MASTER'S THESIS – ENERGY SCIENCE

Cost-effective Hydrogen Production

A comparison of uncertainties in the levelized cost of hydrogen for the dominant hydrogen production pathways

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Written by:

Jan Overbeek

4012968

j.g.a.overbeek@students.uu.nl

Under the supervision of:

Dr. ir. Machteld van den Broek

m.a.vandenbroek@uu.nl

Universiteit Utrecht

Abstract

This research paper compares the levelized cost of hydrogen (LCOH) production of the most used hydrogen production methods. More specifically, it analyzes how uncertainties in techno-economic data from literature affects the LCOH of these production methods. To answer this question, the LCOH was calculated using a range of values for the underlying factors that determine the LCOH. Five pathways were defined containing different production methods. The default location of these pathways is the port of Rotterdam. This location was chosen because it is the largest port of Europe, providing suitable infrastructure required for imported hydrogen to arrive by ship.

Two pathways produce hydrogen through steam methane reforming (SMR). One of these pathways includes implementation of carbon capture and storage (CCS) technology and the other does not include CCS. Two pathways produce hydrogen through electrolysis. One produces hydrogen locally and the other produces hydrogen abroad using renewable electricity. The fifth pathway produces hydrogen abroad through Coal Gasification with CCS.

Data on underlying factors of the LCOH was obtained from literature research for the different pathways. An uncertainty analysis was performed to show the effect of variation of these factors on the calculated LCOH values. This effect was analyzed for the years 2020 and 2030.

Based on the comparison of the pathways under baseline conditions, hydrogen production through SMR without implementation of CCS technology results in the lowest LCOH value. The LCOH values for this pathway under baseline conditions are 1.78 $€_{2019}$/kg H_2 for 2020 and 2.37 $€_{2019}$/kg H_2 for 2030. Additional costs for implementation of CCS results in the LCOH values of 2.08 and 2.45 $€_{2019}$/kg H_2 respectively. The largest LCOH value was found for the pathway that produces hydrogen abroad through CG. For 2020, an LCOH value of 4.53 $€_{2019}$/kg H_2 was found. For 2030, due to a reduction in transport costs, this value decreases to 3.63 $€_{2019}$/kg H_2.

The uncertainty range associated with these calculated LCOH value is significant, showing a variation of -30% and +60% on average as a result of the uncertainty analysis. The largest uncertainty range was found for the pathway that produces hydrogen locally through electrolysis. This value showed a variation of approximately -40 and + 90%. This high level of uncertainty is caused by the large uncertainty range found for the Dutch electricity price.

The results of the uncertainty further showed that variation of the capacity factor and the energy prices cause a high level of uncertainty in the calculated LCOH for all production pathways. This research emphasizes the need to reduce the uncertainty in underlying factors of the LCOH for hydrogen production to facilitate decision making considering hydrogen production in the future.

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List of Abbreviations

CCS	Carbon Capture and Storage
CG	Coal Gasification
CSIRO	Commonwealth Scientific and Industrial Research Organization
CT	Compressed Transport
EW	Electrolysis of Water
IEA	International Energy Agency
IEW	Imported hydrogen from Electrolysis of Water
KHI	Kawasaki Heavy Industries
LCOH	Levelized Cost of Hydrogen
LT	Liquified Transport
O&M	Operation and Maintenance
PEM	Proton Exchange Membrane
SMR	Steam Methane Reforming
SQ	Support Question
UAE	United Arab Emirates
WGSR	Water-Gas Shift Reaction

1 Introduction

Local, national, and international governments are investigating possibilities and opportunities of a hydrogen based economy in a time where the production and consumption of fossil fuels is being discouraged increasingly (Beck, Bridges, Purchase, & Venkataraman, 2019; IEA, 2019c; Jepma, Spijker, & Hofman, 2019; Kanellopoulos & Reano, 2019; Ministry of Economic Affairs and Climate Policy, 2019a; Wijk, Rhee, Reijerkerk, Hellinga, & Lucas, 2019). Current environmental policy focuses on the reduction of CO_2 emissions in almost all sectors (Ministry of Economic Affairs and Climate Policy, 2019a; UNFCCC, 2015). Some sectors, for instance shipping and aviation, are harder to change when it comes to the emission of CO_2 and other greenhouse gases, as they transcend regulatory borders and there is no central authority regulating them (Gritsenko, 2017; Romera & Van Asselt, 2015).

The integration of hydrogen in the energy system could potentially contribute to reducing CO_2 emissions. Hydrogen is an energy carrier that does not produce CO_2 emissions when consumed as a fuel, and can be produced with zero or low CO_2 emissions (Momirlan & Veziroglu, 2005). Depending on the production method, it can also be used to create an energy system with a more flexible energy demand, a useful property in a system with increasing renewable energy (Ibrahim, Ilinca, & Perron, 2008; Paterakis, Erdinç, & Catalão, 2017). Depending on the availability of energy from renewables, hydrogen can then be used to cover part of the energy demand, for example in industry or in the transport sector (Dodds et al., 2015). Adoption of hydrogen vehicles in the transport sector has not yet widely spread but shows opportunities in the future (Kurtz, Sprik, & Bradley, 2019; Ministry of Economic Affairs and Climate Policy, 2019a; Staffell et al., 2019).

When assessing the potential contribution of hydrogen to a more sustainable energy system, multiple possible production methods must be considered. Three categories are often used to group these production methods. These are called grey, blue, and green hydrogen. Figure 1 shows these categories based on their CO_2 emission level and their energy source. Grey hydrogen is produced from fossil fuels, producing high levels of CO_2 emissions compared to the other categories. Blue hydrogen is also produced from fossil fuels, but CO_2 emissions are limited by carbon capture and storage (CCS) technology. Green hydrogen is produced using renewable energy sources, producing zero CO_2 emissions (CertifHy Canada Inc., 2019).

Hydrogen can be produced locally or imported from other regions. For example, multiple institutions in Australia have produced reports analyzing the opportunities for developing a hydrogen export economy (Beck et al., 2019; Bruce et al., 2018). In the case of imported hydrogen, it is important to consider the resource and the production process when it is used to reduce CO_2 emissions or other negative impacts.

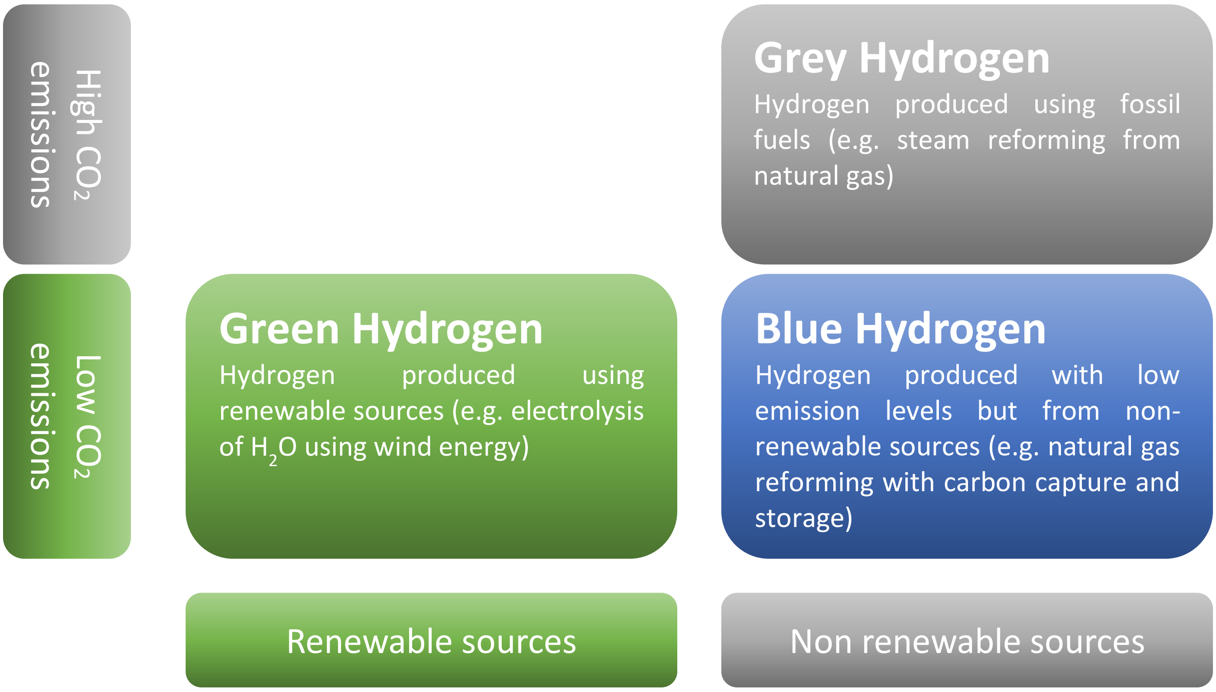

Figure 1. Three main categories of hydrogen production methods positioned based on emission level and renewability of sources (CertifHy Canada Inc., 2019)

As mentioned, many governments are looking at the opportunities to integrate hydrogen in their energy system (Beck et al., 2019; IEA, 2019c; Jepma et al., 2019; Kanellopoulos & Reano, 2019; Ministry of Economic Affairs and Climate Policy, 2019a; Wijk et al., 2019). So far, research has mostly focused on possible applications of hydrogen in the system or on the infrastructure needed for hydrogen transport through the system at a certain point in the future (DNV GL, 2018; Gasunie & TenneT, 2019; Jepma et al., 2019; Murthy Konda, Shah, & Brandon, 2011, 2012). There are reports on the route towards a so-called hydrogen economy, but these do not discuss uncertainties in cost developments (Gigler & Weeda, 2018; Hers, Scholten, van der Veen, van de Water, & Leguijt, 2018; Jepma et al., 2019; Staffell et al., 2019). Also, research that compares different production methods has been performed, but little research looks at the factors that make up the production costs and how uncertainties in these factors affect the costs of hydrogen production (Acar & Dincer, 2019; Baykara, 2018; Chapman et al., 2019; Parra, Valverde, Pino, & Patel, 2019). In general reports the levelized cost of hydrogen (LCOH) is often mentioned, stating the costs of production per kg of hydrogen over the lifetime of a production plant (Gigler & Weeda, 2018; Hers et al., 2018). More detailed research often focuses on one specific factor part in the LCOH Important factors such as the investment costs (Saba, Müller, Robinius, & Stolten, 2018).

This research provides a comprehensive comparison of the costs associated with the dominant hydrogen production methods and how they depend on underlying techno-economic factors. The components that cover production costs are costs for investment, operation and maintenance (O&M), and energy consumption. Other factors that affect the LCOH are also included in this research, namely costs for long distance transport, and costs for CO_2 emissions produced during the hydrogen production process. A more extensive explanation of these factors can be found in the methodology chapter. This research is guided by the following research question:

How do uncertainties in underlying factors affect the LCOH of the dominant hydrogen production methods and how do the effects of the uncertainties on the LCOH results compare to each other?

To answer this research question, the continent of Europe was chosen as a geographic location. In terms of environmental performance, countries in Europe employ the most sustainable policies compared to countries in other continents (Wendling, Emerson, Esty, Levy, & Sherbinin, 2018). A clean energy carrier like hydrogen is more likely to be integrated in more sustainable energy systems. A geographic location was chosen to allow for a calculation of transport costs associated with imported hydrogen. More specifically, the port of Rotterdam was chosen as the location of analysis. This is the largest port of Europe, making it a logical location for imported hydrogen to arrive by shipping (Port of Rotterdam Authority, 2019). Results on the effect of uncertainties on the levelized costs of hydrogen production can be seen in a broader context. Even though transport costs are location specific, other costs and their associated uncertainty are not. The costs are analyzed for 2020 and 2030 to show the effects of the uncertainties for different production methods in the future. To come to a structured answer to the main research question specified above, the following supporting research questions were composed:

SQ1 *What are the most used hydrogen production methods now and in the near future, according to literature?*

SQ2 *What are the underlying techno-economic factors of the selected hydrogen production pathways and their corresponding values for 2020 and 2030?*

SQ3 *What are the ranges of uncertainty associated with the techno-economic factors?*

SQ4 *What is the share of individual factors in the levelized cost of hydrogen production?*

SQ5 *How does the levelized cost of hydrogen production change with varying input factors?*

SQ6 *What are the key factors influencing the levelized cost of hydrogen production for different pathways?*

SQ7 *How do the uncertainties in underlying factors influence the LCOH for the different pathways and how do these effects compare across the different pathways?*

2 Methodology

A visualization and short description of the steps in this research is shown in figure 2. The methodology and the structure of this research were chosen using the support questions introduced earlier. The first three stages of the research can be seen as preparation of input factors, followed by construction of the results needed to answer the research question.

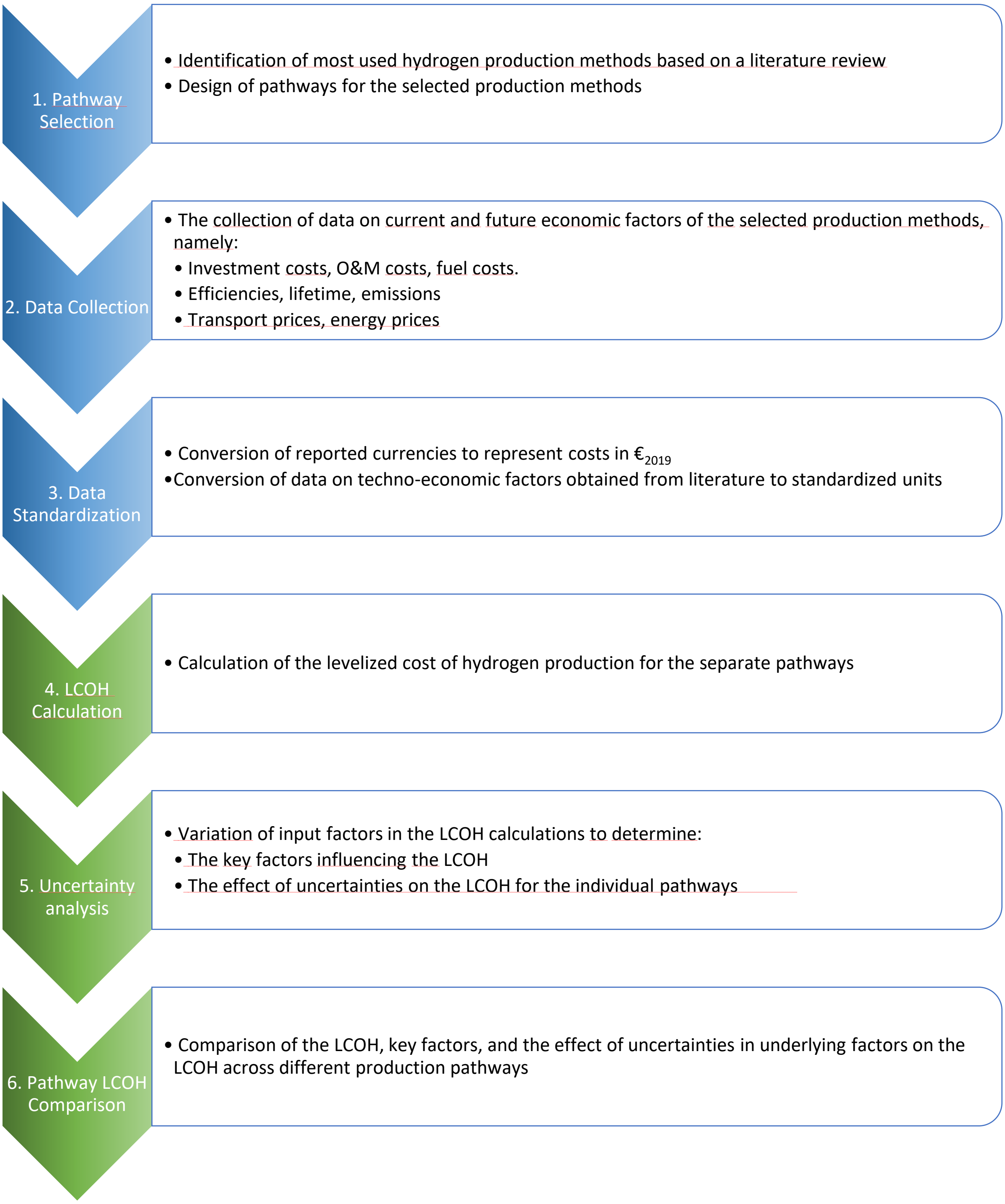

Figure 2. Visualization of the research methodology used in this research

2.1 Pathway Design

Selecting the production methods included in this research was done using the following support question:

SQ1 *What are the most used hydrogen production methods now and in the near future, according to literature?*

Using the selected production methods, different pathways were designed. To choose what production methods were included in the designed pathways, they were analyzed through a literature study. This included scientific literature, reports by governmental organizations and corporate reports. First, an overview was made of the available hydrogen production methods, after which they were filtered based on the amount of hydrogen produced through a specific production method and its expected developments over the coming decade.

For the selected production methods, different pathways were designed. These pathways are distinguished by the used production method and their location. Pathways that use natural gas as a feedstock were designed with the port of Rotterdam as the geographic location. For pathways that use electrolysis, one pathway was designed to produce hydrogen in the port of Rotterdam, and a second pathway was designed to produce hydrogen in the United Arab Emirates (UAE) using electricity from renewables. A pathway using coal gasification (CG) was designed with Melbourne, Australia as the location of production. In case of the pathways located in the UAE and Melbourne, transport was added to the pathway to include the costs associated with the import of hydrogen. The time scope of this research ranges from the present to 2030. This scope is chosen because data on further developments is scarce or not available beyond this time period.

2.2 Data Collection

The data collection of the research is shaped by following these support questions:

SQ2 *What are the underlying techno-economic factors of the selected hydrogen production pathways and their corresponding values for 2020 and 2030?*

SQ3 *What are the ranges of uncertainty associated with the techno-economic factors?*

In this step, data on techno-economic factors was collected for the different pathways. This was done by analyzing literature on the current state of the selected method, as well as on the expected development of their underlying factors. Literature was gathered using Google Scholar, Scopus and ScienceDirect databases. Data was gathered from literature published after 2014, five years before the start of this research project. Older data was excluded to limit the uncertainty of the expected developments of the cost data. A more elaborate explanation of the search process and the search queries that were used can be found in Appendix A. When the value of a factor was not defined accurately by a specific source, the average of the values obtained from other sources was used for calculation of the LCOH. The LCOH could therefore still be determined using the factors that were defined by a specific source. An overview of the factors that were gathered for this research are displayed in Table 1 together with their corresponding standardized units, as specified in the next section.

2.3 Data Standardization

The collected data was standardized to represent the same units across different sources. For cost factors that do not depend on the number of operating hours per year, such as investment costs and fixed O&M costs, the units were standardized to represent the costs per installed kW of hydrogen output. This was done on a lower heating value (LHV) basis, as this is the most commonly used value in literature when it comes to hydrogen production values. The efficiency was standardized to represent the conversion efficiency in %. This value represents both the energy input and energy output on an LHV basis. The efficiency represents the required energy from gas, coal and electricity for SMR, CG and electrolysis respectively. For factors that depend on the number of operating hours per year, the units were standardized to represent the energy consumption or costs per kg of hydrogen produced. A standard capacity factor of 0.8 was chosen to allow for uniform comparison across the different pathways. To show how the capacity factor influences the LCOH, the value was varied in an uncertainty analysis as explained in section 2.5. Costs for implementation of carbon capture technology were included in the investment costs and O&M costs. Costs associated with transport and storage of the captured carbon are reported separately as carbon storage costs in $€_{2019}$/t CO_2.

As shown in Table 1, the currency values obtained from literature were converted to $€_{2019}$. When the obtained data was not reported in euros, the reported currency was converted to euros using the average exchange rate of the year in which the cost data was (Statista, 2020a, 2020b). Next, the value was converted from the specific year to the value it would have in $€_{2019}$ according to annual inflation rates (Eurostat, 2019). Through this standardization, cost and technological data were made comparable between different hydrogen production methods. For calculation of the LCOH, cost data were converted to represent yearly costs, and hydrogen production was converted to yearly production in kg. These units are displayed in the third column of Table 1.

Table 1

Techno-economic factors gathered for calculation of the LCOH of the different pathways and their corresponding standardized units

Techno-economic factor	Standardized unit	Unit for LCOH calculation
Investment costs[a, b]	€$_{2019}$/kW H_2	€$_{2019}$/yr
Fixed O&M costs[a,b]	€$_{2019}$/yr/kW H_2	€$_{2019}$/yr
Variable O&M costs[b]	€$_{2019}$/kg H_2	€$_{2019}$/yr
Efficiency[a, c]	%	€$_{2019}$/yr
Additional electricity consumption[b, c]	kWh/kg H_2	€$_{2019}$/yr
Produced CO_2 emissions	Kg CO_2/kg H_2	€$_{2019}$/yr
Carbon storage costs	€$_{2019}$/t CO_2	€$_{2019}$/yr
Capacity factor[d]	No Unit	No Unit
Lifetime	Years	Years

Notes
[a] These values were standardized based on the LHV energy content of hydrogen (120 MJ/kg H_2)
[b] These values include additional costs for CCS for the pathways where CCS technology is implemented, unless stated otherwise
[c] Efficiencies only include the primary energy input used for specific pathways. Additional electricity consumption was added for pathways with hydrogen production through SMR.
[d] To allow for uniform comparison, a standard capacity factor of 0.8 was chosen for all designed pathways. This value was varied in the uncertainty analysis to show the effects of variation in the capacity factor on the calculated LCOH

2.4 Levelized Cost of Hydrogen calculation

The calculation of the LCOH for the different pathways answers the following supporting research question:

SQ4 What is the share of individual factors in the levelized cost of hydrogen production?

Using the standardized values for the factors as seen in Table 1, the LCOH was calculated using the following equation:

$$\frac{\sum_{t=1}^{n} \frac{C_t + FOM_t + VOM_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

C = Investment costs *[€$_{2019}$]*

FOM = Fixed O&M costs *[€$_{2019}$/yr]*

VOM = Variable O&M costs *[€$_{2019}$/yr]*

H = Hydrogen production *[kg H_2/yr]*

r = Discount rate *[%]*

n = System lifetime *[years]*

t = year

Through this equation, the result is calculated to represent the LCOH in €$_{2019}$ per kg of hydrogen (€$_{2019}$/kg H_2) for a specific pathway. A default discount rate of 0.08 was used and this value was varied between 0.4 and 0.12 in the uncertainty analysis. A large range was chosen for variation of the discount rate to account for the high level of uncertainty associated with other underlying factors. Not all sources from literature provide values for all factors needed for the calculation of the LCOH. For missing values of specific sources from literature, the average of other sources was used. This calculation was performed for the different pathways. The energy prices and the price for CO_2 emissions that were used in the LCOH calculations are shown in Table 2.

Table 2

Prices for feedstock and electricity in the Netherlands, United Arab Emirates and Australia

Price factor	Unit	2020	Range	2030	Range
Dutch electricity price[a]	€$_{2019}$/MWh	43[1]	35-60[1]	57[1]	36-80[1]
Dutch gas price[b]	€$_{2019}$/GJ	6.00[1]	4.74-7.27[1]	7.90[1]	4.74-10.11[1]
UAE renewable electricity price[c]	€$_{2019}$/MWh	26[2]	22-30[2]	22[2]	18-25[2]
Australian coal price[d]	€$_{2019}$/GJ	2.22[3]	1.11-4.45[2]	1.88[3]	0.94-3.76[3]
CO_2 emission price	€$_{2019}$/tCO_2	22[1]	15-30[1]	47[1]	21-80[1]

Notes
[a] Predictions based on the average Dutch energy mix according Dutch Climate and Energy Outlook 2019 by the Netherlands Environmental Assessment Agency
[b] Based on LHV energy content of Dutch Natural Gas (IEA, 2019a)
[c] Predictions based on cost projections for the Noor Abu Dhabi solar plant (Al Naqbi, Tsai, & Mezher, 2019)
[d] Based on LHV energy content of Australian coal (IEA, 2019a)
[1] Schoots & Hammingh, 2019
[2] Al Naqbi, Tsai, & Mezher, 2019
[3] Statista, 2020c

The prices for gas, coal, electricity and CO_2 emissions have a significant effect on the calculated LCOH values for the different pathways. The uncertainty analysis shows how variation of the prices displayed in Table 2 affects the different calculated LCOH values. The Dutch electricity price is based on the average energy mix of the Dutch electricity system. Schoots & Hammingh (2019) state a price of approximately 49 €$_{2019}$/MWh for electricity from renewable sources in 2030. However, calculations in this research are based on a price of 57 €$_{2019}$/MWh. Only using electricity from renewable sources would limit the availability of electricity and therefore the capacity factor of the hydrogen production pathway. The price of 49 €$_{2019}$/MWh is within the range of uncertainty specified for the Dutch electricity price. The calculated LCOH values corresponding to this electricity price are therefore included in the results of the uncertainty analysis.

