
initial capital expenditure (€/kw)	900	600	1400	2500
additional capital expenditure pre-treatment (€/kw)	-	-	350	-
yearly OPEX (%/CAPEX)	3	1.5	4	9
efficiency production plant (MWh H_2/MWh energy input)	75%	80%	50%	85%

The innovative scenario assumes that the capital and operational expenditure of the technologies decrease, while the efficiency increases, due to technological development. The operational expenditure of the technologies is expressed in a share of capital expenditure and hence decreases accordingly. Only for the SWG process, it is assumed that this share is altered in the innovative scenario, from 14% to 9%. This is due to the relatively high share for this technology, which is also high compared to typical considerd industrial averages.

The merit-order of low-carbon hydrogen production for the innovative scenario is depicted in Figure 5.1. The bars represent the estimated LCOH in the innovative scenario, where the dotted area depicts the reduction realized compared to the base case scenario. It can be seen that for most technologies the LCOH significantly decrease, with an exemption of SMR with CCS. The merit-order is only altered in the case of relative stagnation of one technologies with innovation for another technology. For example, CTG can become competitive with electrolysis, if plant performance and costs are close to the innovative scenario if performance and costs of electrolysis do not fully develop to the innovative levels. The same holds for SWG and CTG, respectively. In practice, it is logical to assume that if innovations in one technology occur, other technologies will experience innovations likewise.

Figure 5.1 Merit-order of low-carbon hydrogen production, all technologies, innovative scenario, in 2021 € per kg of hydrogen



Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3, where the assumptions for the innovative case can be found in Table 5.1

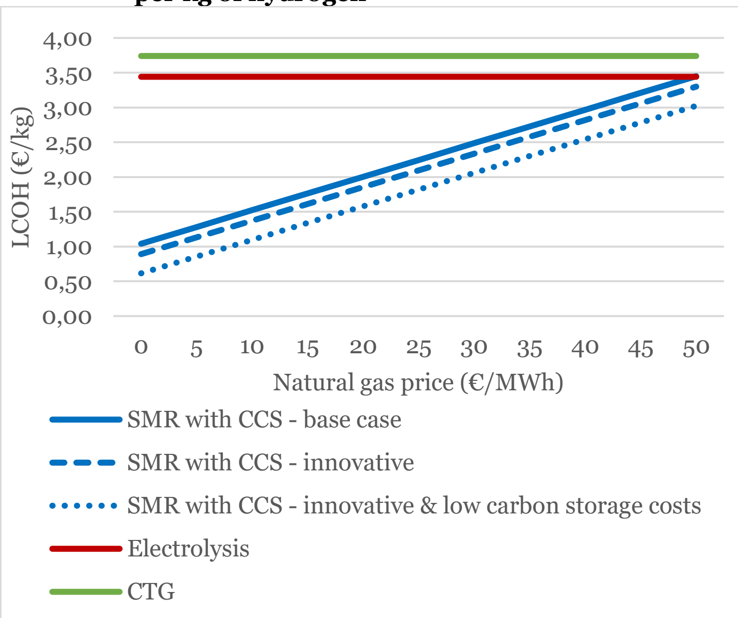
5.3 Sensitivity to input and output prices

As shown in section 4, each technology has a dominant input price influencing the LCOH estimation. For SMR with CCS this is the natural gas price, for electrolysis this is the electricity price and for CTG and SWG it is their respective biomass feedstock price. In this section, it is shown what the influence of these prices is on the LCOH of the technology and their position in the merit-order.

The relation between the natural gas price and the LCOH of SMR with CCS is shown in Figure 5.2. The LCOH of three plant performance and costs scenarios is shown: the base case, the innovative scenario and a scenario where the carbon storage costs are reduced to the lower limit of 15 €/ton, as suggested in literature.

