International competitiveness of low-carbon hydrogen supply to the Northwest European market

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HIGHLIGHTS

- The competitiveness of hydrogen supply depends on production and transport costs.
- At historical gas prices, hydrogen produced by SMR with CCS is most competitive.
- With higher gas prices, import of renewable hydrogen is favourable.
- Import is also competitive when electrolysis is less capital intensive.

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ABSTRACT

This paper analyses which sources of low-carbon hydrogen for the Northwest European market are most competitive, taking into account costs of local production, conversion and transport. Production costs of electrolysis are strongly affected by local renewable electricity costs and capacity factors. Transport costs are the lowest by pipelines for distances under 10,000 km, with costs linearly increasing with distance. For larger distances, transport as ammonia is more efficient, with less relation to distance, despite higher conversion costs. The most competitive low-carbon hydrogen supply to the Northwest European market appears to be local Steam Methane Reforming with Carbon Capture and Storage when international gas prices return back to historical levels. When gas prices, however, remain high, then import from Morocco with electrolysis directly connected to offshore wind generation is found to be the most competitive source of low-carbon hydrogen. These conclusions are robust for various assumptions on costs and capacity factors.

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Introduction

Governments are increasingly promoting hydrogen with low carbon emissions to reach climate policy objectives. The ambition of the European Commission is to gradually deploy low-carbon hydrogen, starting in the industrial and mobility sector, to help reaching climate neutrality in 2050 [1]. This low-carbon hydrogen will be produced either through electrolysis using renewable electricity, or with fossil fuels, through Steam Methane Reforming (SMR), combined with Carbon Capturing and Storage (CCS) technology. In addition to the European ambitions, several EU Member States have presented their national long-term strategies in which they attribute an important role to low-carbon hydrogen to reduce domestic CO₂ emissions (EZK, 2019; [2,3].

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Because of these ambitions, the question is where the required large amounts of low-carbon hydrogen can be produced. Although there are plans for electrolysis production within Europe, research has shown that high local electricity prices make this relatively expensive [4,5]. The production of low-carbon hydrogen with CCS technology seems to be more price-competitive [6], but it still depends on fossil fuels while it is also constrained by the availability of carbon storage facilities. Given these limitations of European supply, other sources of low-carbon hydrogen supply may form efficient alternatives [7,8].

To determine the potential of alternative sources, local conditions for production have to be analysed. One of the crucial economic conditions behind the unit costs of electrolysis hydrogen are the costs of electricity [9]. Hence, regions with more favourable conditions for renewable electricity production have, ceteris paribus, lower costs for electrolysis hydrogen. It appears that the long-term unit costs of hydrogen production with renewable electricity varies in a wide-range due to location specific conditions [10–14].

Although hydrogen production can become more competitive in regions with more favourable conditions for renewable electricity production, the costs of transportation to the end-user have also to be taken into account [15]. Hydrogen transport can be done in various ways and the efficiency of these methods depend on both the transported quantity per period and the distance. For the transport of large volumes, pipelines and liquefied hydrogen per ship are currently seen as most efficient [16–18]. A relatively new, but potentially efficient hydrogen transport method is using liquid ammonia as a hydrogen carrier, where the ammonia contains 50% more hydrogen per unit of volume than liquid hydrogen [19,20].

The main question this paper addresses is: to which extent is the combination of low-carbon hydrogen production at a favourable location with the most efficient transport method able to compete with low-carbon hydrogen production in Northwest Europe? The main contribution of this paper is that, in contrast to others, we focus on the combination of the costs of producing hydrogen in various locations with the costs of transport to the Northwest European market. The paper also contributes to the broader literature on the relationship between location specific factors and hydrogen production by estimating the influence of renewable electricity potential and transportation circumstances on hydrogen supply costs. Using data on production circumstances in several regions as well as data on transport technologies and routes, an international merit-order of hydrogen supply is constructed to determine the competitiveness of low-carbon hydrogen supply from selected locations compared to production in Northwest Europe.

It appears that the production costs of hydrogen using renewable electricity are the lowest in Morocco. The costs of hydrogen transport costs increase strongly with distance, with pipeline transport generally being most suitable for distances below 10,000 km. For the larger distances, transport as ammonia was found to be the most competitive transportation method. For the supply of low carbon hydrogen, hydrogen produced locally through SMR with CCS is estimated as most competitive, with moderate natural gas prices, or gas prices returning to historical levels. If one only considers electrolysis based on renewable electricity, supply from Morocco is less expensive than local production in Europe. When gas prices, however, remain high, then importing from Morocco with electrolysis directly connected to offshore wind generation is found to be the most competitive source of low-carbon hydrogen. Moreover, import of hydrogen is also competitive when electrolysis becomes less capital intensive because of lower investments or higher capacity factors.