For some pathways additional transport is needed from the location of production to the port of Rotterdam. When the transport distance for hydrogen exceeds 4000 kilometers, shipping was found to be the cheapest form of transport (Bruce et al., 2018). Table 3 shows the costs associated with transport of hydrogen per ship from the UAE and from Melbourne, Australia to the port of Rotterdam. It also shows additional costs for the preparation of hydrogen for transport through liquefaction and compression. The energy required for compression of the hydrogen to a pressure of 350 bar equals 4.4 kWh/kg H_2. For liquefaction the hydrogen is cooled to -253^oC, consuming 10 to 13 kWh/kg H_2. Although compression consumes less energy than liquefaction, total costs for liquid transport (LT) are much lower than for compressed storage (CT). The density of compressed hydrogen at 350 bar and 25^oC is approximately 23 kg/m^3, whereas the density of liquid hydrogen is 70.8 kg/m^3. The volume needed for transport of compressed hydrogen is three times as large as for liquified hydrogen. Overall, transport of liquid hydrogen results in lower costs and is therefore chosen as the transport method in this research. The transport costs include the costs for liquefaction of the hydrogen, storing the hydrogen in the transport tanks, and costs for the required ships (Bruce et al., 2018). A special liquid hydrogen carrier is currently being manufactured by Kawasaki Heavy Industries and construction is expected to complete by late 2020 (KHI, 2019). Costs for installations needed for unloading the hydrogen are not mentioned by the report by Bruce et al. (2018). It is unclear from the report whether these costs are included in the costs for transport or whether these are ignored. Potential effects of this uncertainty are considered in the discussion chapter of this research.

Table 3

Levelized cost of liquefied transport (LT) and compressed transport (CT) by ship to the port of Rotterdam from the UAE and from Melbourne, Australia

	Unit	2020	Range	2030	Range
		Preparation for transport			
Liquefaction	€$_{2019}$/kg H_2	1.83[1] 2.36[3]	1.65-2.01[1]	1.13[1]	1.02-1.24[1]
Compression (350 bar)	€$_{2019}$/kg H_2	0.24[1]	0.22-0.27[1]		
		Transport			
Liquified Transport	€$_{2019}$/t H_2/km	0.06[1]			
Compressed Transport	€$_{2019}$/t H_2/km	0.33[1]			
		United Arab Emirates - Rotterdam			
Transport distance	km	11600[2]			
LT excl liquefaction	€$_{2019}$/kg H_2	0.67[1,2]			
LT incl liquefaction	€$_{2019}$/kg H_2	2.50[1,2] 3.03[1,2,3]	2.32-2.68[1,2]	1.80[1,2]	1.69-1.911[1,2]
CT excl compression	€$_{2019}$/kg H_2	3.87[1,2]			
CT incl compression	€$_{2019}$/kg H_2	4.12[1,2]	4.09-4.14[1,2]		
		Melbourne - Rotterdam			
Transport distance	km	20600[3]			
LT excl liquefaction	€$_{2019}$/kg H_2	1.19[1,3]			
LT incl liquefaction	€$_{2019}$/kg H_2	3.01[1,3] 3.55[1,3,4]	2.84-3.20[1,3]	2.32[1,3]	2.21-2.43[1,3]
CT excl compression	€$_{2019}$/kg H_2	6.87[1,3]			
CT incl compression	€$_{2019}$/kg H_2	7.11[1,3]	7.09-7.14[1,3]		

Notes
[1] Bruce et al., 2018
[2] SeaRoutes, 2019
[3] Connelly, Penev, Elgowainy, & Hunter, 2019

2.5 Uncertainty analysis

Uncertainty in data on underlying factors affects the calculated LCOH values for the different pathways. This uncertainty is mainly caused by the fact that it is unknown how costs can and will develop over time. To determine the effect of the uncertainty of underlying factors on the resulting LCOH, the factors were varied using the uncertainty ranges obtained from literature. This research step was guided by the following support question:

SQ5 *How does the levelized cost of hydrogen production change with varying input factors?*

SQ6 *What are the key factors influencing the levelized cost of hydrogen production for different pathways?*

The effect of the uncertainty of each underlying factor was determined by recalculating the LCOH with different values for the individual factors. Prices of gas, coal and electricity were varied according to the range specified earlier in Table 2, as well as the price for CO_2 emissions. Transport costs were varied according to the range specified in Table 3. Factors corresponding to specific production pathways were varied within the obtained range from literature as shown in their respective results sections (Tables 5, 6 and 7). For pathways where SMR and CG are used to produce hydrogen, the capacity factor was varied between the values of 0.65 and 0.95. For pathways that produce hydrogen through electrolysis, the capacity factor was varied between 0.3 and 0.95. For variation of the capacity factor a larger range was chosen for pathways containing electrolysis to simulate dependence of the availability of electricity from renewable energy sources. With individual factors each being responsible for a specific share of the LCOH, variation of different factors has a different effect on the LCOH value. The key factors influencing the LCOH for the different pathways were determined by analyzing the effect of variation of the individual factors on the calculated LCOH.

2.6 Pathway LCOH Comparison

After calculation of the LCOH and determination of the uncertainty caused by variation of individual factors, the results of the uncertainty analysis were compared across pathways. The comparison of the different pathways was guided by the following support question.

SQ7 *How do the uncertainties in underlying factors influence the LCOH for the different pathways and how do these effects compare across the different pathways?*

The variation of the LCOH was calculated for all pathways per factor to show how the LCOH of each pathway is affected. By performing this comparison for all underlying factors, the key factors influencing the LCOH of the different production pathways were identified. Moreover, this comparison shows how variation of individual factors has a different effect on the different pathways. The difference between the effects on different pathways could cause the LCOH of one pathway to drop below the LCOH of another pathway. The results of the comparison of the pathways based on variation of the underlying factors of the LCOH can be found in the pathway comparison in chapter 5. First, chapters 3 and 4 discuss the designed pathways and their corresponding LCOH results.

3 Hydrogen Production Pathways

With an increasing number of parties looking for opportunities in integration of hydrogen in the energy system, more methods to produce hydrogen are being researched and developed. Research on new production methods often focuses on hydrogen production from renewable sources, such as biomass. Many of the production methods are at an early stage in terms of technological development. An overview of the production methods identified from literature that were not included in this research can be found in Appendix C.

From the identified production methods, the most used production methods were selected for further analysis. These methods are steam methane reforming (SMR), coal gasification (CG) and electrolysis of water (EW). Nearly all commercially available hydrogen is currently produced using these three methods with a tiny fraction produced through gasification of heavier oil feedstocks. Of the three dominant production methods, SMR and CG use fossil fuels and account for almost 99% of the global hydrogen production. Around 76% is produced by SMR with natural gas as a feedstock, and close to 23% is produced through gasification of coal (IEA, 2019c). These production processes can be complemented with CCS technology, significantly reducing emissions. Next to these processes, roughly 2% is produced through electrolysis of water using varying sources for electricity generation (Note that the percentages don't add up due to rounding). These three production methods will most probably be the processes of choice in the future (IEA, 2019c). This is the reason that these three methods were selected for further analysis in this research. Other methods were excluded as they only exist in a research and development stage meaning there is little knowledge on their actual implementation and corresponding costs.

3.1 Steam Methane Reforming

As mentioned, three quarters of all hydrogen produced today comes from SMR. This production takes place through a chemical process where natural gas is converted to hydrogen and CO_2 through a multi-stage process. A simplified schematic can be seen in figure 3, showing material and heat flows within the process.

First, the natural gas used as a feedstock is pre-treated to remove impurities such as sulfur from the gas. This way, the gas is reduced to CH_4 as pure as possible to be used in the steam methane reformer. In the reformer the methane (CH_4) reacts with steam (H_2O) to produce synthetic gas or syngas, a gas that consists of carbon monoxide (CO) and hydrogen (H_2). This reaction takes place through the following chemical equation (1):

$$(1)\ CH_4 + H_2O(steam) \rightarrow CO + 3H_2$$

This reaction is highly endothermic and needs an external source to provide the heat for the reaction to take place. The produced syngas has a CO:H_2 ratio of 1:3. By using another chemical process called the water-gas shift reaction (WGSR), extra hydrogen is generated by having the carbon monoxide in the syngas react with more steam. This reaction produces hydrogen and carbon dioxide (CO_2) through the following equation:

$$(2)\ \ CO + H_2O(steam) \rightarrow H_2 + CO_2$$

Combining equations (1) and (2) gives the following equation over the entire process of SMR:

$$(3)\ \ CH_4 + 2H_2O(steam) \rightarrow CO_2 + 4H_2$$

For every kilogram of hydrogen produced through SMR including the WGSR, between 9 and 12 kilograms of CO_2 are produced (Albrecht et al., 2015; DNV GL, 2018; Jakobsen & Åtland, 2016). Currently, almost all CO_2 generated by hydrogen production is released in the atmosphere. These emissions can be reduced by implementing CCS in an SMR plant. CO_2 is captured from the output flow of the system, instead of releasing the produced CO_2 emissions into the atmosphere. This way, up to 90% of the CO_2 emissions are prevented from going into the atmosphere.

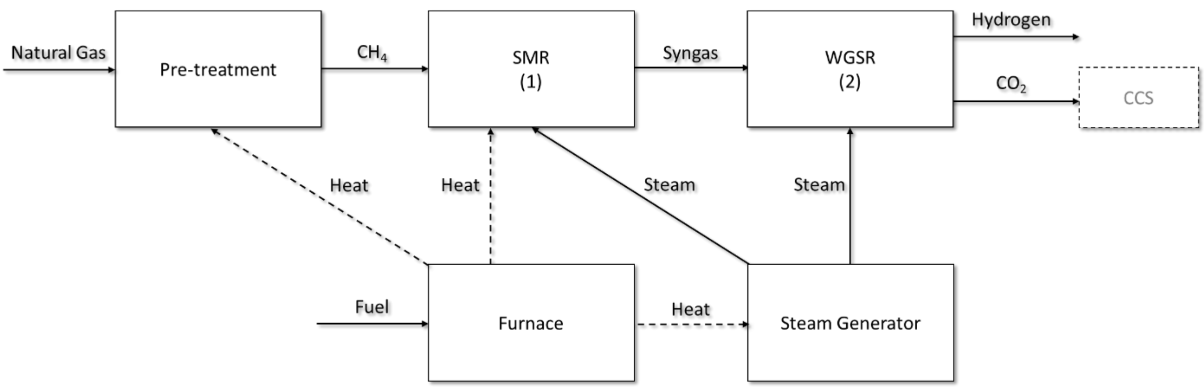

Figure 3. Simplified schematic representation of the steam methane reforming production method with optional carbon capture and storage technology
Notes
(1) Syngas production through chemical equation 1
(2) Hydrogen ration increase through chemical equation 2

In literature, the most important cost factors described for SMR are the investment costs and the cost of the feedstock used for the production process. These make up around 20% and 50% of the production costs on average in the literature that was analyzed. In this research two pathways containing an SMR plant were analyzed, one with implementation of CCS technology and one without CCS technology. For both pathways, the production plant is located in the port of Rotterdam, meaning no additional transport is assumed after production of the hydrogen.

3.2 Electrolysis of Water

Electrolysis of water has existed for a long time as a means to produce hydrogen, the first documented case already taking place in the late 18th century (De Levie, 1999). However, the process is used relatively little compared to the other two selected methods, accounting for only 2% of the total commercially produced hydrogen. For this reason, the technology is also less mature than SMR or CG in terms of cost development. The need for reduction of greenhouse gas emissions has increased the interest in hydrogen production through electrolysis. This leads to an increase in research and development, providing opportunities for cost reductions (Saba et al., 2018). Two types of electrolysis are typically used, namely alkaline and proton exchange membrane (PEM) electrolysis. Alkaline electrolysis is a more mature technology and currently provides a lower cost alternative compared to a PEM electrolyser. Predictions of the development of costs associated with PEM electrolysis show a high level of uncertainty towards 2030 (IEA, 2019c; Saba et al., 2018). Therefore, further analysis in this research is performed using techno-economic data on alkaline electrolysis.

The basic principle of electrolysis is quite simple. In an electrolyser, electricity is used to split water into hydrogen and oxygen. A DC power source provides electrical energy to an electrochemical cell containing an anode and a cathode which are placed in water. Near the anode (positive electrode) oxygen is formed, while at the cathode hydrogen is generated. The reaction at the anode and cathode takes place through the following chemical equation:

(4) Anode reaction: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$

(5) Cathode reaction: $H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Adding these equations together gives the complete reaction taking place in the electrolyser, resulting in the following chemical equation.

(6) $2H_2O \rightarrow O_2 + 2H_2$

The process generates a pure stream of hydrogen and oxygen, making it an emission free source of hydrogen production when the electricity provided comes from renewable sources. Figure 4 shows a simplified process diagram of the electrolysis process.

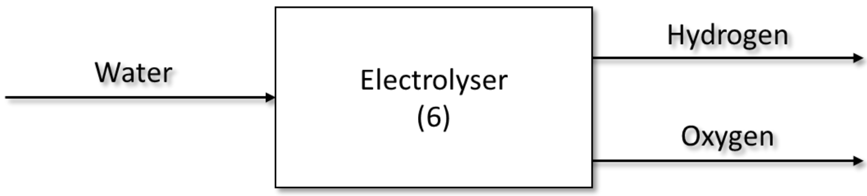

Figure 4. Simplified schematic representation of the electrolysis process with corresponding material flows
Notes
(6) Splitting of water through chemical equation 6

In literature, the most important factor mentioned for the costs of hydrogen production through electrolysis is the electricity consumption. The costs for electricity can account for close to 80% of the hydrogen production costs.

In this research electrolysis of water is implemented in two different pathways. For one pathway, an electrolyser is placed in the port of Rotterdam, meaning no additional transport is assumed after production of the hydrogen. For the other pathway, the production plant is placed near the port of Dubai. Dubai is located at a prime location for renewable solar and wind electricity, enabling hydrogen production from renewable energy sources at a low electricity price. After production, hydrogen is then transported from the port of Dubai to the port of Rotterdam.

3.3 Coal Gasification

After SMR, CG is the most used method to produce hydrogen and it also produces syngas. Figure 5 shows a simplified schematic of the process. Pulverized coal is introduced to a gasifier where incomplete combustion of coal takes place. The amount of oxygen supplied is not sufficient for complete combustion, producing syngas. Assuming the coal feedstock consists of pure carbon, this process happens through the following chemical equation:

$$(7)\ \ 3C + O_2 + \ H_2O(steam) \rightarrow 3CO + H_2$$

Because the coal feedstock does contain impurities, the syngas must be purified before continuing the process. After purification, the WGSR as seen in chemical equation (2) is then used to increase the level of hydrogen in the produced syngas. Combining the chemical equations (2) and (7) gives the following equation for the complete process:

$$(8)\ \ 3C + 2O_2 + \ 2H_2O(steam) \rightarrow 3CO_2 + 2H_2$$

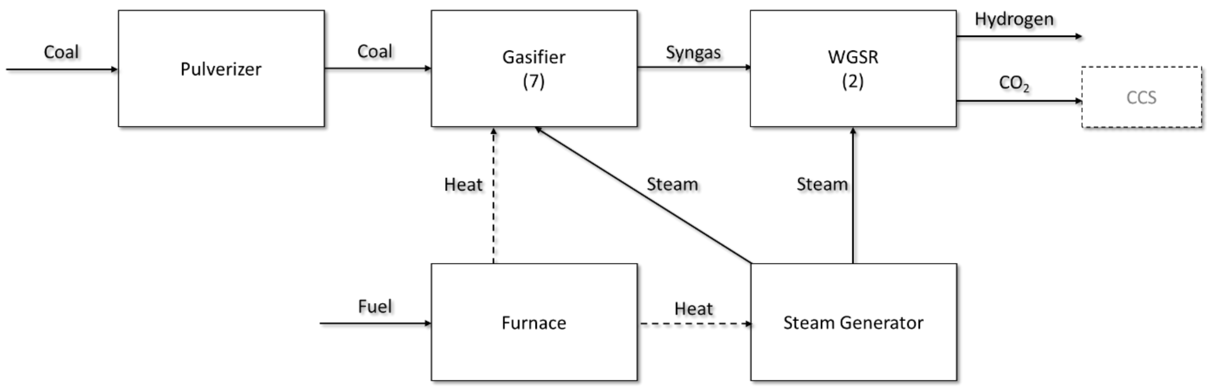

Figure 5. Simplified schematic representation of the steam methane reforming production method with optional carbon capture and storage technology
Notes
(2) Hydrogen ration increase through chemical equation 2
(7) Syngas production through chemical equation 7

In this research, CG is included in a pathway described by Bruce et al. (2018) in the National Hydrogen Roadmap, a report produced by the Commonwealth Scientific and Industrial Research Organization (CSIRO) for the Australian government. CCS technology is implemented in this pathway to limit the produced CO_2 emissions. The location of the CG plant is the Latrobe valley, near Melbourne Australia. This location was chosen because of the availability of carbon storage capacity and the availability of coal. The cost data associated with this pathway were also obtained from the CSIRO report. A domestic pathway with hydrogen production through CG was not included, as the Dutch government plans to shut down coal fired power plants and limit the consumption of coal (Ministry of Economic Affairs and Climate Policy, 2019b).

3.4 Designed Pathways

Table 4 shows an overview of the pathways designed for further analysis using the three selected production methods. The location of analysis is the port of Rotterdam, meaning that either the hydrogen is produced there, or it must be transported to this location. The first three pathways (SMR, SMR + CCS and EW) are located in the port of Rotterdam. The bottom two (IEW; ICG + CCS) are located abroad, and hydrogen produced through these pathways is transported to the Netherlands by ship.

Table 4

Designed pathways for hydrogen production with the end location of the hydrogen set as the port of Rotterdam

Production Location	Pathway	Description
Port of Rotterdam	SMR	Hydrogen produced by a Steam Methane Reformer – A steam methane reforming plant located in the port of Rotterdam without CCS technology
	SMR + CCS	Hydrogen produced by a Steam Methane Reformer with CCS technology – A steam methane reforming plant located in the port of Rotterdam with CCS technology
	EW	Hydrogen produced by Electrolysis of Water – An electrolysis plant in the port of Rotterdam with an alkaline electrolyser
Abu Dhabi, UAE[a]	IEW	Imported hydrogen produced by Electrolysis of Water – An electrolysis plant situated in the UAE, a location highly suited for low-cost renewable energy. Hydrogen is transported to the port of Rotterdam by ship.
Melbourne, Australia	ICG + CCS	Imported hydrogen produced by Coal Gasification with CCS technology – A coal gasification plant with the implementation of CCS technology located in Melbourne, Australia. At this location, coal is available at a relatively low price. Produced hydrogen is transported to the port of Rotterdam by ship.

Notes
[a] United Arab Emirates

4 Techno-economic Data and LCOH Results

4.1 Steam Methane Reforming

Table 5 shows the acquired cost data for SMR from literature. Because of the relatively high level of maturity for hydrogen production through SMR, no distinction was made between 2020 and 2030 values in terms of cost data (IEA, 2019b). The most important difference across sources is the range of efficiencies mentioned for SMR. The highest efficiency is mentioned by Nikolaidis & Poullikkas (2017) and equals 75%, more than 10 percent point higher than the lowest value of 64% stated by Jakobsen & Åtland (2016). The efficiency values for the SMR + CCS pathway were assumed to be equal to the SMR pathway. With gas consumption accounting for a considerable amount of the production costs for SMR, a difference in efficiency has a significant result on the calculated LCOH. This effect is addressed in the pathway comparison chapter. For the SMR + CCS pathway, investment costs were assumed to be 150% of the investment costs for the SMR pathway. Implementation of CCS technology doubles the O&M costs of the SMR + CCS pathway compared to the SMR pathway (IEA, 2019c). Variable O&M costs are almost negligible in the total costs for SMR. This excludes the variable costs of gas and electricity consumption, which are treated separately. The share of CO_2 emissions captured by implementation of the CCS technology was assumed to be 90% of the total CO_2 emissions (IOGP, 2019).

Table 5

Standardized techno-economic data for SMR and SMR + CCS from literature

Techno-economic factor	Unit	SMR	Range	SMR + CCS	Range
Investment costs[a]	€$_{2019}$/kW H_2	750[4] 765[5s] 619[7] 885[7]	660-900[4]	1125[4] 1148[5] 928[2] 1327	990-1350[4]
Fixed O&M costs[a]	€$_{2019}$/kW/yr	36.6[7]	15.0-55.0[7]	73.2[7]	30.0-110.0[7]
Variable O&M costs	€$_{2019}$/kg H_2	0.01[2] 0.01[4]	-	0.01[2] 0.01[4]	-
Efficiency[a]	%	68[2] 66[4] 76[6] 64[7] 75[8]	61-70[4] 70-80[8]	68[2] 66[4] 76[6] 64[7] 75[8]	61-70[4] 70-80[8]
Additional electricity consumption	kWh/kg H_2	0.40[4] 0.72[7]	0.40-0.72[4,7]	0.98[4] 1.3[7]	0.98-1.3[4,7]
CO_2 emissions	kg CO_2/kg H_2	10.8[1] 8.9[5] 8.5[7] 12.0[7]	10.0-11.6[1] 8.5-12[5,7]	1.1[1] 0.9[5] 0.9[7] 1.2[7]	1-1.2[1]
Carbon storage costs	€$_{2019}$/t CO_2	-	-	15.4[2]	4.5-25.6[2]
Lifetime	years	20[1] 25[2] 40[3]	20-40[1,3]	20[1] 25[2] 40[3]	20-40[1,3]

Notes
[a] Based on the LHV energy content of hydrogen
[b] Based on the LHV energy content of Dutch natural gas (IEA, 2019a)
[1] Albrecht et al., 2015
[2] Bruce et al., 2018
[3] Campey et al., 2017
[4] Chardonnet et al., 2017
[5] DNV GL, 2018
[6] Gigler & Weeda, 2018
[7] Jakobsen & Åtland, 2016
[8] Nikolaidis & Poullikkas, 2017

4.1.1 SMR Pathway LCOH

Figure 6 shows the calculated LCOH results across the sources that provided the input data. The calculated LCOH ranges from 1.70 to 1.99 €$_{2019}$/kg H_2 for 2020. On average, the calculated LCOH in 2020 for the SMR pathway is 1.78 €$_{2019}$/kg H_2. Across sources, most variability of the calculated LCOH is due to the differences in efficiency. The lowest LCOH values for 2020 were calculated with data provided by Nikolaidis & Poullikkas (2017) and Gigler & Weeda (2018), resulting in an LCOH of 1.71 and 1.70 €$_{2019}$/kg H_2 respectively. The highest calculated LCOH was obtained from Jakobsen & Åtland (2016) and equals 1.99 €$_{2019}$/kg H_2. Table 5 shows that Jakobsen & Åtland (2016) report an efficiency of 64%

while Nikolaidis & Poullikkas (2017) and Gigler & Weeda (2018) report a much higher efficiency of 75% and 76% respectively.

For 2030 the LCOH results range from 2.26 to 2.66 €$_{2019}$/kg H_2. The average calculated LCOH in 2030 is 2.37 €$_{2019}$/kg H_2. The increase from 2020 to 2030 can be explained by the increase in energy prices and the higher CO_2 emission price as shown in Table 5. These two factors account for 70% of the total calculated LCOH in 2020. This share increases to 77% for 2030. There is a high level of uncertainty in the calculated LCOH values for both 2020 and 2030. This uncertainty is mostly due to the high uncertainty associated with the gas price reported by Schoots & Hammingh (2019). These prices are more uncertain for 2030 than for 2020. This results in a higher uncertainty for the calculated LCOH values in 2030.