One can observe that, in the base case, the average natural gas price has to rise to 50 €/MWh before a similar LCOH to that of electrolysis is estimated. For the innovative scenario and the scenario with low carbon capture and storage costs, this price is higher. Compared to the CTG of biomass, the price has to increase further. Comparing this to the prospects for the future natural gas price, it becomes apparent that SMR with CCS will likely remain the technology with the lowest LCOH, given the base case electricity and biomass input prices.

Figure 5.2 LCOH in relation to natural gas price, per technology, for different scenarios, in 2021 € per kg of hydrogen



Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3, where the assumptions for the innovative case can be found in Table 5.1

In Figure 5.3, the relation of the LCOH for electrolysis and the electricity price is shown, for the base case and the innovative scenario of plant performance and costs. With higher average prices of renewable electricity (around 70 and 80 for the base case and innovative scenario, respectively), the estimated LCOH for electrolysis is higher than CTG. On the other hand, if the price is below 35 €/MWh, the base case LCOH is lower for electrolysis than for SMR with CCS. In an innovative scenario this is with prices below roughly 45 €/MWh. Although this is within the range of estimated future LCOE for wind and solar energy, one must realize that this estimation is based on 8000 operating hours a year. Given the limited capacity factor of wind and solar, there is a need for (more expensive) alternative electricity sources, such as a gas firing power plant[19], for the remaining hours of the year, hence increasing the average electricity input price for the electrolysis operator.

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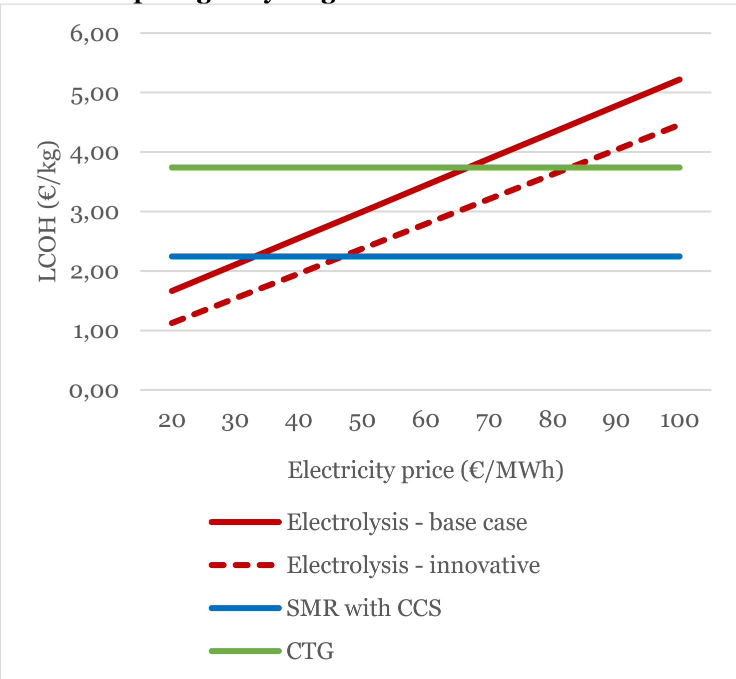
[19] The produced hydrogen can be labelled green by the use of green-certificates, see section 2.3

Figure 5.3 LCOH in relation to electricity price, per technology, for different scenarios, in 2021 € per kg of hydrogen



Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3, where the assumptions for the innovative case can be found in Table 5.1