The paper is structured as follows. Section 2 gives an overview of the current literature on low-carbon hydrogen production and transport and describes how this paper contributes to this literature. In Section 3, the methodology to determine the international merit order is described, including data description. Section 4 presents the results, while it also includes a sensitivity analysis. Finally, Section 5 concludes with the main findings of this work and features to be covered in following work.

Literature review

The studies that investigate the economic feasibility of the supply of low-carbon hydrogen can be classified into four main categories: 1) studies that focus on the comparison of different production techniques and their energy inputs, 2) studies with a focus on economic and spatial conditions affecting hydrogen electrolysis production, 3) studies that analyse and compare the most suitable form of hydrogen transport and 4) studies that examine the feasibility of import of low-carbon hydrogen from other regions. The contribution of this paper is the integration of these four aspects in order to determine the supply costs of various alternative sources of low-carbon hydrogen to the Northwest European market.

Literature on the comparison of low-carbon hydrogen production techniques concentrate on both the levelized production costs and the social and technical feasibility. For all production techniques, the levelized production costs depend on feedstock prices, resource availability and the presence of policy support [21]. With the historical feedstock prices, it is found that hydrogen production with the use of fossil fuels and CCS technology is more cost-competitive than hydrogen production with the use of renewable electricity, with production costs in the ranges of 2.2–3.4 and 2.5–5.5 €/kg, respectively [6,21,22]. As energy prices have risen strongly since these studies were published, this paper assesses the production costs using (much) higher prices of natural gas in order to reflect current market circumstances.

Although CO2 transport and storage are practised for years, it is still debated due to environmental concerns and the need for robust economic support (e.g. Ref. [23]). Similarly, the economic feasibility of hydrogen production by electrolysis with renewable electricity is found to have multiple difficulties, including high costs and limited feedstock availability [6]; Moriarty & Honnery, 2007). It is argued that the European potential of renewable electricity is enough to cover existing electricity demand as well as the electricity needed to produce current hydrogen demand with electrolysis [24]. This paper also focuses on the costs of using renewable electricity, assuming that these costs are only related to the costs of
renewable generation technologies and not to the (scarcity) circumstances in the electricity market which may result in (much) higher electricity prices.

The availability of renewable energy together and corresponding costs belong to the focal points of studies that investigate the effect of economic and spatial conditions for electrolysis. Literature on hydrogen production based on renewable electricity shows that the most important factors influencing the levelized production costs are capital expenditures, the utilisation of the production facility, and electricity costs [9,11,25]. The capital expenditures per unit decrease with the size of an electrolysis plant as an increase in the size is matched with an increase in technical and economic performance [25]. In this paper, it is assumed that large-scale hydrogen production by electrolysis benefits from economies of scale, while there is no constraint on the availability of (local) renewable-electricity capacity.

As the capacity factor of renewable electricity, i.e. the utilisation of the installed capacity, is influenced by spatial conditions, such as geographical situations, solar irradiance and wind speed, many studies have focused on optimizing electrolyser location based on higher availability of renewable energy and hence potential higher utilisation and lower electricity costs. The consensus of these studies is that hydrogen production with the use of renewable electricity is most efficient in locations where there are low levelized costs and high capacity factors of renewable electricity [10,12,14]. This study, therefore, analyses the costs of producing hydrogen for various locations which have favourable natural circumstances.

These locations with a good suitability for hydrogen production are not necessarily demand centres for hydrogen as well, which creates the need for hydrogen transportation. Given the fact that hydrogen has a low volumetric density at standard temperatures and pressures, it must be converted into a higher density form in order to be economically feasible for transportation [26]. This can be achieved by converting hydrogen to a compressed gas, a cryogenic liquid or by attaching the hydrogen to a carrier such as metal hydride or ammonia, which incurs extra energy cost of conversion, as well as, reconversion [27,28]. These various forms of converting are included in our study in order to determine the most competitive supply of low-carbon hydrogen.