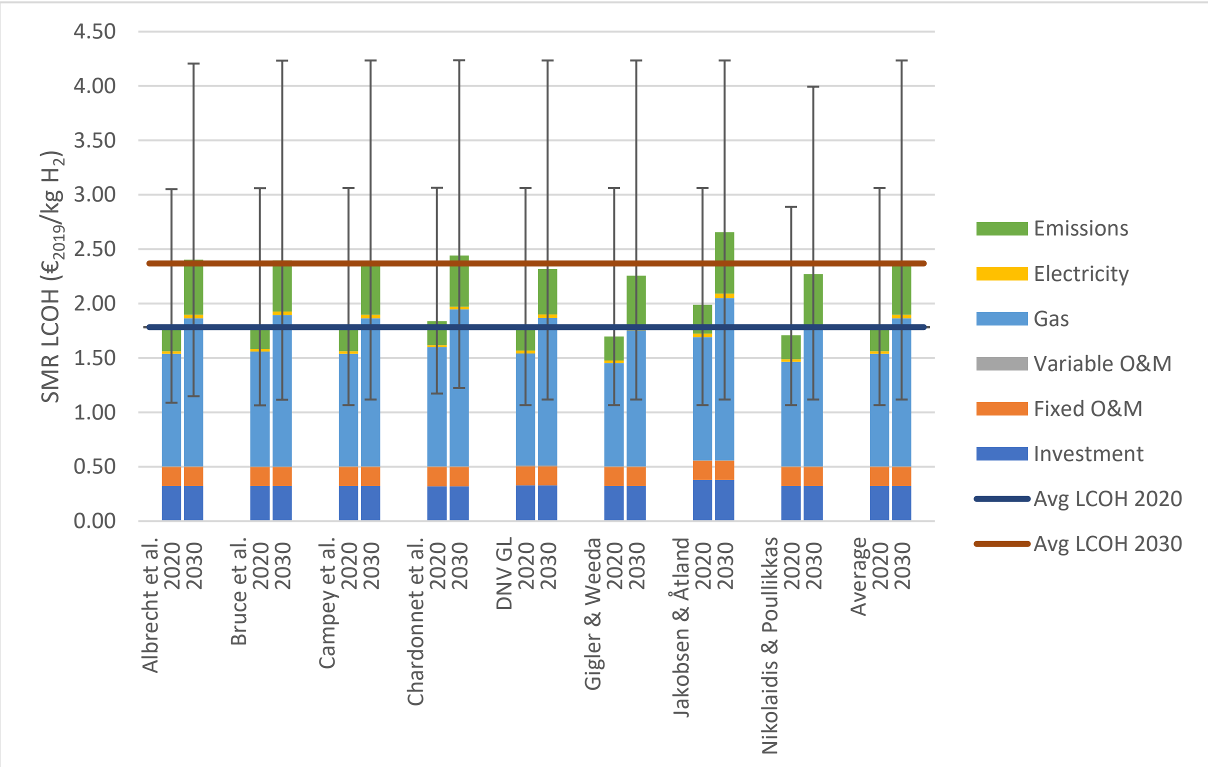

Figure 6. LCOH results for the SMR pathway shown for different data sources. Error bars show the variation in LCOH results for maximum and minimum values of the input factors

Notes

A default capacity factor of 0.8 was assumed

The error bars in Figure 7 show the average effect of the uncertainty of the underlying factors on the calculated LCOH. The factors causing the most uncertainty are the gas price, the capacity factor, the efficiency and the CO_2 emission price. The uncertainty in the price of gas results in a fluctuation of the LCOH between 1.56 and 2.00 €$_{2019}$/kg H_2 in 2020 and between 1.83 and 2.75 €$_{2019}$/kg H_2 in 2030. Another factor that directly influences the costs for gas is the assumed efficiency. The LCOH ranges from 1.65 to 1.93 €$_{2019}$/kg H_2 when varying the efficiency for 2020. For 2030 it fluctuates between 2.1 and 2.56 €$_{2019}$/kg H_2. The capacity factor was varied between the values of 0.65 and 0.95. This has a relatively large effect on the calculated LCOH compared to other factors. This is due to the reduction of the amount of hydrogen produced without a reduction of the investment and fixed O&M costs. This results in a fluctuation of the LCOH between 1.70 and 2.08 €$_{2019}$/kg H_2 for 2020 and between 2.45 and 2.67 €$_{2019}$/kg H_2 for 2030. The maximum LCOH values when varying all factors for 2020 and 2030 are 3.06 and 4.24 €$_{2019}$/kg H_2 respectively.

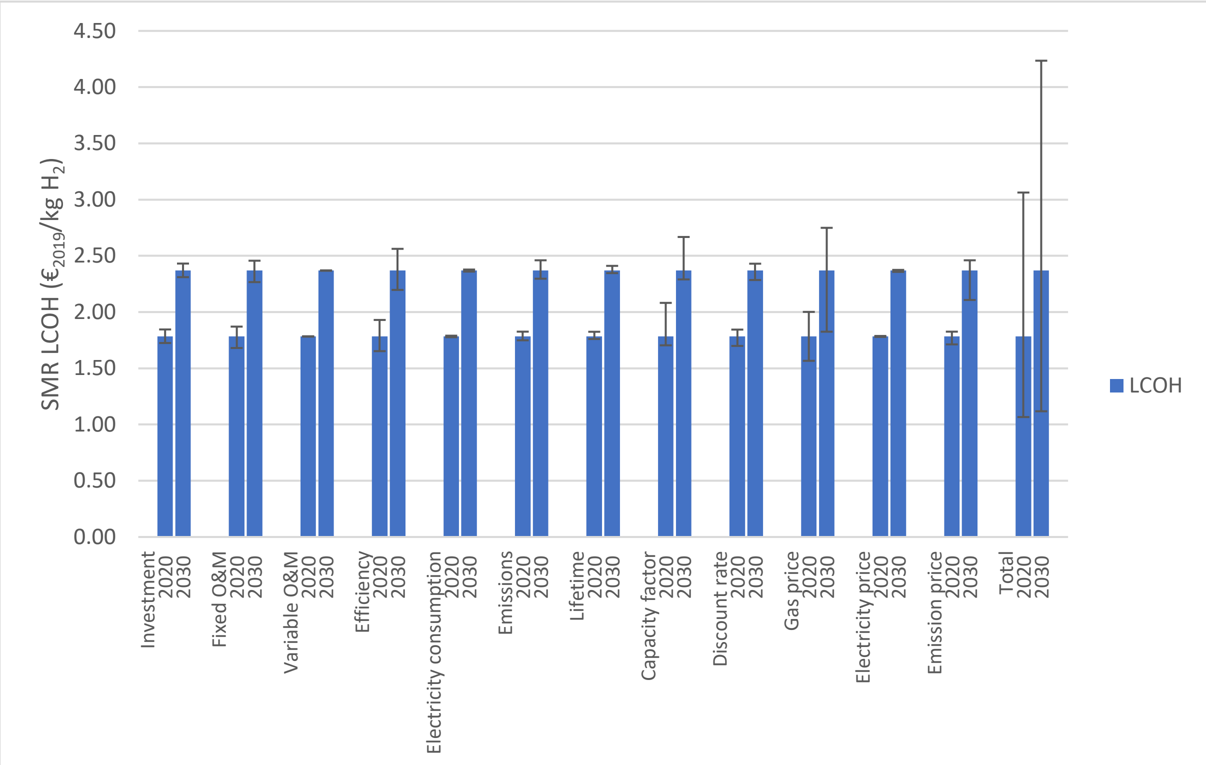

Figure 7. Average effect of the variation of individual factors on the LCOH for the SMR pathway in shown per factor
Notes
An uncertainty range of 0.65-0.95 was assumed for the capacity factor

4.1.2 SMR + CCS Pathway LCOH

Figure 8 gives an overview of the LCOH results calculated for the SMR + CCS pathway. The results range from 2.00 to 2.28 €$_{2019}$/kg H_2 for 2020. On average, the calculated LCOH in 2020 for the SMR + CCS pathway is 2.08 €$_{2019}$/kg H_2. Like the SMR pathway results, most variability of the calculated LCOH for the SMR + CCS pathway is due to the differences in efficiency. The lowest calculated LCOH values for 2020 are 2.00 and 2.01 €$_{2019}$/kg H_2. The highest calculated LCOH was again obtained from Jakobsen & Åtland (2016) and equals 2.28 €$_{2019}$/kg H_2. The investment costs reported by Jakobsen & Åtland (2016) also explain part of the higher LCOH value. These equal 0.57 €$_{2019}$/kg H_2, compared to

0.49 €$_{2019}$/kg H_2 on average. The difference in investment costs explains 40% of the total difference compared to the average calculated LCOH.

For 2030 the LCOH results range from 2.34 to 2.68 €$_{2019}$/kg H_2. The average calculated LCOH in 2030 is 2.45 €$_{2019}$/kg H_2. The increase from 2020 to 2030 can be explained by the increase in energy prices and the higher CO_2 emission price as shown in Table 2. A high level of uncertainty should be considered for the calculated LCOH values for both 2020 and 2030. This is partly due to the same reason as for the SMR pathway, namely the high uncertainty in the gas price. The CO_2 emission price has less effect on the uncertainty compared to the SMR pathway, as most of the CO_2 emissions are captured.

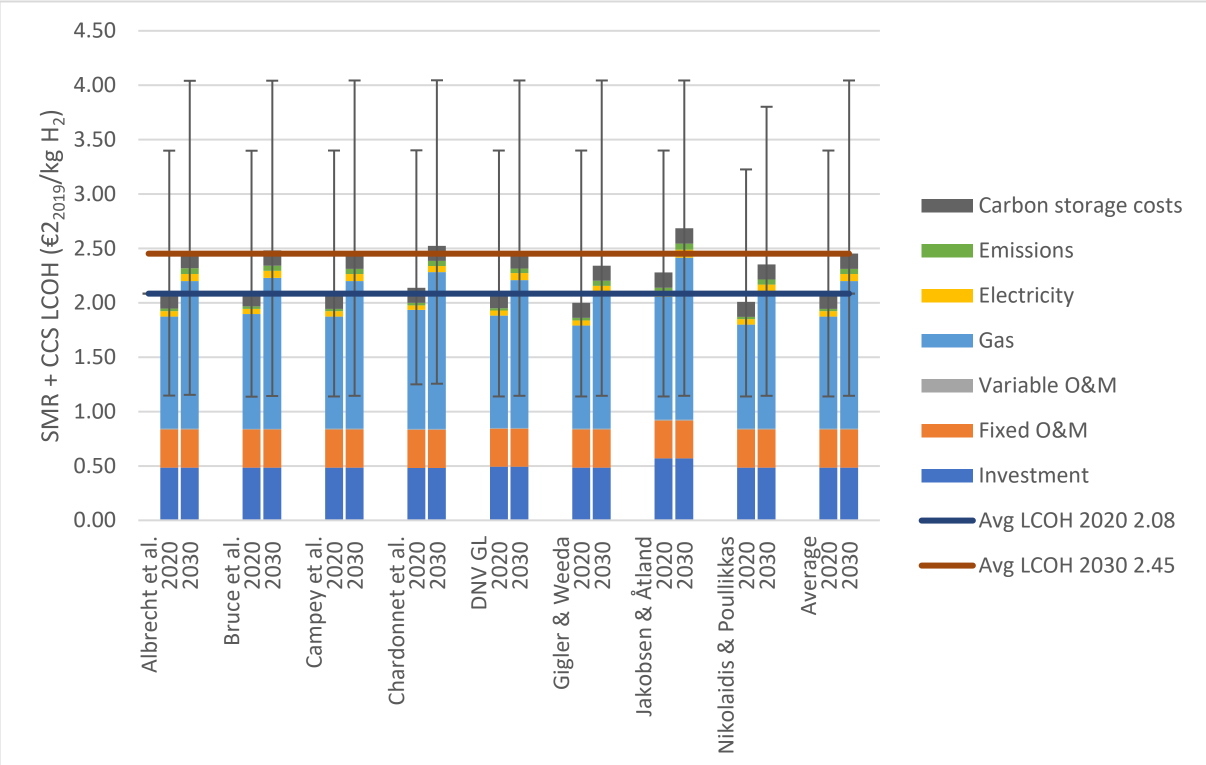

Figure 8. LCOH results for the SMR + CCS pathway shown for different data sources. Error bars show the variation in LCOH results for maximum and minimum values of the input factors
Notes
A default capacity factor of 0.8 was assumed

The error bars in Figure 9 show the average effect of the uncertainty of the underlying factors on the calculated LCOH for the SMR + CCS pathway. Variation of the gas price and the efficiency both cause a high uncertainty level for the calculated LCOH. Variation of the capacity factor causes the most uncertainty in the calculated LCOH after the gas price and the efficiency. The uncertainty in the price of gas results in a fluctuation of the LCOH between 1.86 and 2.330€$_{2019}$/kg H_2 in 2020 and between 1.91

and 2.83 €$_{2019}$/kg H_2 in 2030. The maximum LCOH values when varying all factors for 2020 and 2030 are 3.40 and 4.04 €$_{2019}$/kg H_2 respectively.

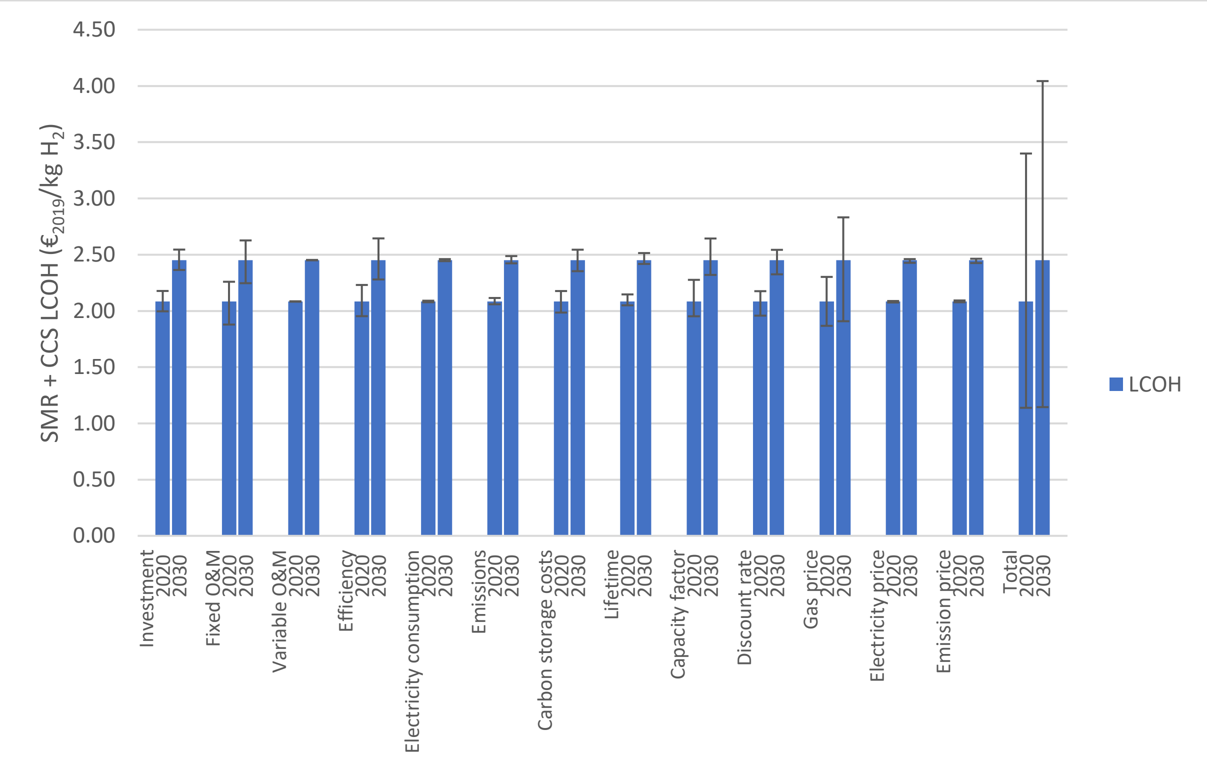

Figure 9. Average effect of the variation of individual factors on the LCOH for the SMR+ CCS pathway in shown per factor
Notes
An uncertainty range of 0.65-0.95 was assumed for the capacity factor

4.2 Electrolysis of Water

Table 6 shows the cost data for electrolysis of water obtained from literature. Looking at the investment costs, literature reports a divergent range of values between different sources. Availability of data is limited for actual costs of projects currently under construction or currently running. The highest value within the range of costs is mentioned by Bertuccioli et al. (2014) and equals 1491 €$_{2019}$/kW H_2. This value is approximately twice as high as the lowest reported value of 763 €$_{2019}$/kW H_2 stated by Saba et al. (2018). Another remarkable result is that some of the values reported for 2030 exceed values stated for 2020. This shows that there is little consensus in literature when it comes to the development of the investment costs for hydrogen production through electrolysis. Looking at O&M, literature does not agree on the costs associated with electrolysis and is also not transparent in the structure of the O&M costs. Bertuccioli et al. (2014) and Jakobsen & Åtland (2016) only report the total O&M costs and do not separate fixed and variable costs. Chardonnet et al. (2017) state that the total O&M costs are one third fixed and two thirds variable costs. Although the ratio is given, the division of underlying components of fixed and variable costs is not explained. This ratio was also applied to the O&M costs from Bertuccioli et al. (2014) and Jakobsen & Åtland (2016) for the LCOH calculations.

Table 6

Standardized techno-economic data for EW from literature

Techno-economic factor	Unit	2020	Range	2030	Range
Investment costs[a]	€$_{2019}$/kW H_2	1043[2] 1004[3] 877[5] 763[6] 1184[7]	612-1491[2] 776-1235[3] 828-1338[7]	923[2] 710[3] 666[6] 685[6] 875[7]	588-1272[2] 494-927[3] 720-1030[7]
Fixed O&M costs[a]	€$_{2019}$/kW H_2/yr	[b]27.5[2] 7.7[3] [b]43.8[5]	[c]15.6-55.6[2] 5.2-10.3[3]	[b]27.8[2] 14.8[3]	[b]6.3-49.3[2] 9.9-19.8[3]
Variable O&M costs	€$_{2019}$/kg H_2	0.057[3]	0.04-0.076[3]		
Efficiency[a]	%	57[2] 61[3] 61[4] 72[5] 62[7]	50-68[2] 57-65[3] 53-75[7]	60[2] 64[3] 67[4] 66[7]	53-69[2] 61-68[3] 55-81[7]
Lifetime	years	30[1] 27.5[2] 20[3]	25-30[2]	30[2] 20[3]	

Notes
[a] Based on LHV energy content of hydrogen
[b] Fixed and Variable costs were not separated in these articles (Bertuccioli et al., 2014; Jakobsen & Åtland, 2016). These articles only reported total yearly O&M costs for full load operation. The share of Fixed O&M costs and Variable O&M costs of the total O&M costs were assumed to be one third and two thirds respectively.
[1] Albrecht et al., 2015
[2] Bertuccioli et al., 2014
[3] Chardonnet et al., 2017
[4] Gigler & Weeda, 2018
[5] Jakobsen & Åtland, 2016
[6] Saba et al., 2018
[7] Schmidt et al., 2017

4.2.1 EW Pathway LCOH

Figure 10 shows the LCOH results for the EW pathway for the different sources from literature. The LCOH results range from 2.56 to 3.06 €$_{2019}$/kg H_2 for 2020. On average, the calculated LCOH in 2020 for the EW pathway is 2.87 €$_{2019}$/kg H_2. For 2030 the LCOH results range from 3.33 to 3.73 €$_{2019}$/kg H_2. The average calculated LCOH in 2030 is 3.45 €$_{2019}$/kg H_2. The increase from 2020 to 2030 is due to a higher electricity price, as described by Schoots & Hammingh (2019) in the Dutch Climate and Energy Outlook. Without this increase in the electricity price, the average LCOH for 2030 would have been 2.72 €$_{2019}$/kg H_2. The cost of electricity determines the largest share of the total LCOH, accounting for 80.2% of the total on average. Across sources, the share of electricity cost in the calculated LCOH fluctuates between 78% and 83%. Data obtained from Jakobsen & Åtland results in the lowest LCOH.

This is due to a higher assumed efficiency compared to other research reports. Table 6 shows that Jakobsen & Åtland use an efficiency of 72%, while Bertuccioli et al. and Chardonnet et al. report a max efficiency of 68% and 65% respectively in 2020. There is a high level of uncertainty in the calculated LCOH values. This uncertainty is mostly due to the high uncertainty in the electricity price.

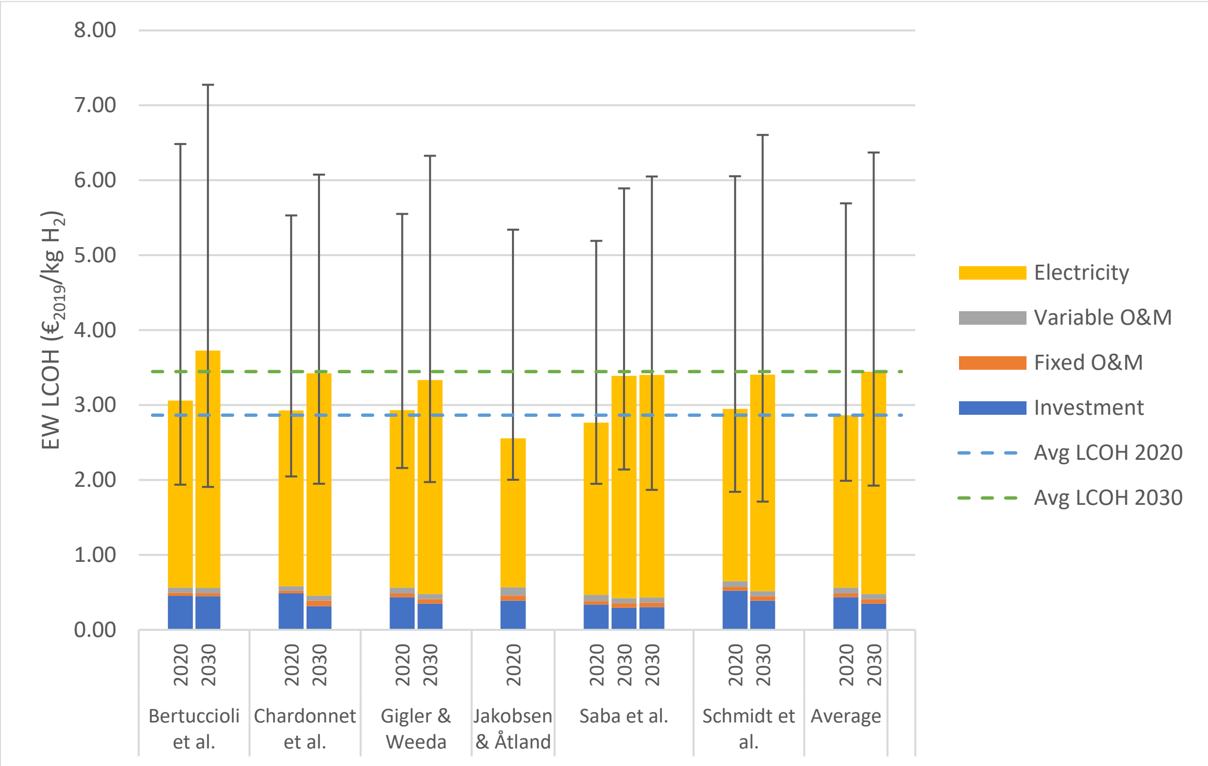

Figure 10. LCOH results for the EW pathway shown for different data sources. Error bars show the variation in LCOH results for maximum and minimum values of the input factors
Notes
A default capacity factor of 0.8 was assumed

Figure 11 shows the average effect of the variation of individual factors on the LCOH. By varying the factors using the ranges reported in Table 2 and Table 6, the variation in electricity price shows the second largest effect on the total LCOH. This is because it has a strong direct effect on the cost for electricity which accounts for the largest share of the total calculated LCOH. The uncertainty in the price of electricity results in a fluctuation of the LCOH between 2.44 and 3.77 $€_{2019}$/kg H_2 in 2020 and between 2.35 and 4.64 $€_{2019}$/kg H_2 in 2030. Another factor that directly influences the costs for electricity is the assumed efficiency. Variation of the efficiency shows the largest effect on the LCOH after the electricity price. The LCOH ranges from 2.56 to 3.13 $€_{2019}$/kg H_2 when varying the efficiency for 2020. Another factor that has a large effect on the LCOH results is the capacity factor. After the electricity price, variation of the capacity factor shows the largest effect on the calculated value for the LCOH. For 2020, the LCOH results range from 2.86 to 3.73 $€_{2019}$/kg H_2 with variation of the capacity factor between 0.3 and 0.95. For 2030 it varies between 3.07 and 3.74 $€_{2019}$/kg H_2. The maximum LCOH values when varying all factors for 2020 and 2030 are 5.69 and 6.37 $€_{2019}$/kg H_2 respectively.