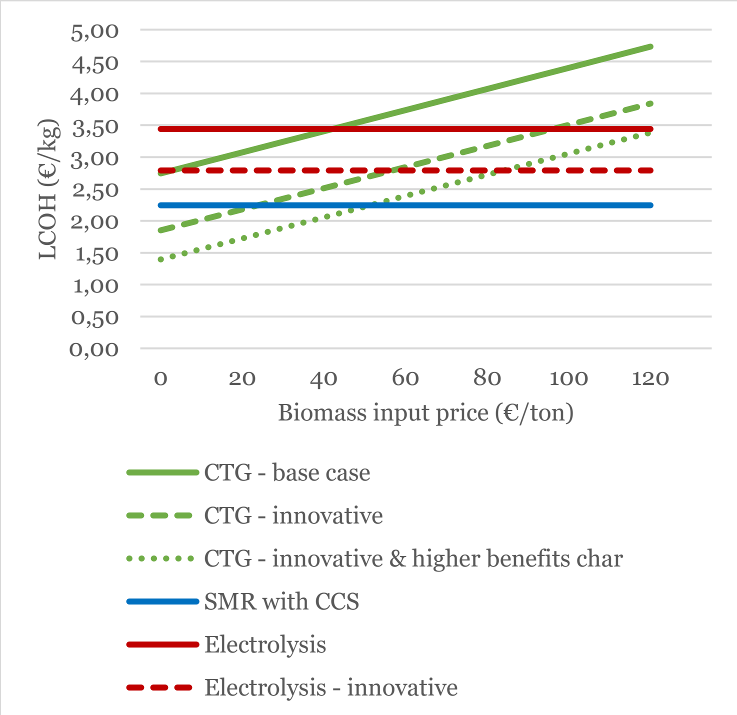
The relation between the price for biomass needed for the CTG process and its LCOH is depicted in Figure 5.4. Depicted for this technology are the estimations for the base case plant scenario, the innovative plant scenario and the innovative plant scenario where the benefit for the produced biochar is increased to 350 €/ton. For the base case, the biomass price for A wood should decrease to 40 €/ton to become competitive with electrolysis, with this threshold increasing to 95 and

120 €/ton for the innovative scenario and the innovative scenario with higher biochar benefits, respectively. If innovation for electrolysis is applicable, but expected long-term electricity prices remain constant, these prices decrease to 0, 55 and 75 €/ton, respectively. So, innovations in CTG of biomass or a reduction in the biomass feedstock price can make it competitive to electrolysis, given that there is less innovation occuring for the latter technology and with the expected long-term electricity prices.

For the estimated LCOH for CTG of biomass to to become competitive with SMR with CCS, both the innovative scenario with high biochar benefits will have to materialize as well as biomass prices below 50 €/ton should occur.

Overall, with a relative more innovatice scenario for CTG, compared to the other technologies, a small price reduction or even with current feedstock prices, the LCOH can become in the same range. If other technologies also experience a high degree of innovation, or the innovation for CTG is at a low level, this need for feedstock price reduction is significantly higher. Induced by demand for biomass for other processes, a significant price reduction and therefore the dedicated use of biomass for hydrogen production seems however not realistic in the near future (Weeda & Niessink, 2020). This could change when cheaper biomass is abundantly available, but there is currently no evidence that this is the case.

Figure 5.4 LCOH in relation to A wood biomass input price, per technology, for different scenarios, in 2021 € per kg of hydrogen