The most economic form of these hydrogen transportation methods is determined by multiple factors such as scale, distance between production and consumption locations, and the spatial and physical characteristics of this distance. For all forms of hydrogen transportation, the major share of costs are capital costs, where for gaseous pipeline transport, the capital costs are linearly related to the distance. In contrast, transport costs of liquid hydrogen or ammonia are mostly determined by the (re)conversion, rather than distance [29,30]. This study includes these various forms of transportation.

In the literature, there seems to be an agreement that for large scale onshore transport, compressed gas pipeline delivery is the most suitable option, whereas large scale offshore transport favours liquid over gaseous hydrogen transportation by ship [26,29,31,32]. Although liquid hydrogen is favoured over compressed gas for offshore transportation, the comparison to ammonia transport is less clear-cut. On the one hand, (re)conversion to ammonia is more costly compared to liquefaction, but on the other hand, the volumetric hydrogen density in ammonia is 45% higher than that of liquid hydrogen and needs less energy input for cooling [22,33]. This means that, compared to liquid hydrogen transport, ammonia transport has higher upfront costs, where the costs for shipment per distance are lower, indicating that larger distances favour ammonia transport. In this paper, all these options are included in order to have a complete picture of the alternative sources of low-carbon hydrogen to the Northwest-European market.

Some studies combine the levelized costs of both production and transport from a potential promising production area to a potential demand area. This is, for instance, done for the supply of low-carbon hydrogen from Patagonia to the potential demand centre Japan. Results of this supply route show that the supply of hydrogen in liquid form or as ammonia can be feasible, with supply costs of 4.40 €/kg, or a positive net present value in an optimized setting [15,34]. For the supply of hydrogen to Europe, it is found that hydrogen supply from locations with relative low-cost renewable electricity production with onshore pipeline transport can be economically feasible, with levelized costs of hydrogen supply to central Europe of 59–123 €/MWh (i.e. 1.97 to 4.10 €/kg)\(^1\) [8]. The contribution of this paper is that it includes more potential production locations and transportation modes to the Northwest-European market, while it also uses more recent data on costs and efficiency parameters.

### Construction of an international merit-order of low-carbon hydrogen supply

The assessment of supply routes of low-carbon hydrogen to the demand centre in Northwest Europe refers to both production in and transport from a selected region. In this paper, an optimal supply route is based on the best possible combination of the two aspects for each region. Therefore, the methodology to calculate the levelized costs of hydrogen supply routes consists of three steps: 1) calculating the levelized costs of hydrogen production in the region, 2) calculating the levelized costs of transporting that hydrogen from the region to the port of Rotterdam, and 3) combine the first two, taking into account the opportunity costs of hydrogen losses during transport, to obtain the levelized costs of hydrogen supply.

### Levelized costs of hydrogen production

#### Model

For the production of low-carbon hydrogen, both Polymer Electrolyte Membrane (PEM) electrolysis technology with renewable electricity, as well as Steam Methane Reforming (SMR) with CCS technology is considered. The selection of PEM technology, rather than other existing electrolysis technologies, such as alkaline, anion exchange membrane (AEM) and solid oxide (SOEC), is based on its short ramp up time and technology readiness [35]. For both technologies, the levelized costs of hydrogen production include the capital costs, where for gaseous pipeline transport, the capital costs are linearly related to the distance. In contrast, transport costs of liquid hydrogen or ammonia are mostly determined by the (re)conversion, rather than distance [29,30]. This study includes these various forms of transportation.

1 Assuming a LHV of hydrogen of 33.33 kWh/kg.
costs of production are defined as the present value of all costs divided by the present value (PV) of hydrogen production during the lifespan of a production plant (eq. (1)).

$$\text{LCOHP}_i = \frac{\text{PV} \left( HPC_{i}^x \right)}{\text{PV} \left( Q_x \right)} = \frac{\sum_{t=1}^{T} \text{HPC}_{i}^x \left( V_{i}^{*} \right)}{\sum_{t=1}^{T} \text{Q}_x}$$  \hspace{1cm} (1)$$

where LCOHP$^i$ is the levelized costs of hydrogen production for method $x$, in region $i$, $T$ is the total lifespan, $HPC_{i}^x$ are the total hydrogen production costs for method $x$, in region $i$ and year $t$, in € and $Q_x^*$ is the produced quantity of hydrogen by production method $x$ in region $i$ and year $t$, in kg. The quantity of hydrogen that is produced is calculated as shown in equation (2).

$$Q_x^* = \frac{S_i^{*} * h_i^{*} * H_{V_i}^{*} * 1000}{\text{LHV}}$$  \hspace{1cm} (2)$$

where $S_i^*$ is the installed capacity of the production plant of type $x$ in region $i$ in MW of energy input, $h$ depicts the operating hours of that plant in year $t$, $\eta$ is the efficiency of the plant and LHV is the lower heating value of hydrogen (33.33 kWh/kg).