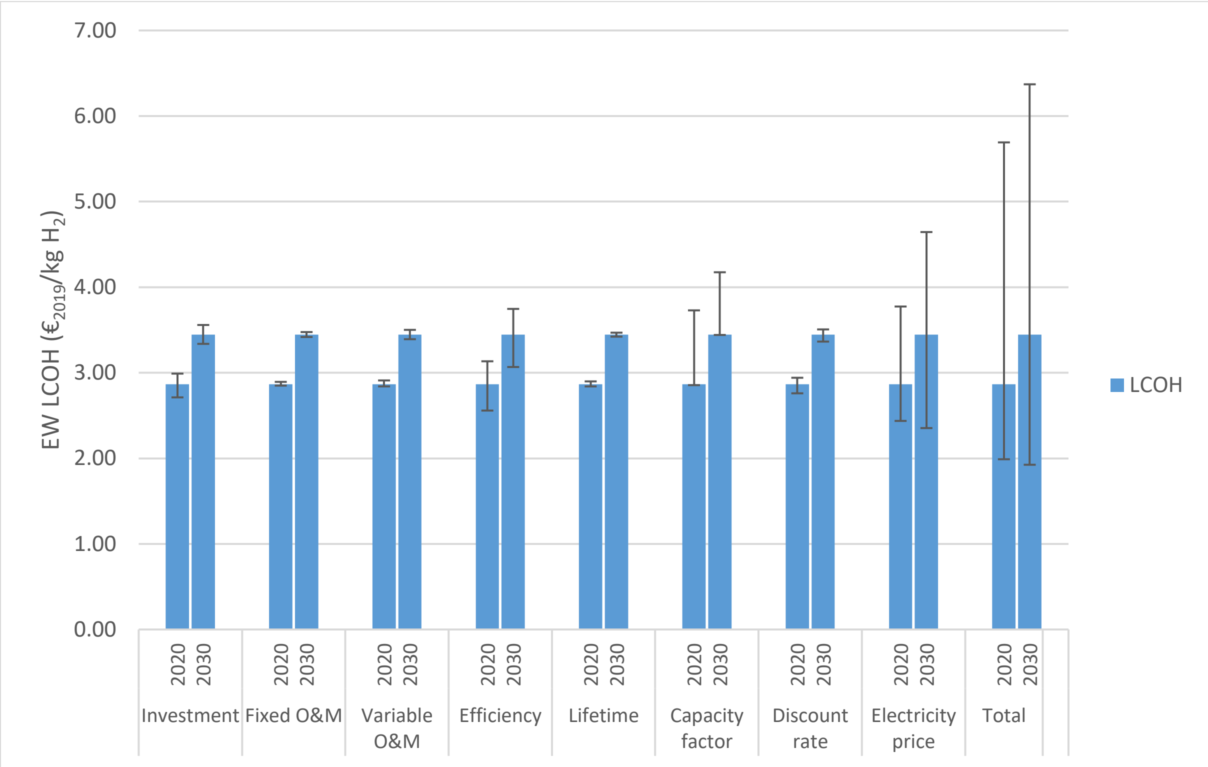

Figure 11. Average effect of the variation of individual factors on the LCOH for the EW pathway in shown per factor
Notes
An uncertainty range of 0.3-0.95 was assumed for the capacity factor

4.2.2 IEW Pathway LCOH

Figure 12 shows the LCOH results for the IEW pathway for the different sources from literature. The LCOH results range from 1.78 to 2.09 $€_{2019}$/kg H_2 for 2020. On average, the calculated LCOH in 2020 for the IEW pathway is 1.97 $€_{2019}$/kg H_2. For 2030 the LCOH results range from 1.55 to 1.76 $€_{2019}$/kg H_2. The average calculated LCOH in 2030 is 1.60 $€_{2019}$/kg H_2. This decrease is due to the improved efficiency of electrolyser and a decrease in electricity price. The level of uncertainty in the calculated LCOH values is lower for 2030 than for 2020. This is due to lower variance in the efficiency values for 2030 compared to 2020 stated by literature. The IEW pathway results in lower calculated LCOH values compared to the EW pathway. This is caused by a significantly lower electricity price. However, the LCOH for the IEW pathway becomes larger than for the EW pathway when including transport costs. The transport costs can be seen in Figure 13. These add 2.50 $€_{2019}$/kg H_2 for 2020 LCOH values and 1.80 $€_{2019}$/kg H_2 for 2030 values. This means that the total LCOH for the IEW pathway for 2020 are 4.47 $€_{2019}$/kg H_2. For 2030 the total LCOH is 3.40 $€_{2019}$/kg H_2.

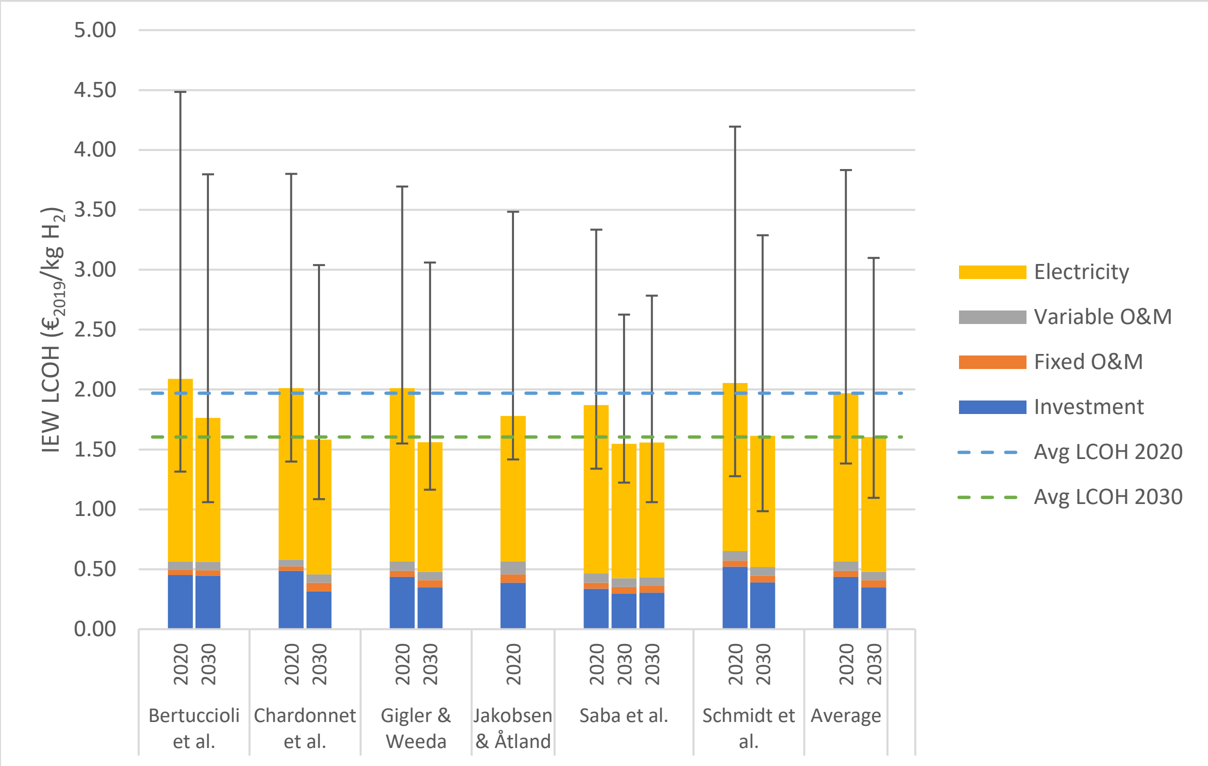

Figure 13. LCOH results for the IEW pathway shown for different data sources. Error bars show the variation in LCOH results for maximum and minimum values of the input factors

Notes

A default capacity factor of 0.8 was assumed

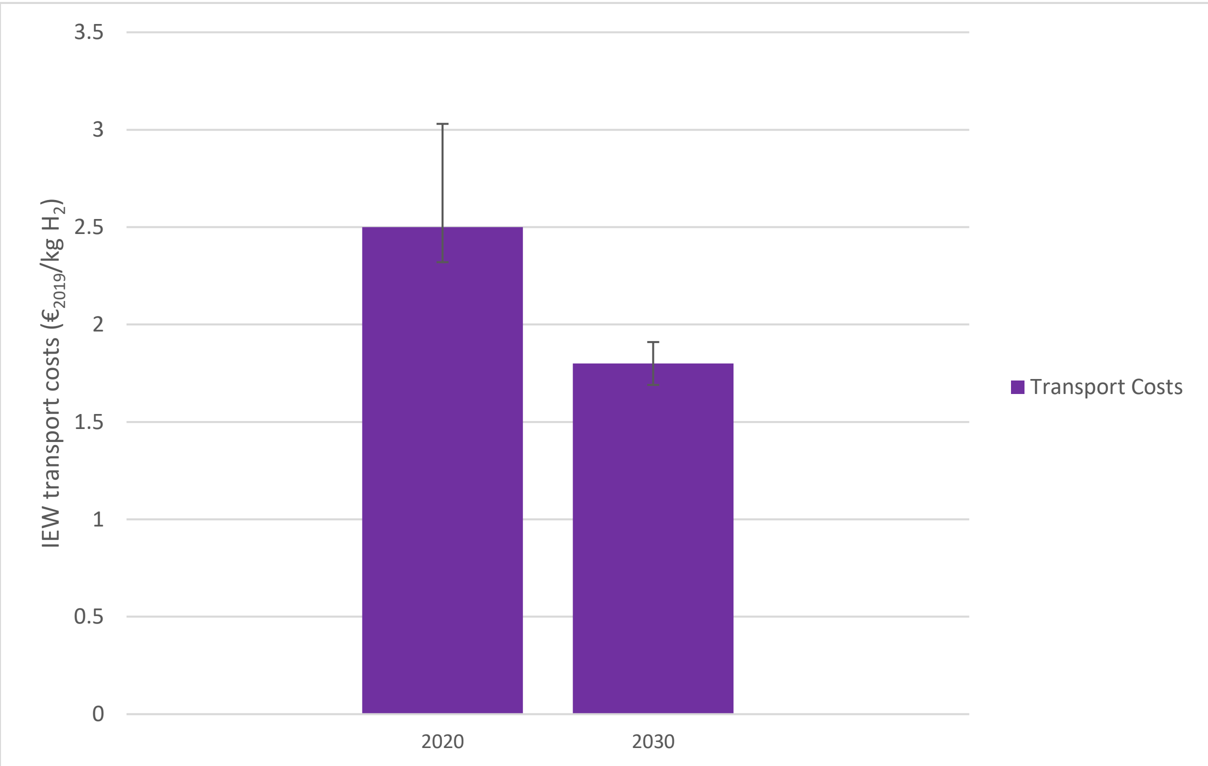

Figure 12. Transport costs for the CG + CCS scenario from the UAE to the port of Rotterdam

Notes

Transport costs were based on cost projections of liquified hydrogen transport by (Bruce et al., 2018)

Figure 14 shows the average effect of the variation of individual factors on the LCOH. As for the EW pathway the variation of factors that influence the electricity costs show a large effect on the total LCOH. The uncertainty in the price of electricity results in a fluctuation of the LCOH between 1.76 and 2.18 $€_{2019}$/kg H_2 in 2020 and between 1.44 and 1.77 $€_{2019}$/kg H_2 in 2030. Variation of the efficiency also shows a significant effect on the LCOH. The LCOH ranges from 1.78 to 1.13 $€_{2019}$/kg H_2 when varying the efficiency for 2020. For 2030 it varies between 1.46 to 1.72 $€_{2019}$/kg H_2. The factor that has the largest effect on the LCOH results is the capacity factor. The value of the capacity factor was varied between 0.3 and 0.95. This lower bound of 0.3 was chosen for the possible dependence of variable renewable electricity production. A limited availability of solar energy could lead to the capacity factor being limited. The LCOH results range from 1.96 to 2.83 $€_{2019}$/kg H_2 with variation of the capacity factor between 0.3 and 0.95 for 2020. For 2030, the LCOH results range from 1.60 to 2.33 $€_{2019}$/kg H_2. The maximum LCOH values when varying all factors for 2020 and 2030 are 3.83 and 3.10 $€_{2019}$/kg H_2 respectively. When including transport costs and the associated uncertainty the maximum total LCOH values for delivered hydrogen are 6.86 $€_{2019}$/kg H_2 for 2020 and 5.01 $€_{2019}$/kg H_2 for 2030.

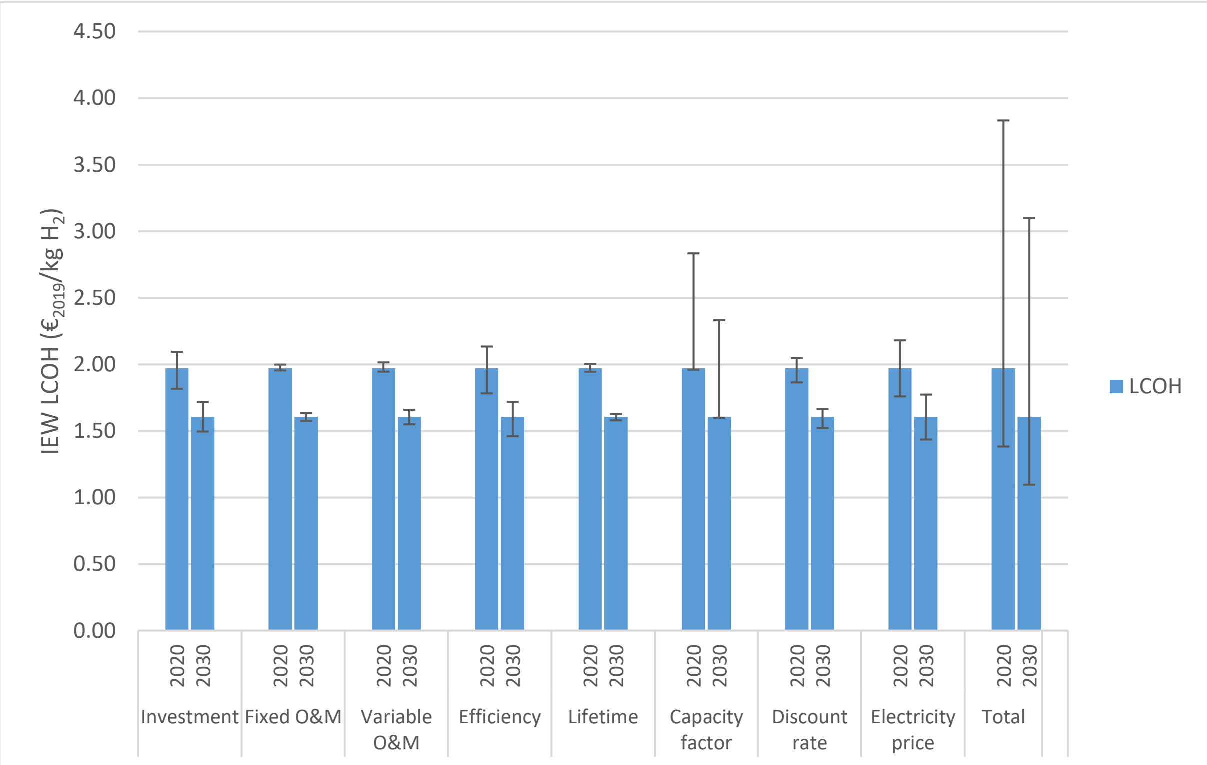

Figure 14. Average effect of the variation of individual factors on the LCOH for the IEW pathway in shown per factor
Notes
An uncertainty range of 0.3-0.95 was assumed for the capacity factor

4.3 Coal Gasification

The techno-economic data for the CG + CCS pathway was obtained from the National Hydrogen Roadmap (Bruce et al., 2018). The corresponding values are shown in Table 7. In this report two coal gasification plants with CCS technology were modelled in the Latrobe valley near Melbourne, Australia. For 2020 the base case values from the report were chosen. For 2030 the best-case values were applied to account for possible cost reductions. The costs for CCS technology are included in the investment costs and the O&M costs. Additional costs for storage of the captured carbon were separated.

Table 7

Standardized techno-economic data for CG + CCS from literature

Techno-economic factor	Unit	2020	Range	2030	Low
Investment costs[a]	$€_{2019}$/kW H_2	1488[1] 1759[1]	1190-1786[1]	1394	1115-1672[1]
Fixed O&M costs[a]	$€_{2019}$/kW/yr	60.6[1] 69.0[1]	48.5-72.7[1] 55.2-82.8[1]	57.2[1]	45.8-68.7[1]
Variable O&M costs	$€_{2019}$/kg H_2	0.03[1]	0.02-0.03[1]	0.03[1]	0.02-0.03[1]
Efficiency[a]	%	63[2]	57-69[2]	70[2]	63-77[2]
CO_2 emissions	kg CO_2/kg H_2	0.7[1]	0.5-1.5[1]	0.7[1]	0.5-1.5[1]
Carbon storage costs	$€_{2019}$/t CO_2	15.4[1]	4.5-25.6[1]	15.4[1]	4.5-25.6[1]
Lifetime	years	40[1]	30-40[1]	40[1]	30-40[1]

Notes
[a] Based on the LHV energy content of hydrogen
[1] Bruce et al., 2018
[2] Campey et al., 2017

4.3.1 CG + CCS Pathway

In Figure 15 the calculated LCOH results are displayed for the CG + CCS pathway. The calculated LCOH for 2020 is 1.52 on average. For 2030 the LCOH was calculated to be 1.31 $€_{2019}$/kg H_2. The transport costs associated with the CG + CCS pathway are 3.01 and 2.32 $€_{2019}$/kg H_2 for 2020 and 2030 respectively. Including transport costs, the total LCOH values are 4.53 in 2020 and 3.63 in 2030. When excluding the costs for shipping the hydrogen the largest share of the LCOH is explained by the investment costs. These account for close to 40% of the LCOH.

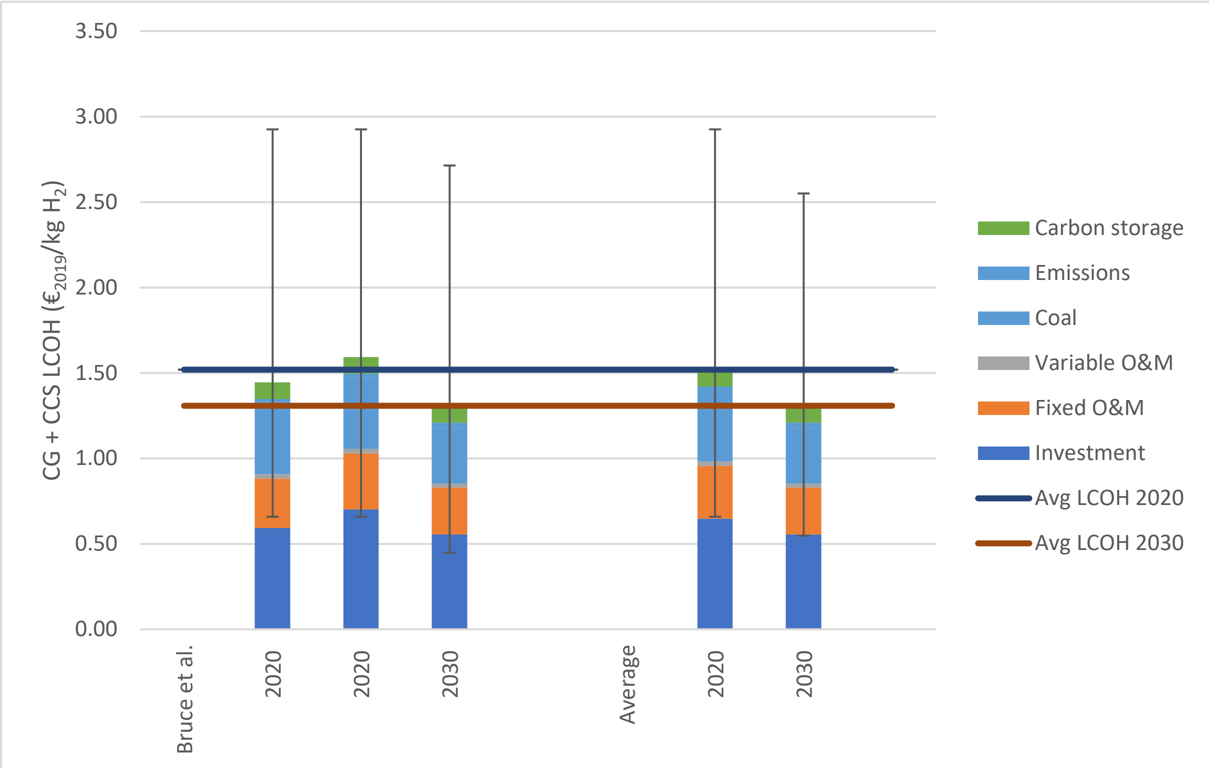

Figure 16. LCOH results for the CG + CCS pathway shown for different data sources. Error bars show the variation in LCOH results for maximum and minimum values of the input factors
Notes
A default capacity factor of 0.8 was assumed

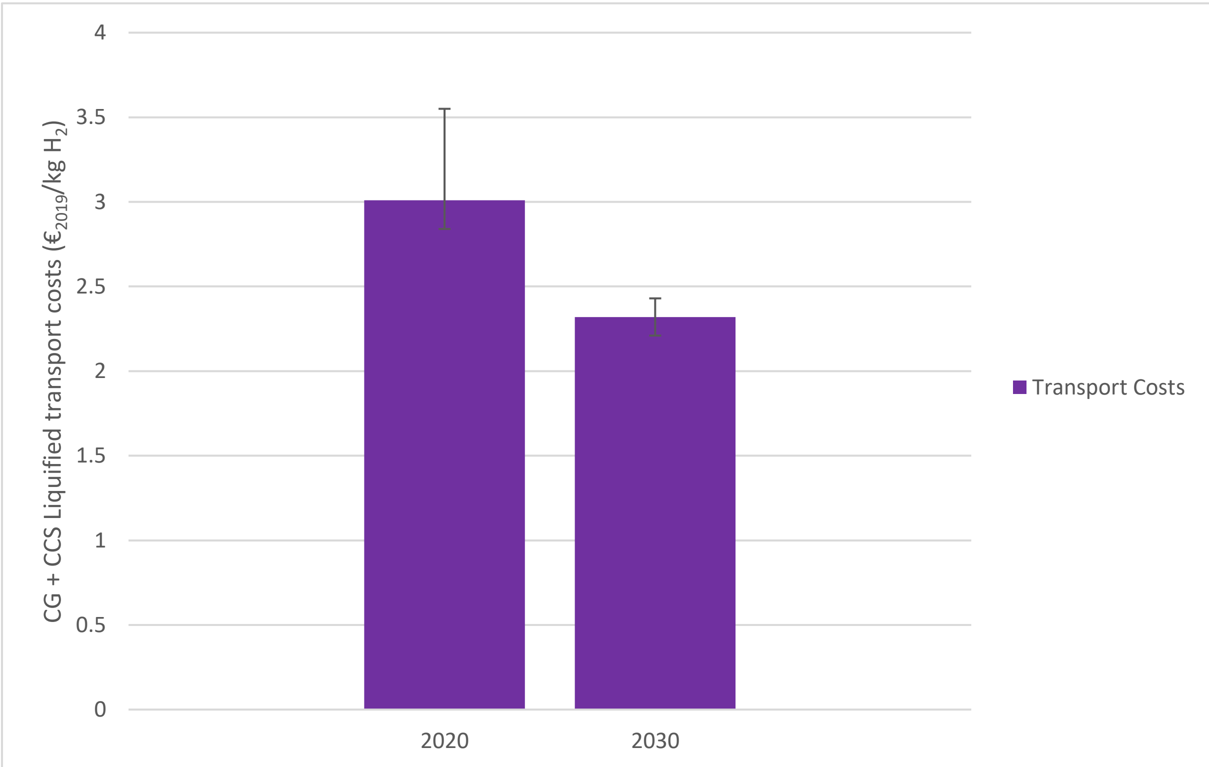

Figure 15. Transport costs for the CG + CCS scenario from Melbourne, Australia to the port of Rotterdam
Notes
Transport costs were based on cost projections of liquified hydrogen transport by (Bruce et al., 2018)

Figure 17 shows the average effect of the variation of individual factors on the LCOH. The uncertainty in the price of coal results in a fluctuation of the LCOH between 1.31 and 1.94 $€_{2019}$/kg H_2 in 2020 and between 1.47 and 1.63 $€_{2019}$/kg H_2 in 2030. Variation of the capacity factor shows the largest effect on the LCOH after the coal price. This is because CG comes with high investment costs, especially when combined with CCS technology. The LCOH ranges from 1.45 to 1.59 $€_{2019}$/kg H_2 when varying the carbon storage costs for 2020. For 2030 it varies between 1.24 and 1.37 $€_{2019}$/kg H_2. The maximum LCOH values when varying all factors for 2020 and 2030 are 3.02 and 2.65 $€_{2019}$/kg H_2 respectively. When including transport costs and the associated uncertainty the maximum total LCOH values for delivered hydrogen are 6.57 $€_{2019}$/kg H_2 for 2020 and 5.08 $€_{2019}$/kg H_2 for 2030.