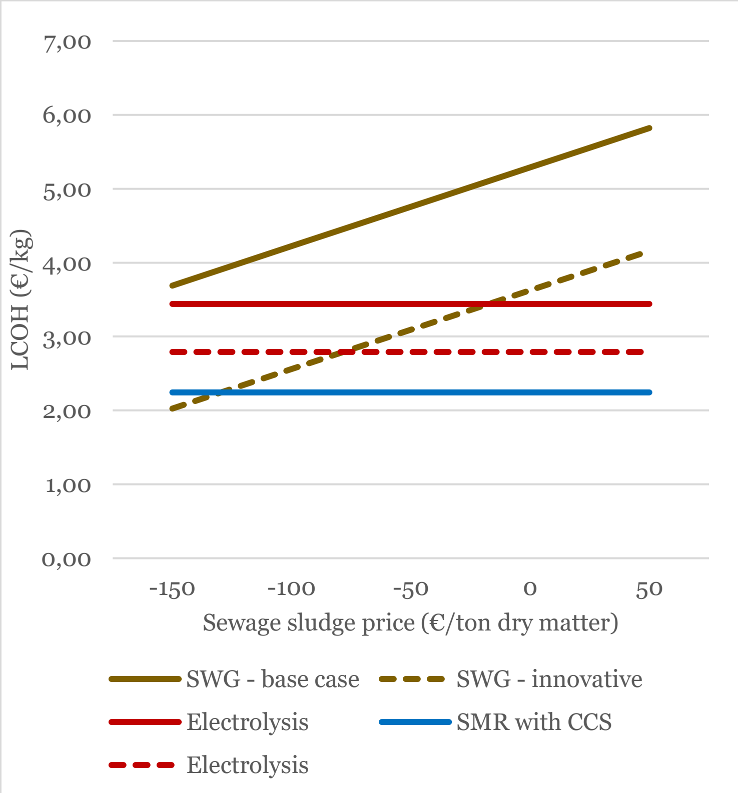


Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3, where the assumptions for the innovative case can be found in Table 5.1

Finally, Figure 5.5 depicts the relationship between the sewage sludge input price and the estimated LCOH for SWG. In the base case scenario, negative prices of well below 150 €/ton must be realized before the SWG process becomes competitive with electrolysis. For the innovative scenario, this required negative price is around 20 €/ton.

As described in section 3.4.1, although water treatment plant operators are possibly willing to pay for the disposal of sewage sludge, this is currently most likely (partly) offset by the costs that are involved with the proper treatment of the waste. An intuitive thought behind this reasoning is the fact that if there were cheaper options of the treatment of sewage sludge available, these would most likely already be implemented by the water treatment plant operators. Future innovations for SWG can potentially reduce the costs of treatment of sewage sludge, resulting in negative experienced prices for the feedstock. The threshold price of -20 €/ton for the innovative SWG system to become competitive to electrolysis (base case) is imaginable. In an innovative scenario for electrolysis, the threshold price goes to -80 €/ton for an innovative SWG, while the base case SWG needs substantially lower prices. To become competitive with SMR with CCS, the SWG process needs negative prices under 130 €/ton in the innovative scenario. For the base case scenario, these required negative prices are substantially higher.

Figure 5.5 LCOH in relation to sewage sludge input price, per technology, for different scenarios, in 2021 € per kg of hydrogen



Note: the assumptions for the base case can be found in Tables 3.1, 3.2 and 3.3, where the assumptions for the innovative case can be found in Table 5.1

6. Concluding remarks

6.1 Introduction

Low-carbon hydrogen is increasingly being included in European and national climate and energy strategies. The produced hydrogen can be deployed by the energy-intensive industry, transportation and heating to replace fossil fuels. Also, in the case of electrolysis, it can be used as flexibility option for the electricity sector. Despite the ambitious plans and technical possibilities recently presented, the production plants for low-carbon hydrogen have yet to be build. Moreover, there is no consensus yet on which low-carbon hydrogen production technology is most useful for now and in the future, or if technologies can be developed in parallel.

In this report, four different low-carbon hydrogen production technologies have been analysed and compared based on their Levelized Costs Of Hydrogen (LCOH). This analysis is based on two aspects: a) the current competitiveness of bio-hydrogen compared to electrolysis and SMR with CCS and b) the future outlook of low-carbon hydrogen production for each of the technologies.[20]

6.2 Competitiveness of bio-hydrogen

To determine the competitiveness of bio-hydrogen technologies (combined torrefaction and gasification of biomass and supercritical water gasification), this report compares the LCOH of these technologies with other production technologies of low-carbon hydrogen. Specifically, both the total as well as the breakdown of the LCOH of combined torrefaction and gasification (CTG) of biomass,

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[20] The assumptions for estimations in this report are derived from publicly available literature or based on discussions with industry experts.

supercritical water gasification (SWG) of sewage sludge, electrolysis and SMR with CCS have been compared. Based on the analysis in this report, we formulate the following conclusions:

- At the market prices for natural gas, electricity and biomass as assumed, closer to the historical levels than current record high prices, bio-hydrogen is not able to compete with both SMR with CCS and electrolysis. The production of low-carbon hydrogen through SMR with CCS is, economically, the most attractive option, with electrolysis ranking second. While the estimated LCOH of CTG is relatively close to electrolysis, the LCOH of SWG is significantly higher, mainly induced by higher capital and operational costs.
- This conclusion changes with more optimistic assumptions on higher efficiencies and lower investment costs of bio-hydrogen production plants. These cost reductions because of technological developments, which are possible and conceivable in an innovative scenario, can alter the ranking of low-carbon hydrogen production according to their total costs per unit (i.e. the long-term merit order). However, this only holds in the case of a lower level of techno-economic innovation for electrolysis, combined with a high degree of innovation for bio-hydrogen technologies. Given spill over effects of innovations in hydrogen production technologies, combined with investments in research and development for electrolysis this scenario seems unlikely in the near future.
- The LCOH of SMR with CCS and electrolysis are to a large extent determined by the costs of natural gas and electricity, respectively. Consequently, both technologies see limited cost reductions options in the innovative scenarios which assume significant

advances in both plant efficiencies and capital costs. The reasoning that electrolysis becomes more competitive by lower capital costs alone, is not really convincing as the impact of lower capital costs on overall production costs appears to be fairly limited.

- For the production of hydrogen from biomass, combined torrefaction and gasification (CTG) is more competitive than supercritical water gasification (SWG) of sewage sludge, given the market prices for technologies and their inputs in the base case. Again, this conclusion only changes in a scenario where innovations for SWG lead to significantly lower costs, where at the same time techno-economic developments for CTG are assumed to (almost completely) stagnate.
- Market prices for biomass depend strongly on the availability of the biomass feedstock. For the CTG, there is competition for the most suitable biomass feedstock, which is A-wood, as there are numerous other applications for this biomass. This competition is reflected in a substantial biomass price of 60 €/ton, which in turn increases the LCOH of this technology. Other lower classified feedstocks, e.g. verge grass, can have lower market prices, but create high transportation costs. Furthermore, the availability of these feedstocks is limited and seasonable, making it currently unsuitable for large-scale stable hydrogen production.
- In the case of SWG, the biomass feedstock, sewage sludge, can be seen as a waste stream that has a market price of zero, or a one that is even negative. However, the use of sewage sludge may also bring the burden of having to treat all the chemical waste imposing a cost on the SWG operator. Currently, there is no evidence that using sewage sludge creates a benefit for the operator, but future

developments in SWG can potentially help to accomplish that. Furthermore, the availability of sewage sludge for large scale hydrogen production is a constraint. To operate the in this report assumed SWG plant size that produces 0.21 TWh, 0.7% of current Dutch hydrogen demand, the sewage sludge produced by a city of over 2 million people is needed. This makes that the implementation of SWG to produce hydrogen is extremely unlikely to play a significant role.

6.3 Future outlook of low-carbon hydrogen production

Since the competitiveness of the technologies hardly changes when alternative values are chosen for the assumptions regarding technical efficiencies, as well as capital and operational costs, the future outlook of the low-carbon hydrogen production technologies is mainly determined by energy and biomass feedstock markets. This report analyses the influence of these prices and indicates under which potential future scenarios, the competitiveness of the technologies changes. Based on the analysis in this report, the following conclusions are formulated:

- The strong relation between the LCOH and the input prices of energy or biomass feedstock, results in these being the most reasonable inputs that could change the merit-order of low-carbon hydrogen production. For the LCOH of SMR with CCS to rise above the costs of the next best alternative (i.e. electrolysis), the average natural gas price has to rise above 50 €/MWh at assumed average electricity prices (60 €/MWh). Alternatively, the average electricity price throughout the year has to become lower than 45 €/MWh for electrolysis to become competitive with SMR with CCS at assumed gas prices (25 €/MWh). Although global natural gas prices are currently above this level, long-term forward prices indicate the gas price will be much lower than current ones and closer to the historical levels, resulting in an outlook where prices will not remain as high in the future. Therefore, only in the scenario where the average price for (renewable) electricity[21] is significantly reduced, electrolysis can become more competitive. Given that for the foreseeable future the electricity price is heavily influenced by the natural gas price, this scenario is unlikely.