The composition of the total hydrogen production costs for both the technologies consists of three distinct parts. First, there are the fixed costs of capital and operational expenditures, dependent on the installed capacity of the production plant. These costs are related to the plant size, rather than actual production output. Second, there are the costs of the energy input, which depend on the unit costs of the energy input, size and operating hours of the plant. For electrolysis, the unit cost of energy input is the cost of renewable electricity price for the electrolyser operator is equal to the electricity costs and the production output. As a consequence, both the electricity costs and the number of operating hours of the electrolyser are based on the renewable power generator. Hence, the number of operating hours of the electrolyser are similar to the number of hours of renewable power production (i.e. its capacity factor) and the electricity price for the electrolysis operator is equal to the levelized costs of energy (LCOE) of that renewable power plant.

In this paper, the second situation, where the electrolyser is directly coupled to the renewable power generator, is assumed. The reason for this is that in some regions there is a lack of well-functioning electricity and certificate markets, whilst it is also difficult to assess what the impact on GHG is, i.e. whether there is a direct increase of green electricity production. As a consequence, both the electricity costs and the number of operating hours of the electrolyser are based on the renewable power generator. Hence, the number of operating hours of the electrolyser are similar to the number of hours of renewable power production (i.e. its capacity factor) and the electricity price for the electrolysis operator is equal to the levelized costs of energy (LCOE) of that renewable power plant.

For all regions in consideration, this paper analyses the use of four different renewable electricity production techniques,

### Table 1 – Operating hours and lower heating value efficiency electrolyser. Own assumptions based on [36].

<table>
<thead>
<tr>
<th>Number of operating hours per year</th>
<th>Assumed lower heating value efficiency electrolyser</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3000</td>
<td>0.65%</td>
</tr>
<tr>
<td>≥3000 and &lt;7000</td>
<td>0.7%</td>
</tr>
<tr>
<td>≥7000</td>
<td>0.75%</td>
</tr>
</tbody>
</table>
when feasible; wind turbines on- and off-shore, industrial sized solar PV and solar CSP. Data on capacity factors, technical and financial parameters used to calculate the LCOE per technique per country can be found in Appendices A.7, B.2 and B.3. The calculated LCOE of the different renewable energy sources for the selected regions, depicted in Fig. 1, show that the most suitable renewable electricity source and its corresponding price varies among regions. All feasible techniques for each region are assessed and used to calculate the corresponding LCOHP. Given that this paper searches for the optimal LCOHP, it only shows the most optimal renewable electricity source per region for the remainder of this paper.

Location specific factors for SMR with CCS

When producing hydrogen with the SMR-technique, the location specific inputs that influence the LCOHP are the costs of natural gas, the carbon costs and the number of operating hours. Given that natural gas markets are global well-functioning markets [37], it may be assumed that the availability of natural gas is not a limitation for the operating hours of the SMR plant and, hence, the producer can optimize the operating hours. Similarly, since natural gas markets are liquid and transparent, the expected costs of natural gas for a SMR-plant operator are depicted by the future wholesale prices for natural gas in that region.

The costs of carbon consist of two components. On the one hand, a producer is obliged to buy allowances for the emissions of carbon by his plant in an emission trading system (ETS). An ETS is a market-based instrument to incorporate the costs of the negative externality of carbon emission in the production costs of the emitting entity. On the other hand, the SMR plant captures carbon dioxide from the process through the CCS installation. The transport and storage of that CO₂ comes with an associated cost that is region specific. One of the determining elements of those costs is the availability of storage facilities. All the assumptions regarding country specific inputs for the SMR technique can be found in Appendix B.