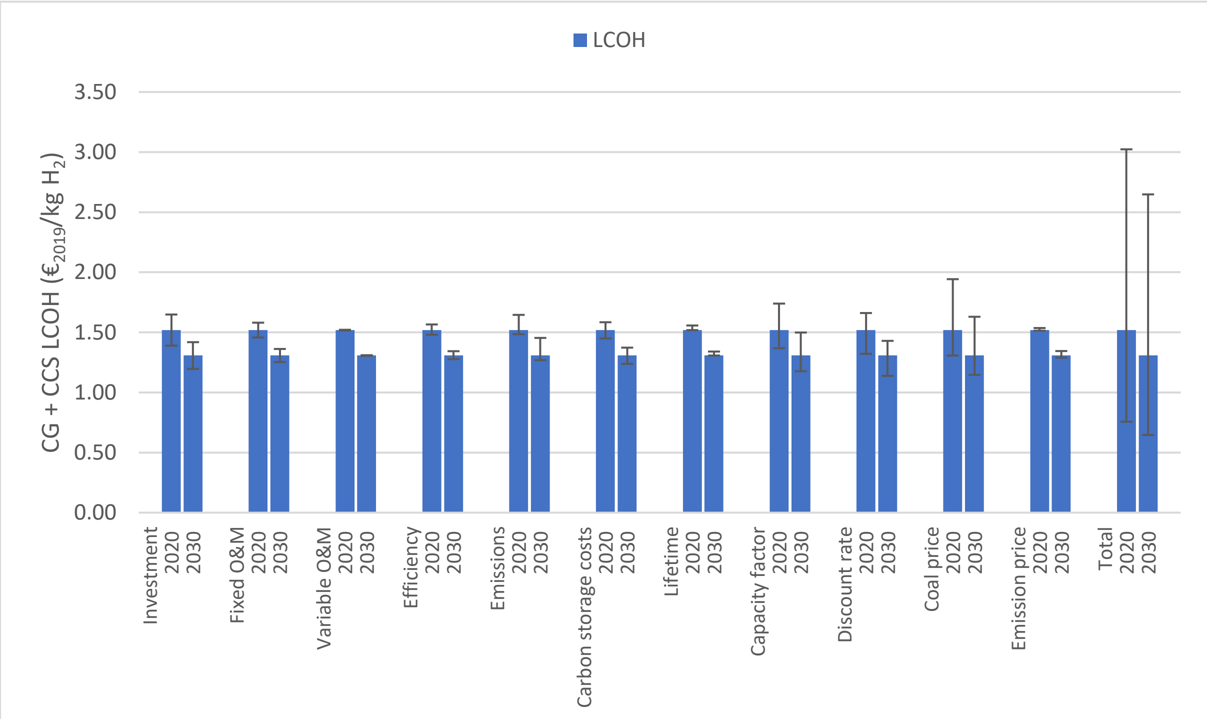

Figure 17. Average effect of the variation of individual factors on the LCOH for the CG + CCS pathway in shown per factor
Notes
An uncertainty range of 0.65-0.95 was assumed for the capacity factor

5 Pathway Comparison

The calculated LCOH values and the corresponding uncertainty ranges for the different pathways are shown in Table 8. Figure 18 shows these LCOH values and the underlying factors for all pathways. For both 2020 and 2030 the pathways that use steam methane reforming result in the lowest LCOH values. The calculated LCOH value for SMR + CCS pathway is larger than for the SMR pathway, due to the additional costs associated with implementation of CCS technology. For 2020 the calculated LCOH for the SMR and the SMR + CCS pathways are 1.78 and 2.08 $€_{2019}$/kg H_2 respectively. The difference in LCOH values for these pathways is 0.30 $€_{2019}$/kg H_2. For 2030, the difference between the LCOH values of these two pathways is 0.08 $€_{2019}$/kg H_2. The reason for this change in difference is the cost associated with produced CO_2 emissions. These costs result in an increase of the LCOH of the SMR pathway of 0.25 $€_{2019}$/kg H_2 for 2030 compared to 2020. For the SMR + CCS pathway, these costs increase by 0.03 $€_{2019}$/kg H_2, as most of the CO_2 emissions are captured and stored.

Table 8

Calculated LCOH values for the different pathways and corresponding uncertainty ranges

Pathway	**LCOH ($€_{2019}$/kg H_2)**			
	2020	Uncertainty Range	2030	Uncertainty Range
SMR	1.78	1.07-3.06	2.37	1.12-4.24
SMR + CCS	2.08	1.14-3.40	2.45	1.14-4.04
EW	2.87	1.99-5.69	3.45	1.92-6.37
IEW	4.47	3.70-6.86	3.40	2.79-5.01
CG + CCS	4.53	3.60-6.57	3.63	2.86-5.08

The pathways where hydrogen is imported (IEW and CG + CCS) result in the highest LCOH values. Figure 18 shows that the transport costs have a large effect on the LCOH values for these two pathways. For the IEW pathway, transport costs account for 56% of the total LCOH value for 2020. The share of these costs equals 53% of the total for 2030. For the CG + CCS pathway the share of the transport costs equals 66% and 64% for 2020 and 2030 respectively. Without transport costs, the pathways where hydrogen is imported would correspond to the lowest LCOH values for 2030.

The highest level of uncertainty was found for the EW pathway. For 2030, the upper limit of the uncertainty range found for the calculated LCOH was 5.69 $€_{2019}$/kg H_2, a doubling of the LCOH value found without variation of underlying factors. This is due to the high level of uncertainty associated with the Dutch electricity price. The costs for electricity consumption account for 80% of the total LCOH value in 2020, and 86% in 2030. In 2030 the calculated LCOH of the EW pathway exceeds the value found for the IEW pathway, even with transport costs included for the IEW pathway. If calculations for the EW pathway would be performed with an electricity price similar to the level in the UAE would result in an LCOH of 1.60 €$_{2019}$/kg H_2. However, this electricity price is not within the uncertainty range associated with projected developments of the Dutch electricity price (Schoots & Hammingh, 2019).

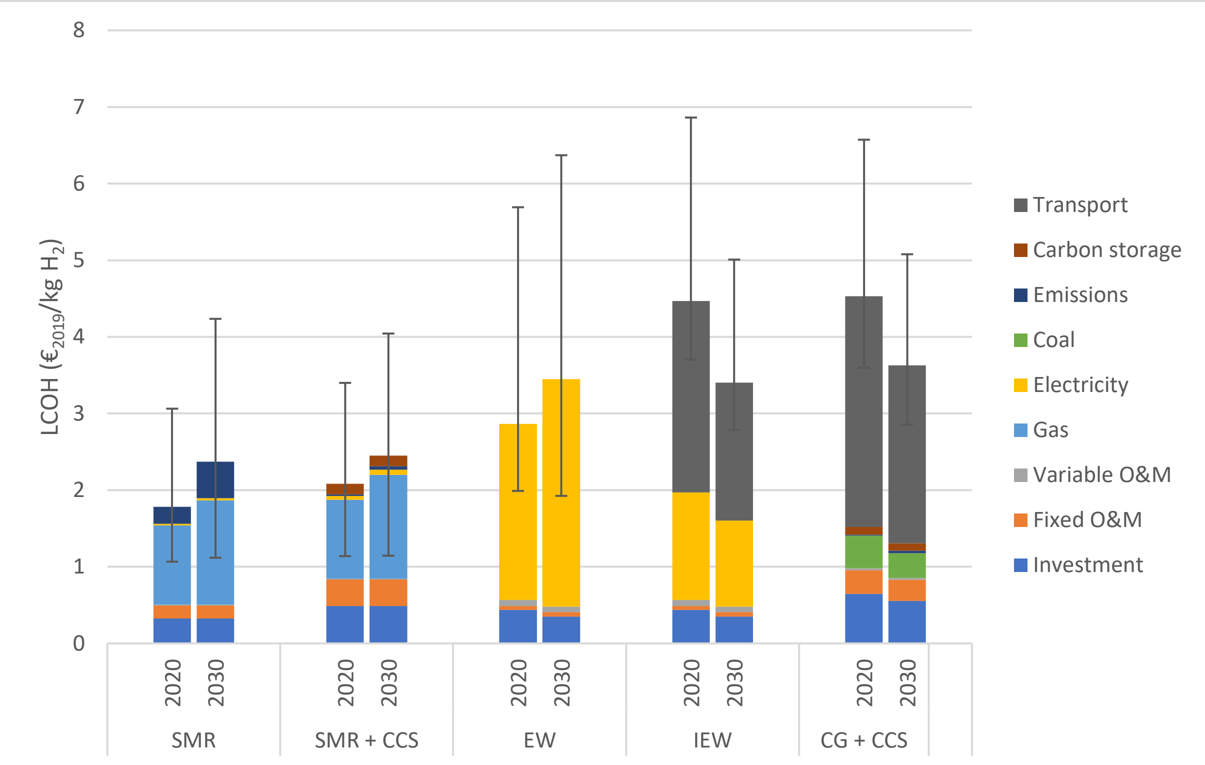

Figure 18. Average LCOH values for the different scenarios for 2020 and 2030

The error bars in Figure 18 imply that variation of specific factors could result in a different ranking of the LCOH values. Sections 5.1 through 5.6 discuss the effect of the variation of individual factors on the LCOH values of the different pathways. Appendix E shows the results for variation of all individual factors. Sections 5.1 through 5.6 only discuss the results for the variation of factors that result in a change in the ranking of the LCOH values of the pathways.

5.1 Capacity Factor

Figures 19 and 20 show the effect of variation of the capacity factor between 0.1 and 1.0 on the LCOH values of the different pathways. Figure 19 displays the results for 2020 and Figure 20 shows the results for 2030. For both 2020 and 2030, the ranking of the LCOH values changes at a capacity factor value of approximately 0.25. The SMR + CSS pathway results in a higher LCOH value than the EW pathway for a capacity factor lower than approximately 0.25. A capacity factor this low could apply to the electrolysis pathways, for example when electrolysis is used to provide net balancing. Another situation where the capacity factor could reach a value below 0.25 is when the availability of electricity is limited due to the use of renewable energy sources. However, this value is unrealistically low for an SMR plant.

At a capacity factor above 0.9, the IEW and CG + CCS pathway result in a similar LCOH of around 4.4 €$_{2019}$/kg H_2 for 2020. A capacity factor above 0.9 results in a lower LCOH value for the CG + CCS pathway. This is a realistic value for a CG plant as it has a reliable energy supply from coal. The capacity factor of the IEW pathway is dependent on the availability of renewable energy. A capacity factor of 0.9 is therefore quite unrealistic for the IEW pathway. This means the LCOH value of the CG + CCS pathway is realistically lower than the LCOH value for the IEW pathway.

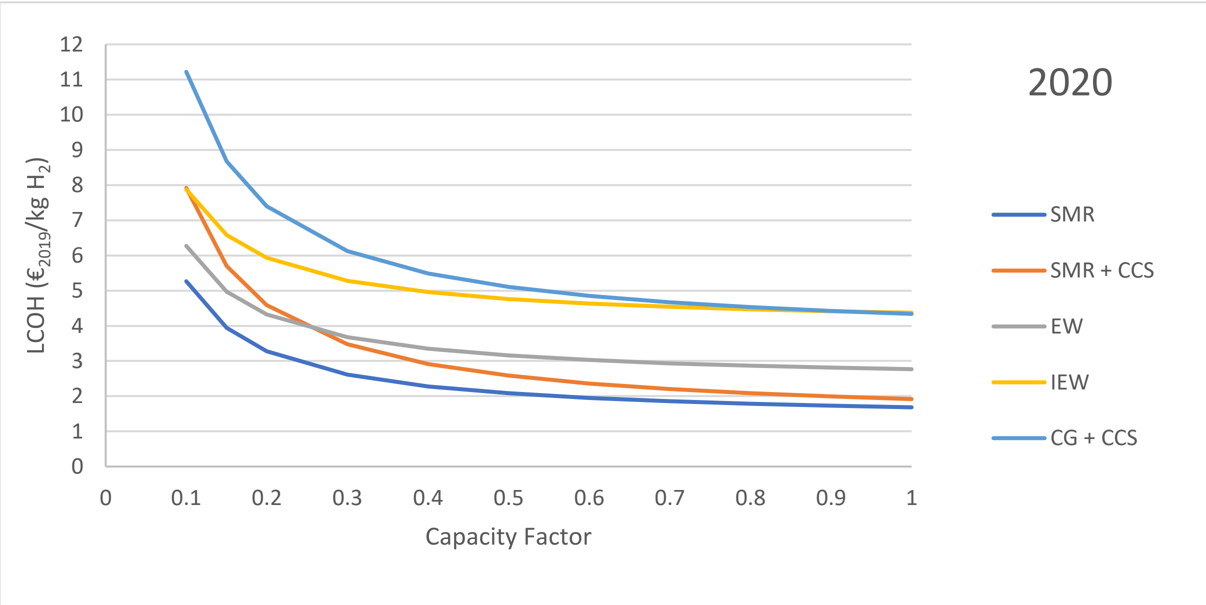

Figure 19. Effect of variation of the capacity factor on the calculated LCOH values of the different scenarios for 2020
Notes
A default value of 0.8 was assumed for the capacity factor

Figure 20 shows the effect of variation of the capacity factor on the LCOH values for 2030. The results are similar to the effect seen for 2020, showing a change in the ranking of the LCOH values around a capacity factor of 0.25.

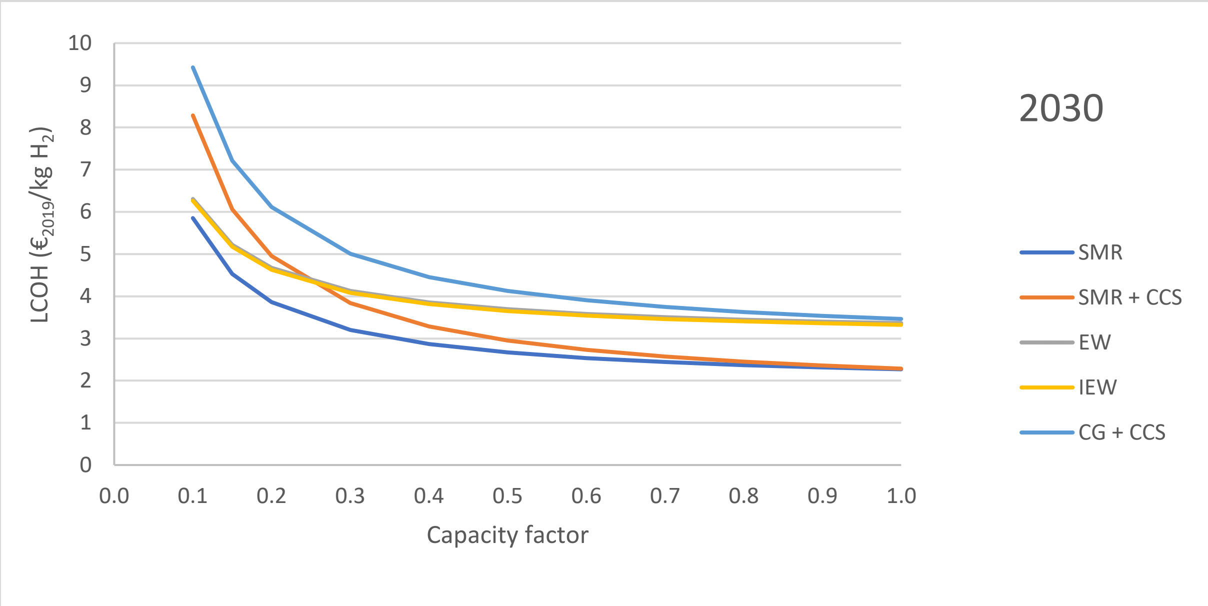

Figure 20. Effect of variation of the capacity factor on the calculated LCOH values of the different scenarios for 2030
Notes
A default value of 0.8 was assumed for the capacity factor

5.2 Fixed O&M costs

Figure 21 shows the effect of variation of the fixed O&M costs on the calculated LCOH in 2020. A reduction of the fixed O&M costs by approximately 25% results in a similar LCOH for the CG + CCS pathway compared to the IEW pathway. Further reduction of fixed O&M costs results in a lower LCOH value for the CG + CCS pathway compared to the IEW pathway. Increasing research is being conducted on CCS technology and installed capacity is expected to increase. This could lead to the cost reductions required for the LCOH of the CG + CCS pathway to drop below the LCOH value of the IEW pathway.

The difference in the effect of reduction of the fixed O&M costs between the SMR and SMR + CCS pathways can be explained by the large share of O&M costs coming from implementation of CCS technology. This means there is a higher level of variation of the fixed O&M for the SMR + CCS pathway.

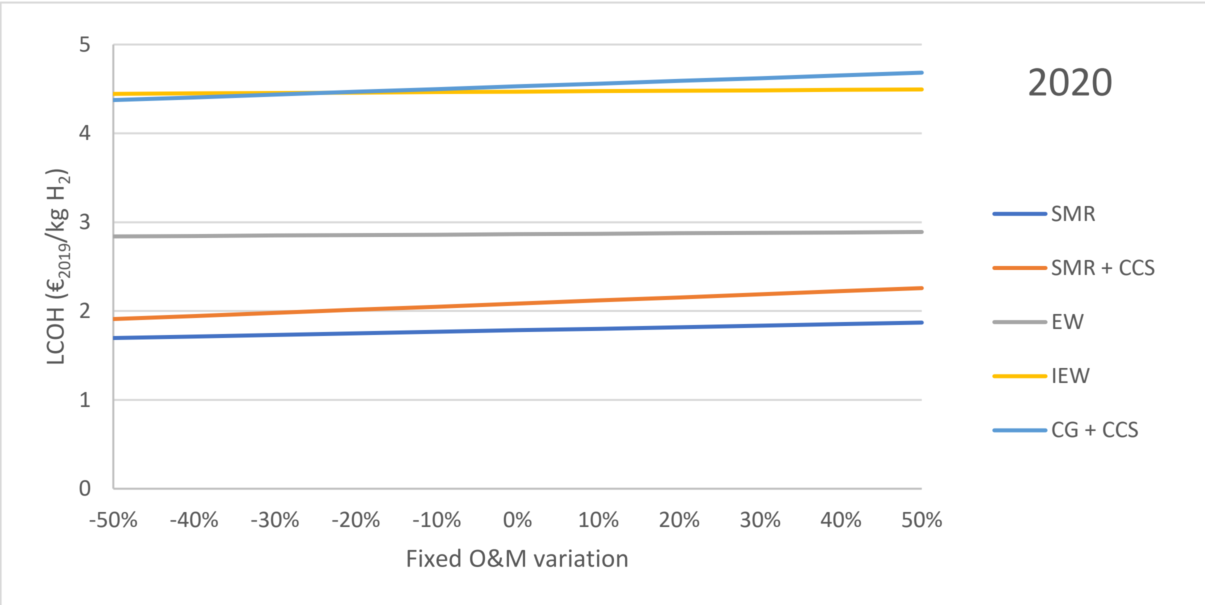

Figure 21. Effect of variation of the Fixed O&M costs on the calculated LCOH values of the different scenarios for 2020

5.3 Efficiency

Another technological factor that could affect the ranking of the pathways for 2030 is the efficiency. Figure 22 shows the LCOH results for the pathways with variation of the efficiency. A slight increase of approximately 1.5 percent point of the efficiency of the production methods would result in a lower LCOH for the EW pathway compared to the IEW pathway. An improvement in efficiency has a larger effect on the LCOH value of the EW pathway as the electricity price is higher for this pathway. Therefore, a similar decrease in the amount of electricity required results in a larger reduction of the calculated LCOH.

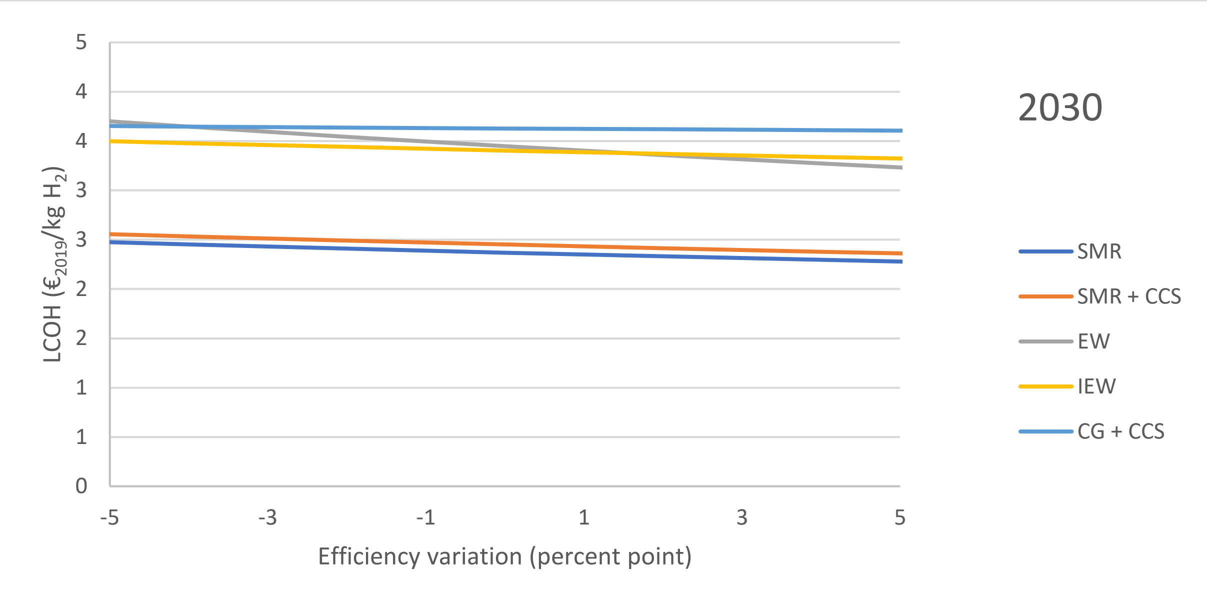

Figure 22. Effect of variation of the efficiency on the calculated LCOH values of the different scenarios for 2030

5.4 CO_2 emission price

Figure 23 shows the effect of variation of the CO_2 emission price on the LCOH in 2030. The default CO_2 emission price was assumed to be 47 $€_{2019}$/t CO_2. This value was varied between 21 and 80 $€_{2019}$/t CO_2. The LCOH value of the SMR pathway shows a strong effect compared to the LCOH values of the other pathways. Those LCOH results show little or no change when it comes to variation of the CO_2 emission price as the pathways with electrolysis do not produce CO_2 and the CG + CCS and SMR + CCS pathways produce limited CO_2 emissions because of the implementation of CCS technology. At a CO_2 emission price above 55 $€_{2019}$/t CO_2 the calculated LCOH value of the SMR pathway exceeds the LCOH value of the SMR + CCS pathway.