- With the current state of technology, hydrogen production through CTG of biomass is competitive with electrolysis when the biomass feedstock prices are below 40 €/ton. This price increases to 95 and 120 €/ton for the innovative scenario and the innovative scenario with higher biochar benefits, respectively. If innovation for electrolysis is applicable, these prices decrease to 0, 55 and 75 €/ton, respectively. So, innovations in CTG of biomass can make it competitive to electrolysis, given that there is less innovation occuring for the latter technology. CTG of biomass only becomes competitive with SMR with CCS in an innovative scenario with higher biochar benefits, where the biomass price is below 50 €/ton. Overall, with a more innovatice scenario for CTG, compared to the other technologies, a small price reduction or even with current feedstock prices, the LCOH can become in the same range. If other technologies also experience a high degree of innovation, or the innovation for CTG is at a low level, this need for feedstock price reduction is significantly higher.

[21] This means either electricity directly from a renewable power generator or electricity from the grid in combination with Guarantees-of-Origin

- Hydrogen production through SWG of sewage sludge needs substantial negative prices to become competitive with electrolysis and SMR with CCS. In the base case scenario, the LCOH of SWG is only with a negative price for sewage sludge as low as 150 €/ton competitive with electrolysis, with SMR with CCS being even further away. In an innovative scenario, with significantly reduced capital and operational costs, the negative price for sewage sludge required to become competitive with a stagnated electrolysis technology is around 20 €/ton. This value is within a realistic range, given that SWG is a technology that is in development. For SMR with CCS, this required negative price is 130 €/ton. This substantially negative required sewage sludge price, in combination with the very limited available feedstock, makes it unlikely that SWG of sewage sludge will play any significant role in the production of low-carbon hydrogen.

In conclusion, from the findings in this report it can be inferred that bio-hydrogen is currently not competitive with SMR with CCS, while the LCOH for CTG is slightly higher than for electrolysis. With a relative more innovatice scenario for CTG, compared to the other technologies, a small price reduction or even with current feedstock prices, the LCOH can become in the same range. It is however likely that electrolysis will also experience high innovation, given that most hydrogen policy seems to be targeted at innovation of this specific technology. Given the high anticipated demand for hydrogen and novelty of the technology, more research and development in CTG is advised to stimulate innovation for this technology as well. The availability of the required biomass makes it hard to imagine a significant role for hydrogen production from SWG in the near future.

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Production and deployment of low-carbon hydrogen is seen as a promising route in realising a successful energy transition to a carbon neutral energy system. Hydrogen strategies are developed on a national, European and global level. The most common low-carbon hydrogen technology that is anticipated in these strategies is electrolysis with the use of renewable electricity. However, several other technologies to produce low-carbon hydrogen exist,, such as steam methane reforming (SMR) in combination with carbon capturing and storage (CCS). Furthermore, there is the production route of "bio-hydrogen", i.e. hydrogen from the (supercritical) gasification of bio-based raw materials.

In this research, the focus is on assessing the current and future outlook for the levelized production costs of these different low-carbon hydrogen production technologies. For each of the production technologies, the levelized costs of hydrogen production is estimated, based on information regarding the technical performance, operational costs and energy and feedstock prices. The most relevant cost components are determined, after which the technologies are compared by constructing a merit order.

From this merit order it follows that currently bio-hydrogen is not able to compete with both SMR with CCS and electrolysis. To be able to explore the influence of adjusting assumptions on the future outlook, a sensitivity analysis on both technical components as well as the energy and feedstock prices is conducted. It is found that levelized hydrogen costs are strongly determined by energy input and biomass feedstock prices. Although one can think of specific scenarios where bio-hydrogen becomes competitive, the probability of these scenarios is questionable. Given these circumstances, it seems more likely that the available biomass is used for other processes than dedicated hydrogen production.

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