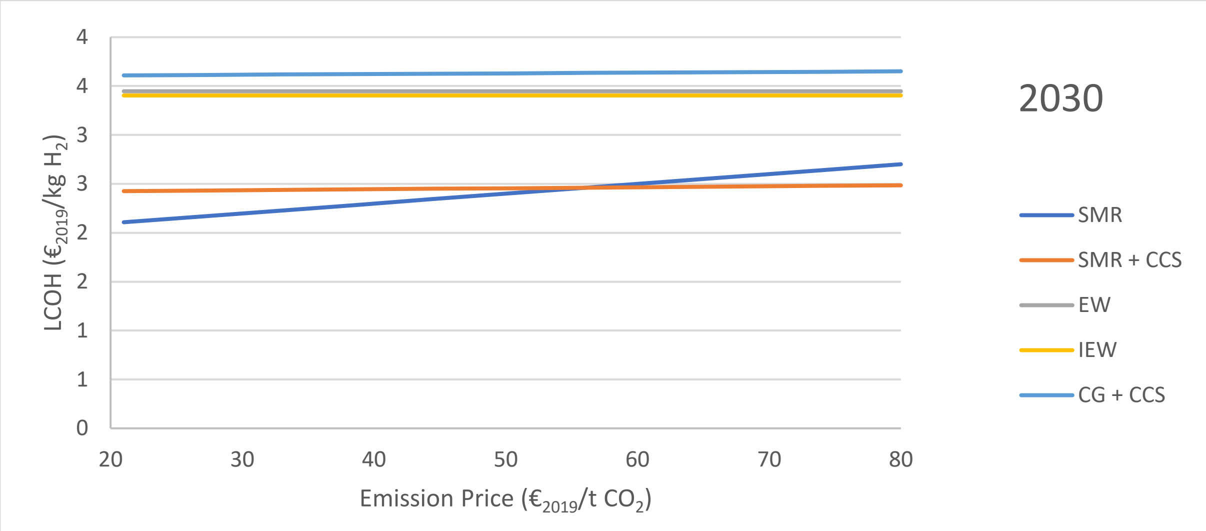

Figure 23. Effect of variation of the CO_2 emission price on the calculated LCOH values of the different scenarios for 2030
Notes
A default CO_2 emission price of 47 $€_{2019}$/t CO_2 was assumed for 2030

5.5 Energy Prices

Figure 24 shows the effect of variation of the energy prices on the LCOH values of the different pathways for 2030. The energy prices were varied according to the ranges specified in Table 2 in section 2.4. The effect of variation of individual energy prices on the calculated LCOH values can be found in appendix E. Figure 24 shows the effect of variation of all energy prices. For the SMR and SMR + CCS pathways, it shows the effect of the variation of the gas price. For the EW and IEW pathways, it shows the effect of fluctuation of the electricity price. For the CG + CCS pathway the effect of variation of the coal price is displayed. The largest effect is found for the EW pathway. One reason for this is the fact that a relatively large share of the total LCOH is explained by costs for electricity consumption, directly affected by the electricity price. Another reason is the large uncertainty range associated with the Dutch electricity price in 2030 (Schoots & Hammingh, 2019).

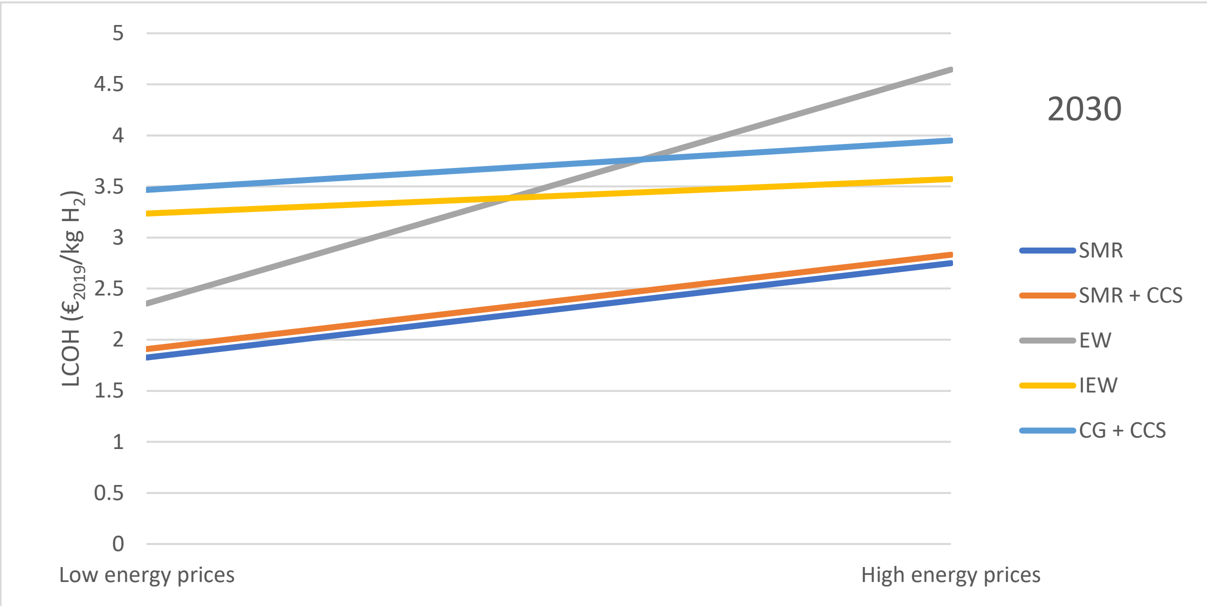

Figure 24: Effect of variation of the energy prices on the calculated LCOH values of the different scenarios for 2030

5.6 Transport Costs

The final factor that affects the ranking of the calculated LCOH values for the pathways is the cost for transport. The effect of variation of the transport costs on the LCOH is shown in Figure 25. Only the IEW and CG + CCS pathways are affected as the other pathways do not include transport costs. For 2030, the transport costs for the IEW pathway from the UAE to Rotterdam were originally assumed to be 1.80 $€_{2019}$/kg H_2. At a value above 1.85 $€_{2019}$/kg H_2 the EW pathway results in a lower LCOH, making local production of hydrogen the cheaper option. For CG + CCS, the transport costs from Melbourne, Australia to the port of Rotterdam were assumed to be 2.32 $€_{2019}$/kg H_2 in 2030. If these costs are reduced to a value under 2.10 $€_{2019}$/kg H_2, the calculated LCOH for the EW pathway would exceed the value of the LCOH for the CG + CCS pathway. As liquified hydrogen transport by ship is a new technology, cost reductions can be expected if implementation proves successful. This could make the IEW and CG + CCS pathways competitive alternatives compared to the EW pathway.

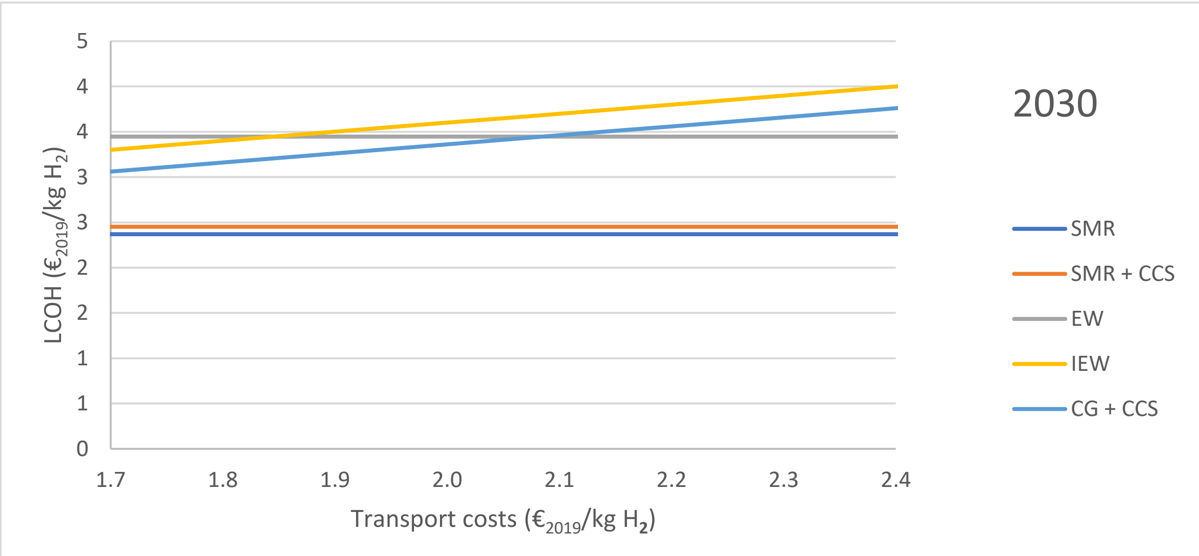

Figure 25: Effect of variation of the transport costs on the calculated LCOH values of the different scenarios for 2030

6 Discussion

The comparison of the calculated LCOH values and their sensitivity to variation of underlying factors shows that there is a lot of uncertainty in terms of the costs associated with the different production methods. The most important factors in the uncertainty of the LCOH for the pathways in this research are the prices of the feedstocks and electricity required for the hydrogen production processes. The uncertainty in prices of coal, gas and electricity has a direct effect on the costs for energy consumption of the production methods. These costs account for a large share of the total LCOH for the different pathways. With a high level uncertainty in the expected development of energy prices into the future, the actual LCOH of the production methods is hard to predict and can change significantly. However, the comparison shows that even with a large variation of factors affecting the LCOH, two pathways show the lowest LCOH values. Both in 2020 and 2030, the SMR and the SMR + CCS pathways result in the lowest calculated LCOH. The pathways where hydrogen is imported result in the highest LCOH values due to the high costs associated with transport.

6.1 Limitations

There are aspects outside of the scope of this research that should be considered when analyzing hydrogen production. One factor that was not included is the desired pressure of the final hydrogen product. Depending on the purpose of the hydrogen, the desired pressure can be different. If additional transport of is required from the port of Rotterdam, it must be compressed for transport by truck or pipeline. Imported liquified hydrogen can be pressurized during the unloading process, building up pressure as the liquified hydrogen heats up and evaporates. This means that additional costs for compression would have a larger effect on the total costs for hydrogen produced locally than for imported hydrogen. Compression of hydrogen to a pressure of 350 bar can add 0.2-0.3 $€_{2019}$/kg H_2 to the total costs. This would result increase the LCOH of the EW pathway in this research from 3.45 to 3.75 $€_{2019}$/kg H_2. For imported hydrogen, these costs are partially avoided due to the buildup of pressure during the unloading process. However, installations must also be constructed to unload the liquified hydrogen. Without specific costs for these installations, the impact of costs of compression on the comparison of the LCOH cannot be determined in detail.

Another limitation of this research is the number of pathways analyzed. There are many possible pathway configurations possible for the available production methods. An example of a possible pathway is the production of hydrogen through electrolysis to cope with fluctuating renewable energy sources in the Netherlands. This would require a different level of analysis to determine the capacity factor and the electricity price associated with integrating electrolysis in this way. Moreover, other production methods could be added to the comparison to get a more inclusive overview of the costs of hydrogen production. However, other production methods show a level of uncertainty that is even higher than the production methods included in this research, as many of them are still in an early development phase. Calculated LCOH values and a comparison of the pathways would therefore not be very robust.

6.2 Comparison to other studies

The calculated LCOH from this research can be compared to values stated by other reports and hydrogen roadmaps. Table 9 shows a range of values stated by multiple reports. For 2020, this research shows similar results compared to the values stated by the analyzed reports. For example, the reported costs for hydrogen production through SMR range from 0.9 to 2.5 $€_{2019}$/kg H_2 for 2020, compared to a calculated LCOH of 1.78 $€_{2019}$/kg H_2 found in this research. The uncertainty found in this research includes a range between 1.07 and 3.06 $€_{2019}$/kg H_2.

For hydrogen production through CG, the value found in this research was significantly higher compared to values mentioned by other reports. For example, the a report by the IEA states LCOH values ranging from approximately 2.0 $€_{2019}$/kg H_2 for CG with implementation of CCS technology in 2020 (IEA, 2019c). The value found in this report was 4.53 $€_{2019}$/kg H_2. This is due to the transport costs included in the CG + CCS pathway in this research.

For 2030, the LCOH values found in this research are significantly higher compared to values reported in literature. For the pathways where hydrogen is imported, this difference is explained by the additional transport costs included in this research. For the pathways where hydrogen is produced domestically, this difference is due to the assumed energy prices. For these pathways, calculations in this research were performed using the Dutch energy prices. The values shown for other reports often refer to LCOH values associated with best case scenarios.

Table 9

Examples of LCOH values stated by literature for different hydrogen production methods

Production method	Calculated LCOH (€2019/kg H_2)		LCOH from literature (€2019/kg H_2)	
	2020	2030	2020	2030
SMR	1.78	2.37	1.52-2.53[2] 1.01-1.52[3] 1.00[4] 0.9-1.8[5]	1.70[4] 0.9-1.8[5]
SMR with CCS	2.08	2.45	1.45-1.77[1] 1.34-2.67[5]	1.63-1.98[1]
Electrolysis	2.87	3.45	3.06-3.74[1] 5.00-5.50[3]	1.20-1.47[1] 2.00-3[3]
Renewable electrolysis	4.47	3.40	5.29[4] 2.23-5.34[5]	2.95[4]
CG with CCS	4.53	3.63	1.64-2.01[1] 2.0[5]	1.29-1.58[1]

Notes
[1] Bruce et al., 2018
[2] DNV GL, 2018
[3] Gigler & Weeda, 2018
[4] Hers et al., 2018
[5] IEA, 2019c

6.3 Policy implications and research recommendations

The results of this research can be considered in a broader context. The costs hydrogen can be compared to other energy carriers. For instance, fuel cell vehicles consume hydrogen to drive an electric engine. H2 Mobility (2019) states that currently available fuel cell vehicles consume between 0.76 and 1.0 kg of hydrogen per 100 km driven. As seen in Table 9, the calculated LCOH values for hydrogen production in this research range from 1.78 to 4.53 $€_{2019}$/kg H_2. The costs of hydrogen for driving 100 km driven are therefore in the range of 1.35-4.53 $€_{2019}$. For electric cars with 2019 as the model year, the electricity consumed per 100 km range from approximately 15 to 35 kWh (US Environmental Protection Agency, 2019). At a consumer electricity price of approximately 0.20 $€_{2019}$/kWh (CBS, 2019), costs for driving 100 km are in the range of 3-7 $€_{2019}$. Cars for model year 2019 that run on traditional fuels, average consumption equals roughly 9 L per 100 km driven on average (U.S. Environmental Protection Agency, 2020). The average price of gasoline for the Netherlands in 2019 was 1.76 $€_{2019}$/L. From these values, the cost of fuel for driving 100 km using gasoline equals 15.84 $€_{2019}$. However, the costs for hydrogen do not include transport of the hydrogen to the fuel stations, and investments required to build the infrastructure for distribution. Moreover, hydrogen vehicles are typically more expensive as they are relatively new.

For future policy, when the costs of produced hydrogen are deemed the most important factor in choosing a production method, SMR should be implemented. Depending on the costs for produced CO_2 emissions, this should be either with or without implementation of CCS technology. A CO_2 emission price above 55 $€_{2019}$/t CO_2 results in a higher LCOH value for SMR without CCS technology compared to an SMR plant with implementation of CCS technology.

Producing hydrogen abroad is more expensive than producing it locally through SMR. The costs associated with long distance shipping are high. Producing hydrogen abroad causes a level of energy dependence. However, hydrogen production through electrolysis using renewable energy sources can be implemented at relatively low-cost compared to domestic production. When deciding on future hydrogen production projects, these factors should be considered.

Future research should focus on reducing the uncertainty associated with underlying cost factors. By reducing the uncertainty in data on underlying factors, future costs can be estimated with more precision. This facilitates the decision-making process in creation of future policy considering hydrogen production.

Conclusion

The goal of this research was to compare the effects of uncertainties in underlying factors on the LCOH of the dominant hydrogen production methods and to compare these effects across production methods. The hydrogen production methods that were analyzed in this research were SMR, electrolysis and CG. Five pathways were designed to calculate the LCOH with variation of the underlying factors. The port of Rotterdam was chosen as the location of analysis. For the different pathways, hydrogen is either produced locally, or transported to the port of Rotterdam by ship. The five pathways that were designed are the SMR, SMR + CCS, EW, IEW and CG + CCS pathways. The LCOH was calculated with variation of the underlying factors for both 2020 and 2030.

The SMR and SMR + CCS pathways were designed to produce hydrogen from natural gas, with CCS technology implemented in the SMR + CCS pathway to reduce CO_2 emissions. The EW and IEW pathway produce hydrogen through electrolysis. The EW pathway acquires electricity from the Dutch grid. The IEW pathway produces hydrogen in the UAE using electricity from renewable energy sources. The produced hydrogen for the IEW pathway is then transported using liquified hydrogen transport by ship. For the CG + CCS pathway hydrogen is produced through CG with implementation of CCS technology. The pathway location is Melbourne, Australia. Produced hydrogen is transported by ship.

For both 2020 and 2030 the SMR pathway resulted in the lowest LCOH value. The calculated LCOH values with default values for the underlying factors were 1.78 and 2.37 $€_{2019}$/kg H_2 for 2020 and 2030 respectively. The SMR + CCS pathway resulted in an LCOH of 2.08 $€_{2019}$/kg H_2 for 2020 and 2.45 $€_{2019}$/kg H_2 for 2030. For the SMR and SMR + CCS scenarios, costs for gas consumption accounted for the largest share of the total LCOH. For this reason, the price of gas is the largest source for uncertainty of the calculated LCOH for these pathways. For the EW pathway, costs for electricity consumption account for roughly 80% of the total LCOH value of 2.87 $€_{2019}$/kg H_2 for 2020. For 2030, this share increases to 86% of the total value of 3.45 $€_{2019}$/kg H_2. Variation of the capacity factor and the price of electricity cause the most uncertainty in the calculated LCOH for this pathway. For the IEW and CG + CCS pathways, transport costs account for the largest share of the calculated LCOH values. For 2020 the IEW and CG + CCS pathways result in an LCOH of 4.47 and 4.53 $€_{2019}$/kg H_2 respectively. For 2030, the IEW pathway corresponds to an LCOH value of 3.40 $€_{2019}$/kg H_2 and the CG + CCS pathway corresponds to an LCOH value of 3.63 $€_{2019}$/kg H_2.

There is a high level of uncertainty associated with the underlying factors of the LCOH of hydrogen production. Scientific literature states divergent cost data, and available projections of future cost developments are limited. Through calculations with variation of the underlying factors this research showed the effects of the uncertainty of these factors on the levelized costs of hydrogen production. The uncertainties in underlying factors cause a high level of uncertainty in the calculated LCOH for the different pathways.

The most important factors causing the uncertainty in the LCOH for hydrogen production through CG, SMR, and electrolysis are the prices for coal, gas and electricity respectively. Costs for energy consumption explain the largest share of the LCOH associated with the production process. For hydrogen produced abroad, transport costs account for the largest share of the total LCOH.

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Appendix A: Data Acquisition

Data on the costs of different production methods was gathered from academic literature, books, (inter)governmental reports and corporate reports. The reference list gives a complete overview of the literature used to write this research. These documents were acquired by searching the Scopus database and by using the Google Scholar search engine. Search queries included, but were not limited to:

- Hydrogen
- Hydrogen production
- Hydrogen production cost
- Hydrogen cost projections
- Hydrogen production pathway comparison
- Hydrogen production technologies
- Hydrogen production methods
- Hydrogen cost
- Hydrogen cost development
- Steam Methane Reforming
- Steam Methane Reforming cost
- SMR cost
- Gas Reforming
- Natural Gas Reforming
- Steam reforming
- Electrolysis
- Electrolysis of water
- Hydrogen electrolysis
- Electrolysis costs
- Electrolysis investment cost
- Alkaline electrolysis
- Alkaline electrolysis cost
- AEC
- AEC cost
- Levelized cost of hydrogen production
- LCOH
- LCOH comparison
- Steam methane reforming LCOH
- SMR LCOH
- Electrolysis LCOH
- Coal gasification LCOH
- Coal gasification hydrogen production

Next to direct search queries for literature through the main search engines, literature was also found by going through specific academic journals. These journals were obtained in two ways. First, journals containing multiple articles were searched for more relevant articles by using the same queries as when using the main search engine. Additionally, journals and books were found through ScienceDirect by Elsevier by searching for the following queries (These are only the search queries that yielded relevant results from the ScienceDirect database):

- Hydrogen
- Hydrogen production
- Coal

- Carbon capture

The method of looking at the journals that relevant articles were published in combined with searching specifically in the journal and book database resulted in the following journals and books/book chapters:

Journals

- International Journal of Hydrogen Energy
- Journal of Cleaner Production
- Renewable and Sustainable Energy Reviews

Books

- Basile, A., & Iulianelli, A. (2014). Advances in Hydrogen Production, Storage and Distribution. In *Advances in Hydrogen Production, Storage and Distribution*. https://doi.org/10.1016/C2013-0-16359-3

- Scipioni, A., Manzardo, A., & Ren, J. (2017). *Hydrogen Economy: Supply Chain, Life Cycle Analysis and Energy Transition for Sustainability*. Retrieved from https://www-sciencedirect-com.proxy.library.uu.nl/book/9780128111321/hydrogen-economy

- Stephenson, M. (2013). Accounting for carbon. In *Returning Coal and Carbon to Nature* (pp. 121–143). https://doi.org/https://doi.org/10.1016/B978-0-12-407671-6.00006-9

The journals mentioned above were searched for articles containing data on the production methods relevant for this research. Next, articles that were cited for data values were scanned for additional relevant data as well. Data from articles before 2014 was not used in this research as those cost values might not represent current costs well enough.

Appendix B: Exchange Rates and Inflation Rates

Table B1

Average yearly exchange rates of USD and AUD to EUR and cumulative inflation rates from 2010 to 2019

Year	EUR – USD[1]	EUR – AUD[2]	EUR – EUR_{2019}[3]
2010	0.75	0.69	1.13
2011	0.72	0.74	1.10
2012	0.78	0.81	1.07
2013	0.75	0.72	1.05
2014	0.75	0.68	1.05
2015	0.90	0.68	1.05
2016	0.90	0.67	1.05
2017	0.88	0.68	1.03
2018	0.85	0.63	1.01
2019	0.89	0.62	1.00

Notes
[1] Statista, 2020b
[2] Statista, 2020a
[3] Eurostat, 2019

Appendix C: List of Hydrogen Production Methods

Table C1

List of identified hydrogen production methods

Production Method	**Short description**
Artificial photosynthesis	Chemically engineered systems mimic photosynthesis to generate H_2
Biomass conversion	Thermocatalytic conversion
Biomass gasification	Conversion of biomass into syngas, similar to coal gasification
Biomass reforming	Conversion of liquid biomass (biofuels) into H_2
Biophotolysis	Biological systems (microbes, bacteria, etc.) are used to generate H_2
Dark fermentation	Biological systems are used to generate H_2 in the absence of light
Fossil fuel reforming	Fossil fuels are converted to H_2 and CO_2
Hybrid thermochemical cycles	Electrical and thermal energy are used together to drive cyclical chemical reactions
Photo-catalysis	Water is split into H_2 and O_2 by using the electron-hole pair generated by the photocatalyst
Photoelectrochemical method	A hybrid cell simultaneously produces current and voltage upon absorption of light
Photoelectrolysis	Photoelectrodes and external electricity are used to drive water electrolysis
Photofermentation	Fermentation process activated by exposure to light
Plasma arc decomposition	Cleaned natural gas is passed through plasma arc to generate H_2 and carbon soot
Thermolysis	Thermal decomposition of water (steam) at temperatures over 2500 K
Water splitting	Cyclical chemical reactions (net reaction: water splitting into H_2)

Notes
Production methods and corresponding descriptions were reprinted from Dincer, I., & Acar, C. (2015). Review and evaluation of hydrogen production methods for better sustainability. International Journal of Hydrogen Energy, 40(34), 11094–11111.

Appendix D: Shipping Routes

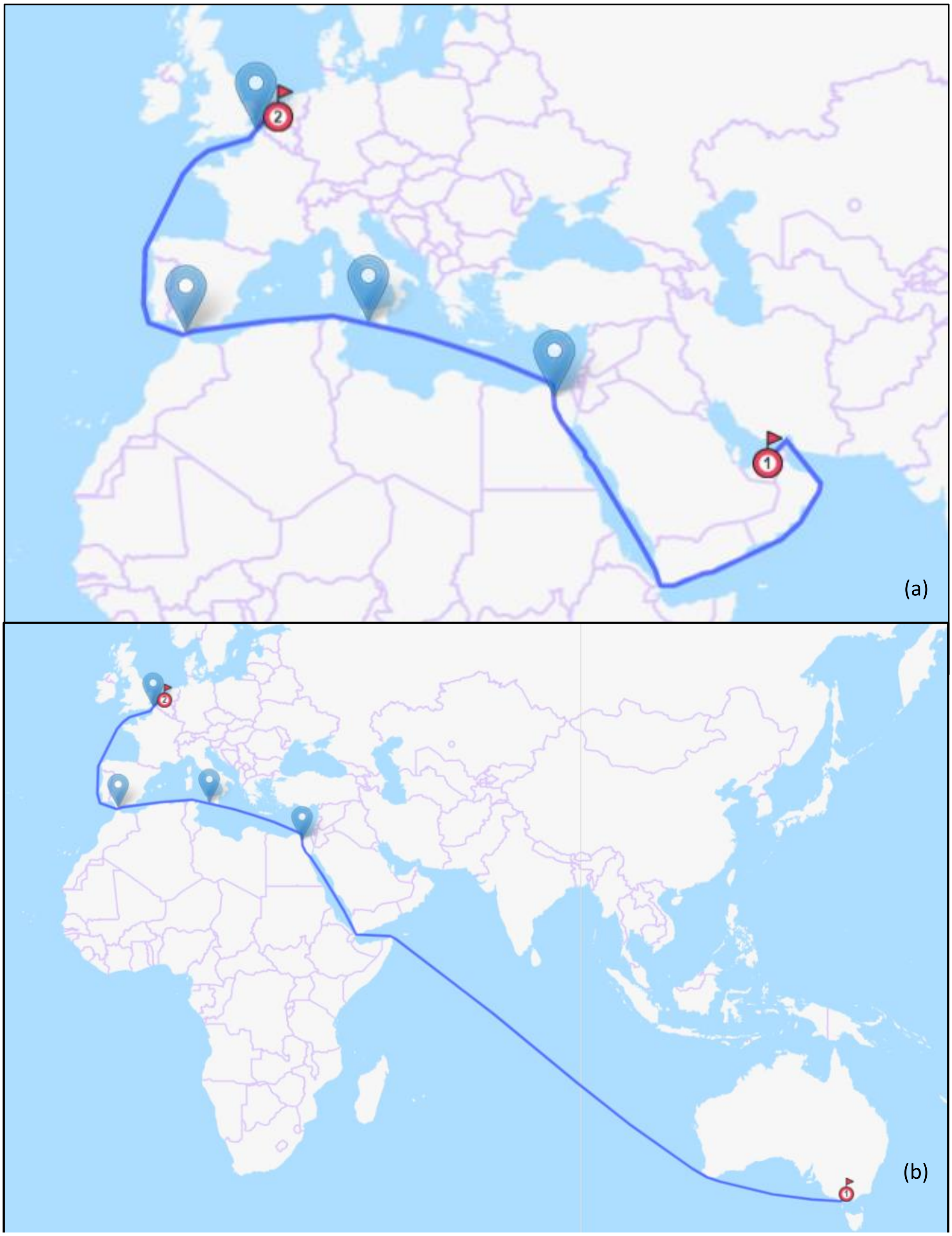

Figure D1. Shipping routes from the United Arab Emirates (a) and Melbourne, Australia (b) to the port of Rotterdam (SeaRoutes, 2019)

(a) Shipping distance from 1 Abu Dhabi, United Arab Emirates to 2 Rotterdam, the Netherlands - 11600 km

(b) Shipping distance from 1 Gladstone, Australia to 2 Rotterdam, the Netherlands - 20600 km

Appendix E: Uncertainty analysis results

This appendix shows the results for variation of the individual underlying factors on the LCOH of the different pathways. The X-axis shows the varied factor and its variation. On the Y-axis, the resulting LCOH values are shown for the different pathways.

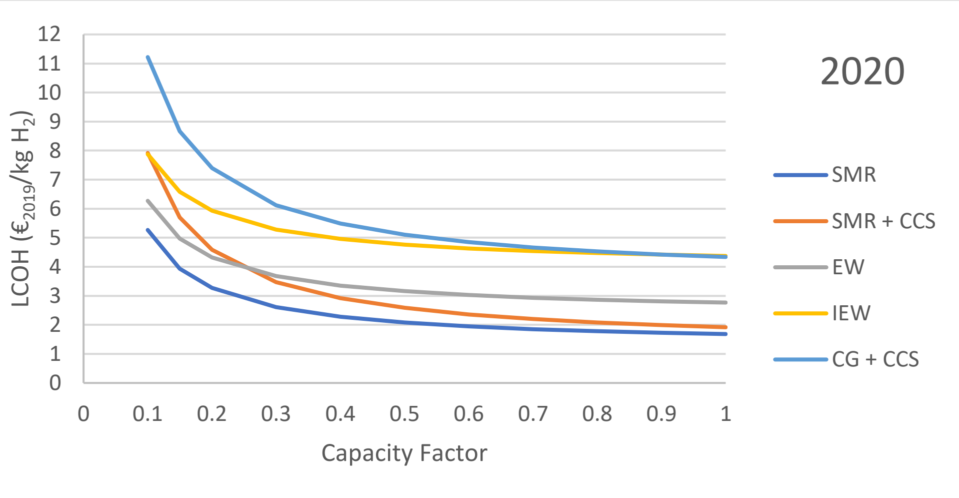

Figure E 1. Effect of variation of the capacity factor on the calculated LCOH values of the different pathways for 2020

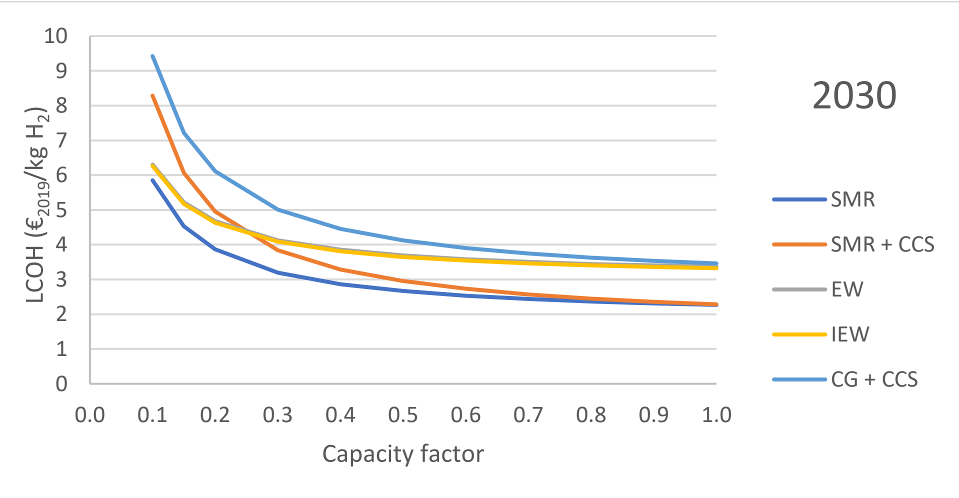

Figure E 2. Effect of variation of the capacity factor on the calculated LCOH values of the different pathways for 2030

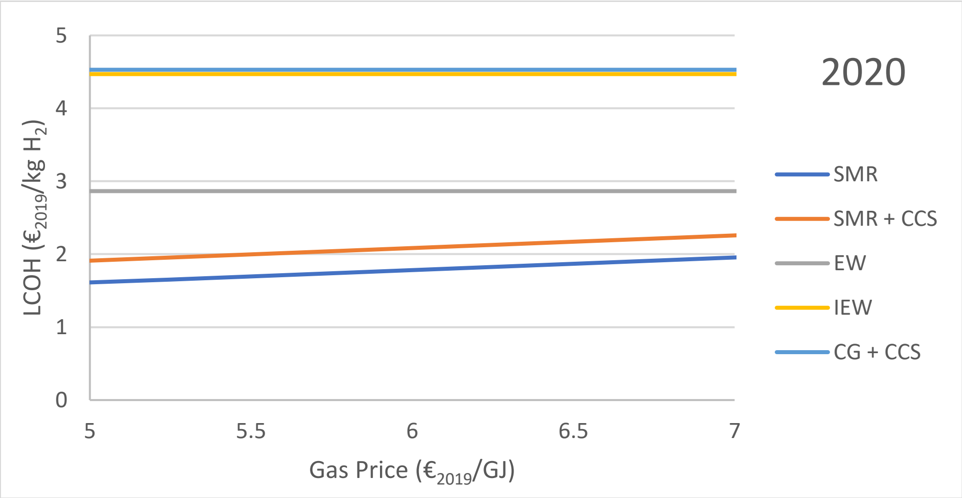

Figure E 3. Effect of variation of the gas price on the calculated LCOH values of the different pathways for 2020

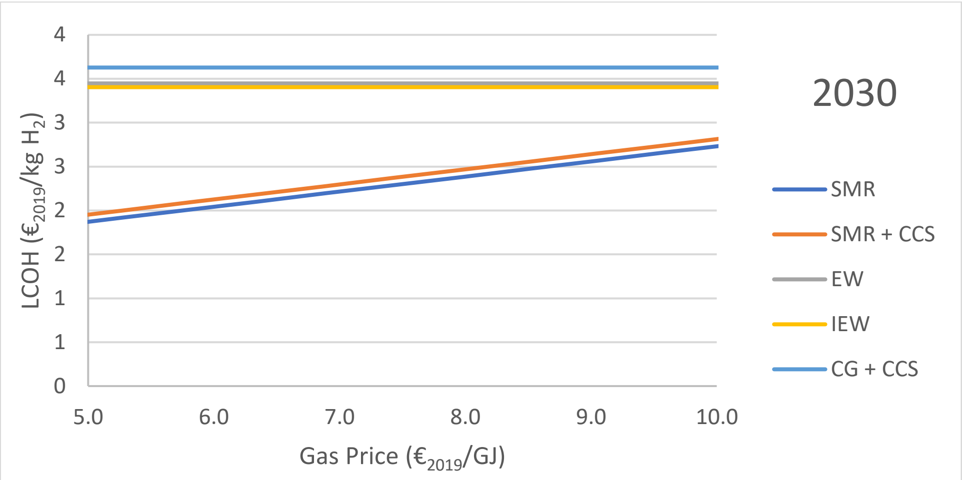

Figure E 4. Effect of variation of the gas price on the calculated LCOH values of the different pathways for 2030

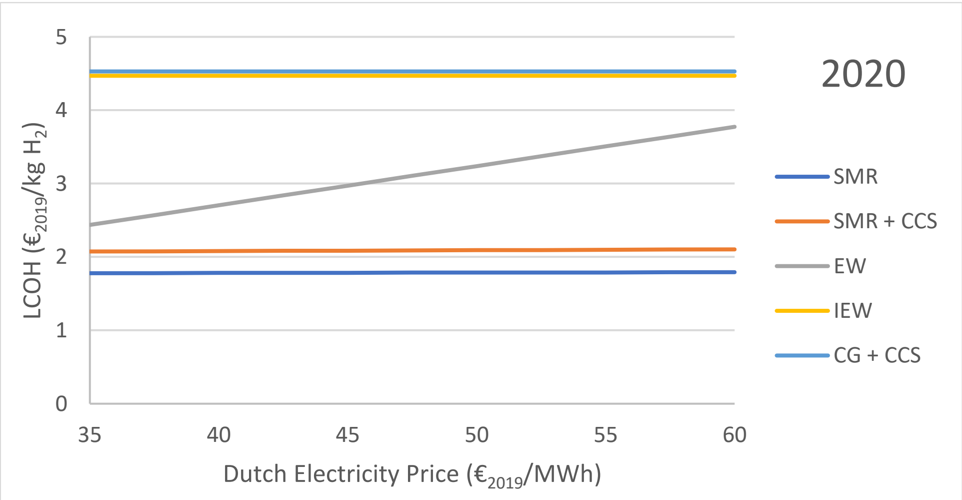

Figure E 5. Effect of variation of the Dutch electricity price on the calculated LCOH values of the different pathways for 2020

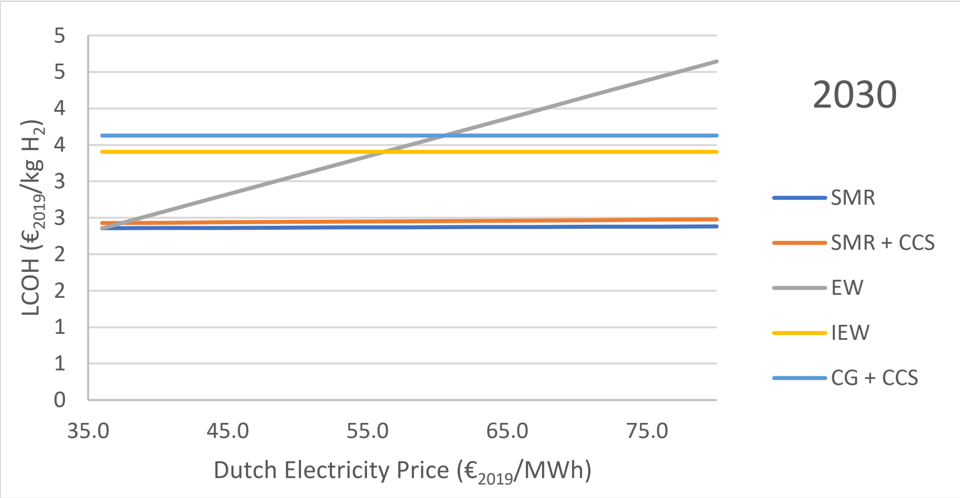

Figure E 6. Effect of variation of the Dutch electricity price on the calculated LCOH values of the different pathways for 2030

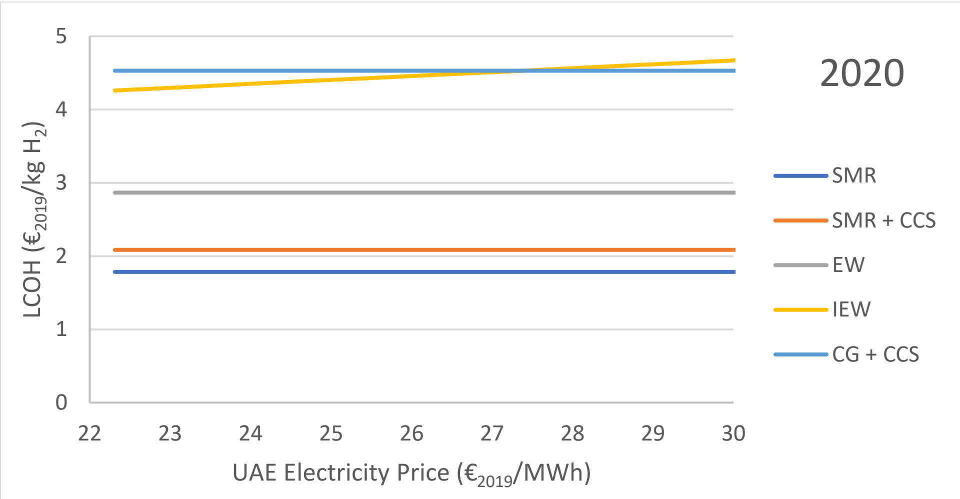

Figure E 7. Effect of variation of the UAE renewable electricity price on the calculated LCOH values of the different pathways for 2020

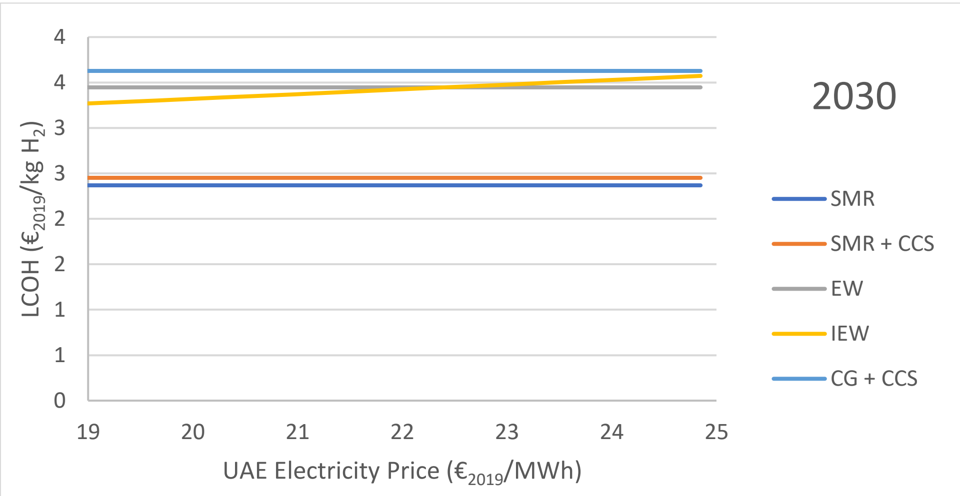

Figure E 8. Effect of variation of the UAE renewable electricity price on the calculated LCOH values of the different pathways for 2030

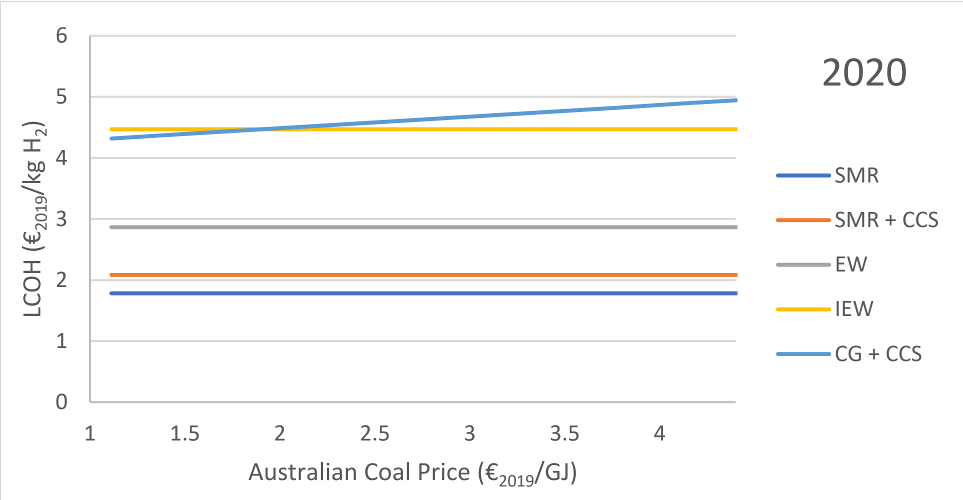

Figure E 9. Effect of variation of the Australian coal price on the calculated LCOH values of the different pathways for 2020

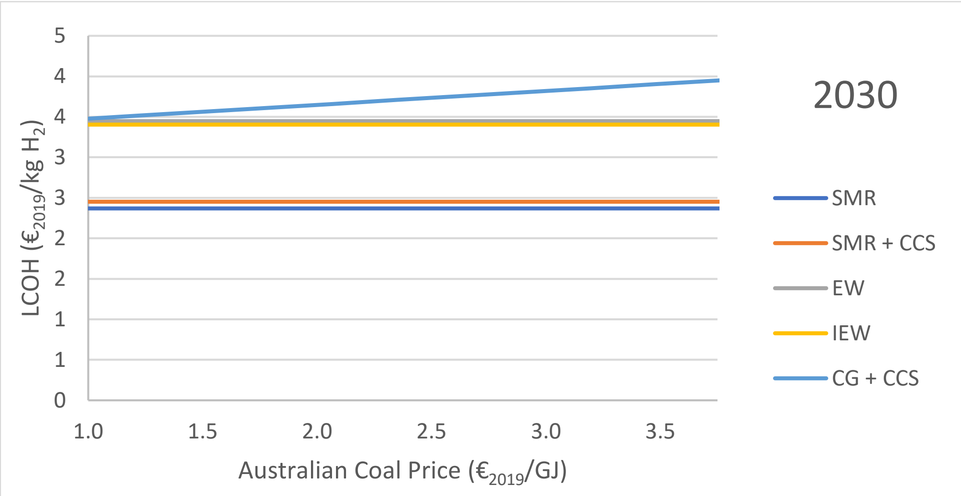

Figure E 10. Effect of variation of the Australian coal price on the calculated LCOH values of the different pathways for 2030

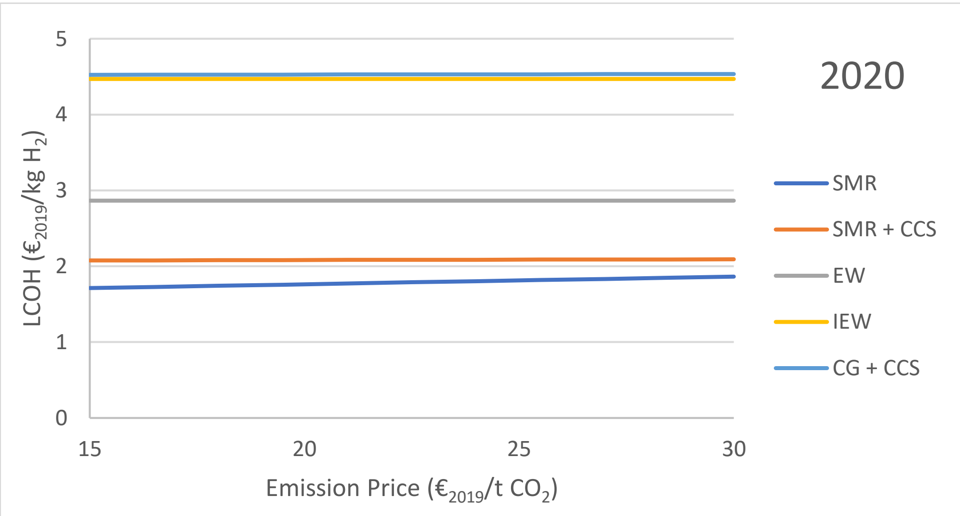

Figure E 11. Effect of variation of the CO_2 emission price on the calculated LCOH values of the different pathways for 2020

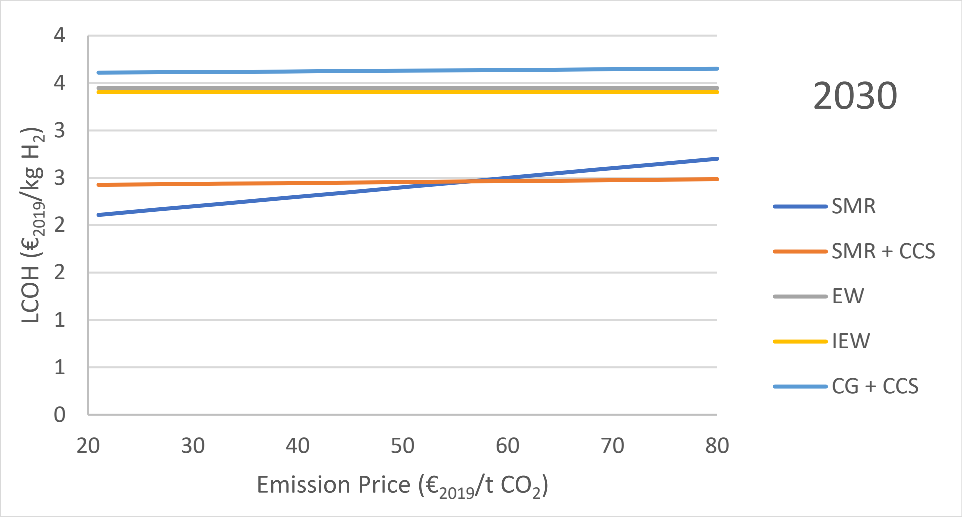

Figure E 12. Effect of variation of the CO_2 emission price on the calculated LCOH values of the different pathways for 2030

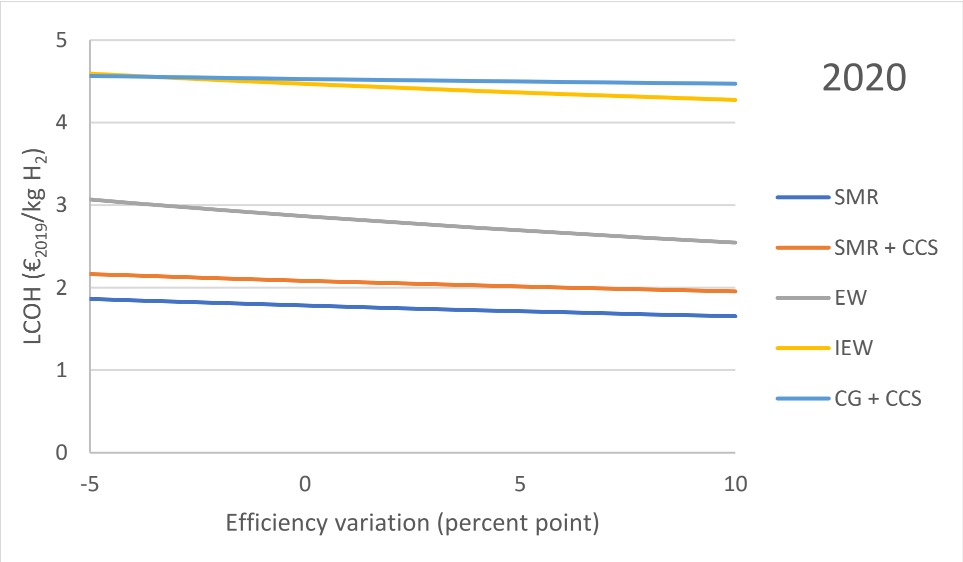

Figure E 13. Effect of variation of the efficiency on the calculated LCOH values of the different pathways for 2020

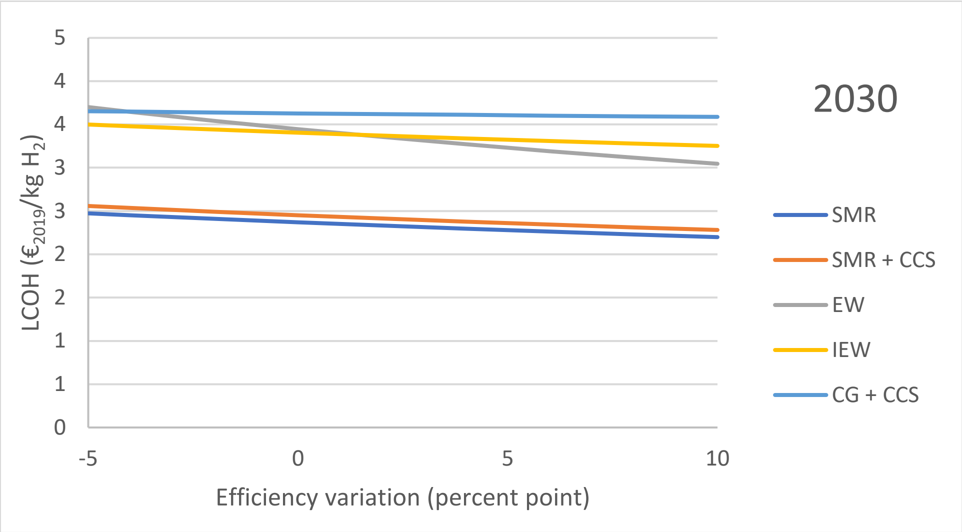

Figure E 14. Effect of variation of the efficiency on the calculated LCOH values of the different pathways for 2030

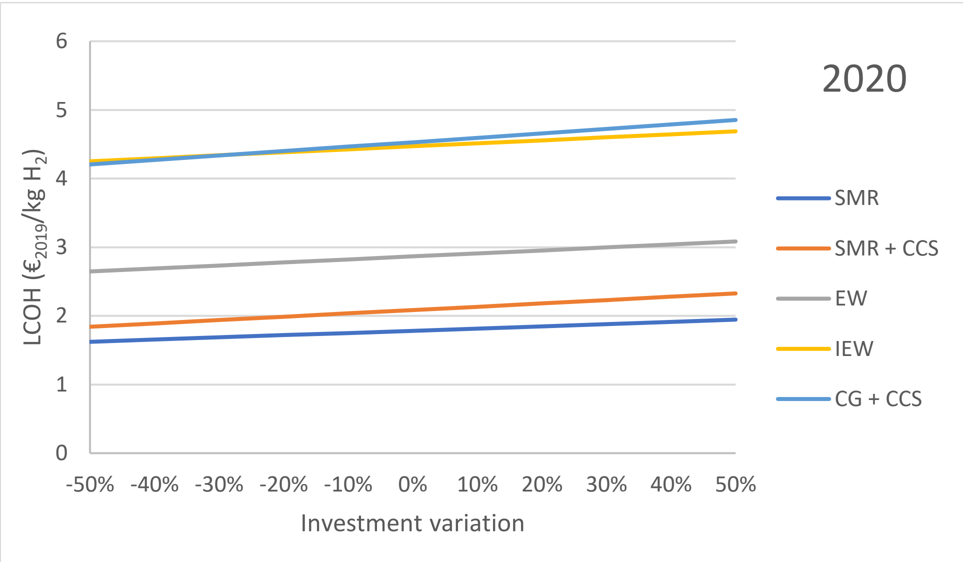

Figure E 15. Effect of variation of the investment costs on the calculated LCOH values of the different pathways for 2020

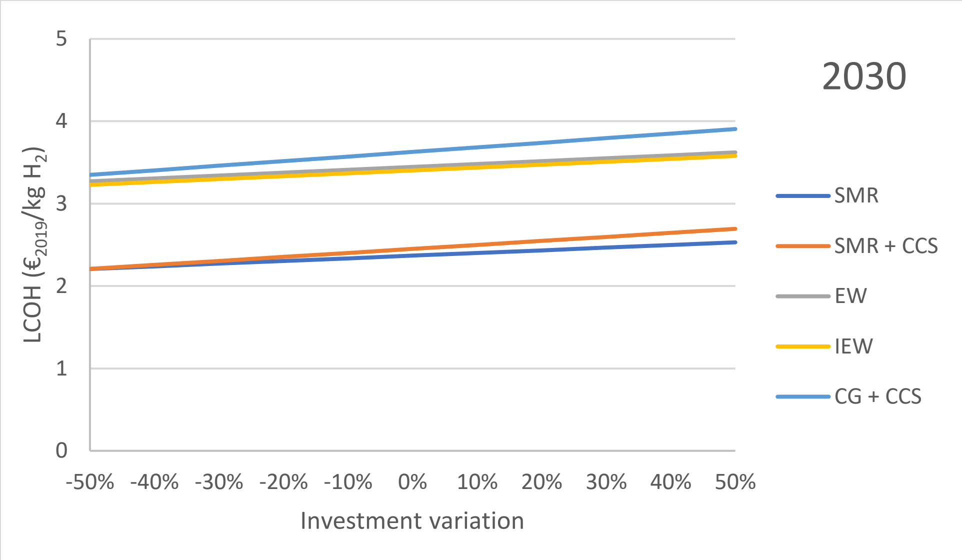

Figure E 16. Effect of variation of the investment costs on the calculated LCOH values of the different pathways for 2030

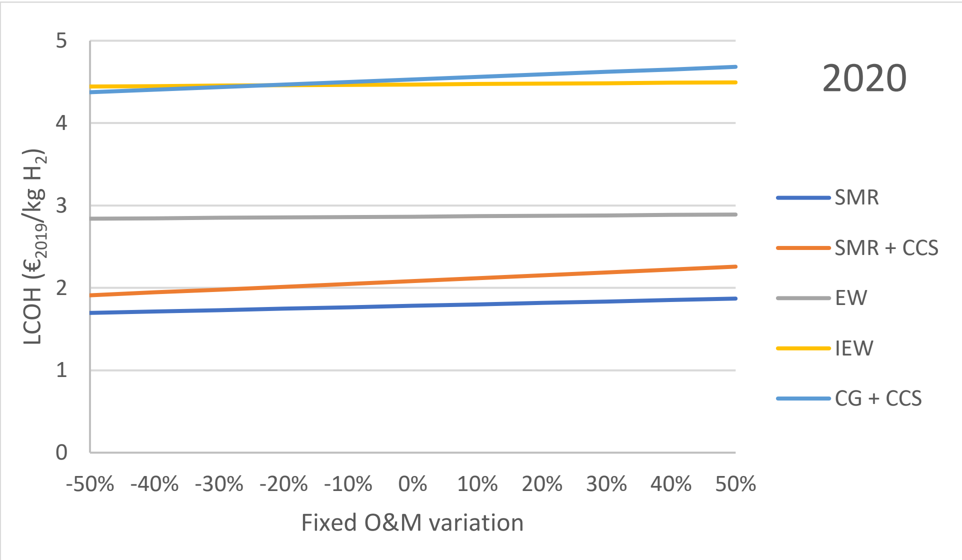

Figure E 17. Effect of variation of the fixed O&M costs on the calculated LCOH values of the different pathways for 2020

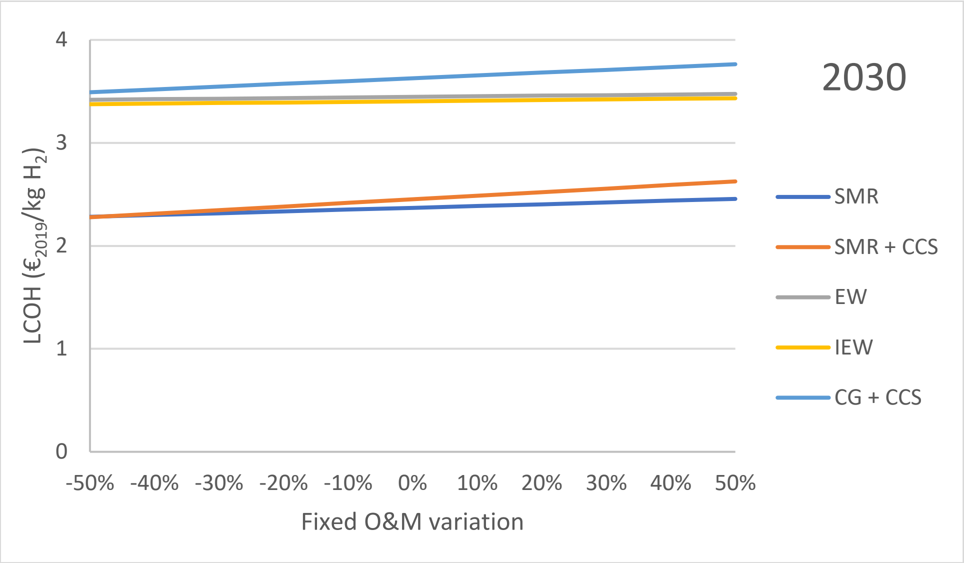

Figure E 18. Effect of variation of the variable O&M costs on the calculated LCOH values of the different pathways for 2030

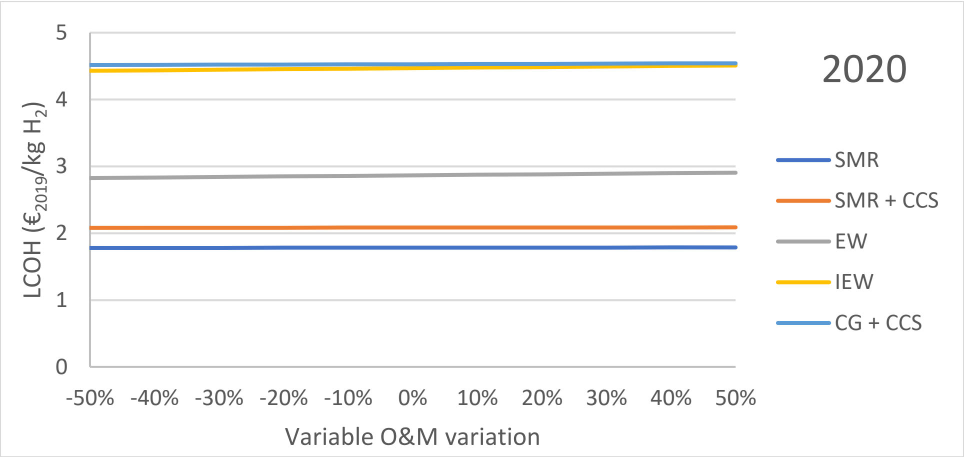

Figure E 19. Effect of variation of the variable O&M costs on the calculated LCOH values of the different pathways for 2020

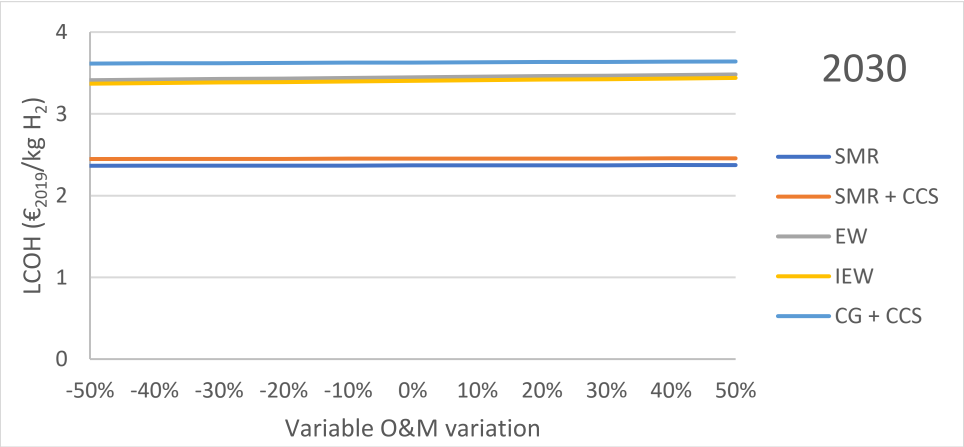

Figure E 20. Effect of variation of the fixed O&M costs on the calculated LCOH values of the different pathways for 2030

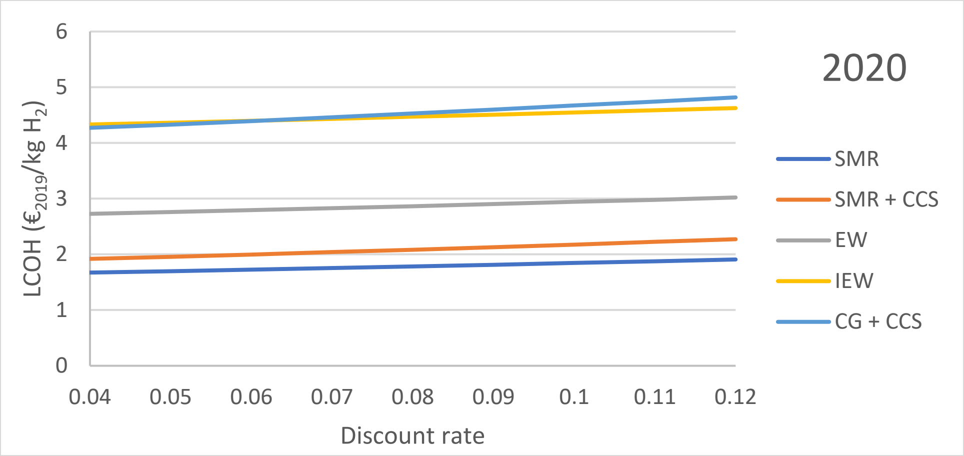

Figure E 21. Effect of variation of the discount rate on the calculated LCOH values of the different pathways for 2020

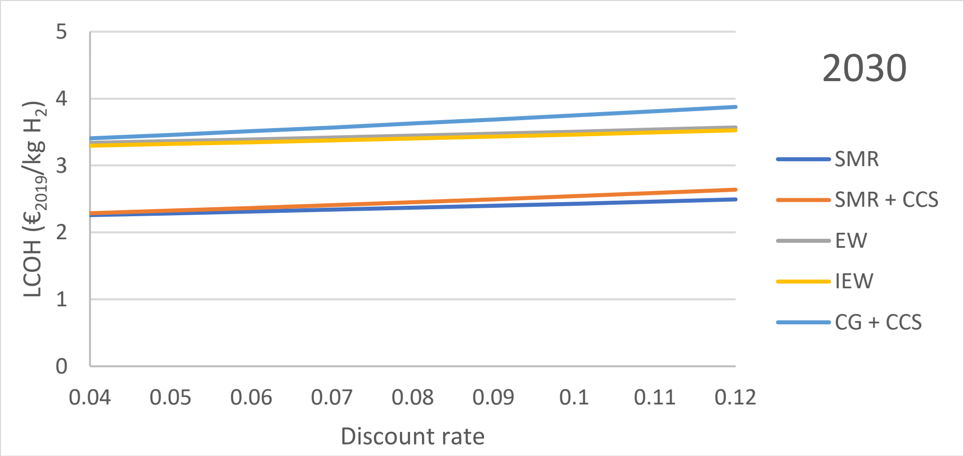

Figure E 22. Effect of variation of the discount rate on the calculated LCOH values of the different pathways for 2030

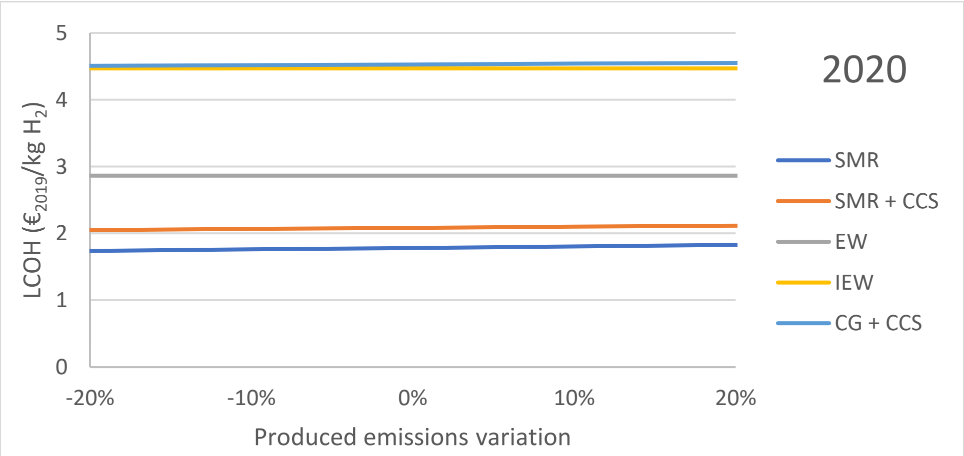

Figure E 23. Effect of variation of the produced CO_2 emissions on the calculated LCOH values of the different pathways for 2020

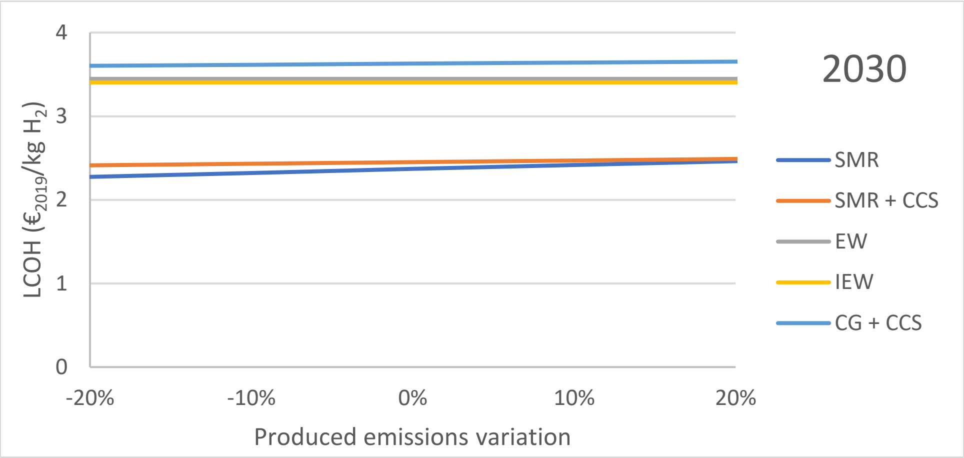

Figure E 24. Effect of variation of the produced CO_2 emissions on the calculated LCOH values of the different pathways for 2030

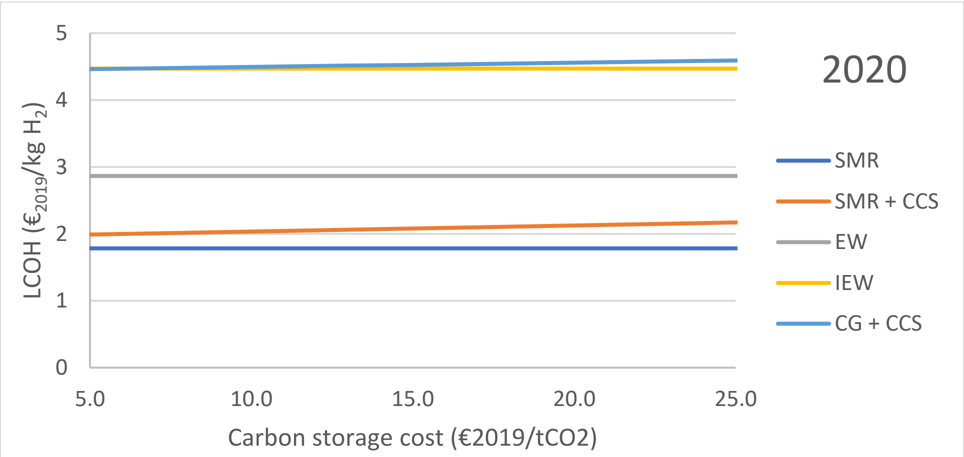

Figure E 25. Effect of variation of the carbon storage costs on the calculated LCOH values of the different pathways for 2020

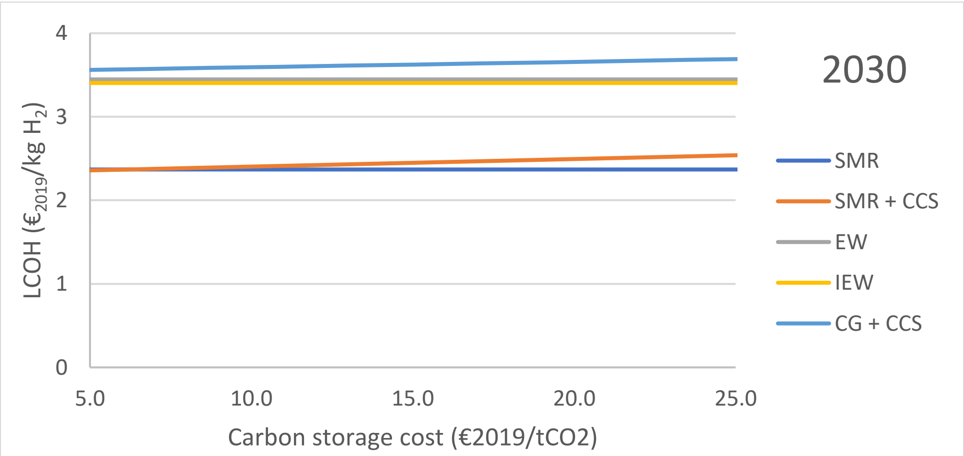

Figure E 26. Effect of variation of the carbon storage costs on the calculated LCOH values of the different pathways for 2030

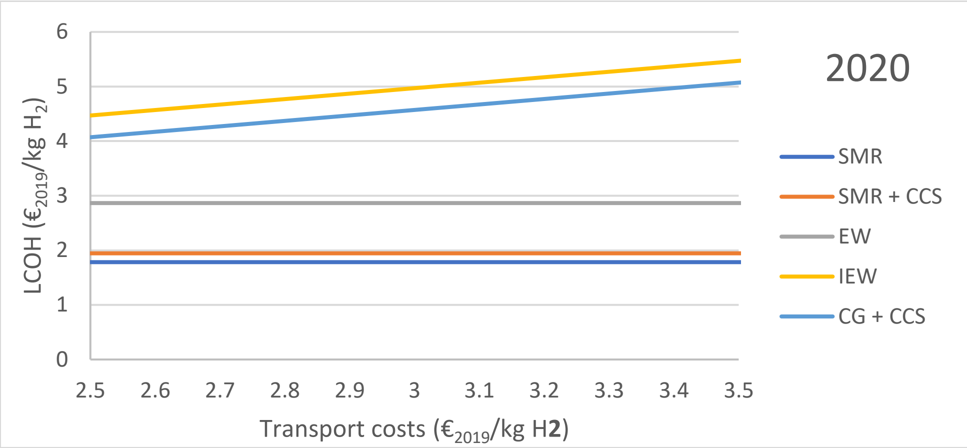

Figure E 27. Effect of variation of the transport costs on the calculated LCOH values of the different pathways for 2020

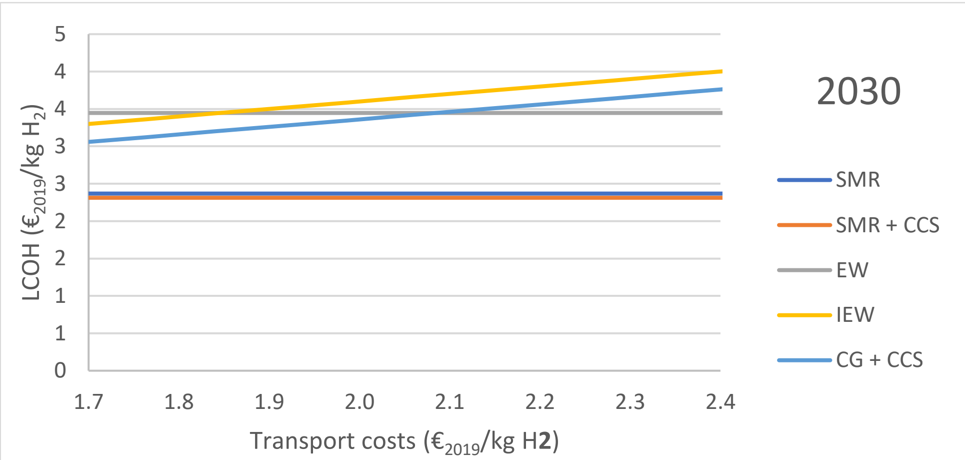

Figure E 28. Effect of variation of the transport costs on the calculated LCOH values of the different pathways for 2030