Levelized costs of hydrogen transport

Model

The levelized costs of hydrogen transport in €/kg to the port of Rotterdam from region \( i \) is calculated as the minimal levelized costs of three transport methods: by pipeline, by ship in liquid form, and as ammonia by ship in equation (5).

\[
LCOHT_i = \min \left\{ LCOHT^{pipe}_i, LCOHT^{liquid}_i, LCOHT^{amm}_i \right\}
\]

where \( LCOHT^{pipe}_i \) are levelized costs of hydrogen transport via pipeline from region \( i \) in €/kg \( H_2 \), \( LCOHT^{liquid}_i \) are levelized costs of hydrogen transport via ship in liquid form from region \( i \) in €/kg \( H_2 \), and \( LCOHT^{amm}_i \) are levelized costs of hydrogen transport via ship as ammonia from region \( i \) in €/kg \( H_2 \).

The levelized costs of transport are calculated as the present value of the hydrogen transport costs from region \( i \), divided by the present value of the volume that is delivered in the lifespan of the transport route in equation (6).

\[
LCOHT_x = \frac{PV}{C_0} \frac{HTC_x}{PV} \frac{volume_x}{C_1} = \frac{1}{\left(1 + r\right)^T} \sum_{t=1}^{T} \frac{HTC_x}{volume_x} \frac{volumex}{C_1}
\]

where \( T \) is the total lifespan, \( HTC_x \) are hydrogen transport costs through transport type \( x \), from region \( i \), in year \( t \), in €, and \( volumex \) is the delivered volume through transport type \( x \), from region \( i \), in year \( t \), in kg \( H_2 \), which is calculated as the production from equation (2) minus the losses in the transport chain per transport method, as shown in equation (7).

\[
volumex = \text{production}_x \cdot \left(1 - \gamma\right)
\]

where \( \gamma \) is the hydrogen loss in the total transport chain of transport method \( x \) in percentage of total hydrogen input. The hydrogen transport costs for pipelines are distinguished in onshore and offshore segments, which both come with different costs, and the electricity costs for compression, as can be seen in equation (8).

**Fig. 1** – Levelized cost of renewable energy production, per technique and country. The calculations are based on Appendices A.7, B.2 and B.3.
\[ \text{HTC}_{\text{pipe}}^t = \left( \text{CAPEX}_{\text{on}}^t + \text{OPEX}_{\text{on}}^t \right) \cdot d_{\text{on}}^t + \left( \text{CAPEX}_{\text{off}}^t + \text{OPEX}_{\text{off}}^t \right) \cdot d_{\text{off}}^t \]
\[ + \frac{\text{el}_{\text{pipe}}^t \cdot P_{\text{fuel}}^t}{\text{electricity costs}} \]

For both types of pipelines, CAPEX, are the capital expenditures in year \( t \), in €, OPEX, are the operational expenditures in year \( t \), in €, and \( d \) is the length of the pipeline segment in km. For the electricity costs, \( \text{el}_{\text{pipe}}^t \) is the electricity needed for the flow through the pipe in kWh and \( P_{\text{fuel}}^t \) is the price of electricity in region \( i \) and year \( t \) in €/kWh. For both the transport methods by ship, in liquid form and as ammonia, the structure of the levelized costs of transport is fairly similar, with shipment costs and treatment costs, shown in equations (9) and (10). For transport in liquid form, these are liquefaction costs and for transport as ammonia, these are the conversion costs:

\[ \text{HTC}_{\text{in}}^t = \text{LC}_{\text{in}}^t + \text{SC}_{\text{in}}^t \]
\[ \text{HTC}_{\text{in}}^t = \text{CC}_{\text{in}}^t + \text{SC}_{\text{in}}^{\text{amm}} \]

where \( \text{LC}_{\text{in}}^t \) are the liquefaction costs in € in region \( i \) and year \( t \), \( \text{CC}_{\text{in}}^t \) are the conversion costs in € in region \( i \) and year \( t \), and \( \text{SC}_{\text{in}}^t \) are the shipment costs for transport method \( x \) from region \( i \) in year \( t \). Below we explain the computation of the elements of both transport methods, where again, CAPEX, and OPEX, are the capital and operational expenditures in year \( t \), in €, respectively. The shipment costs are a combination of investment costs for yearly transport capacity and fuel costs, depending on distance and velocity, as can be seen in equations (11) and (12).

\[ \text{SC}_{\text{x}}^t = \frac{\text{CAPEX}_{\text{x}}^{\text{ship.x}} + \text{OPEX}_{\text{x}}^{\text{ship.x}} + \left( \frac{1}{\text{V}_{\text{d}}^{\text{ship.x}} \cdot \text{d}_{\text{ship}}^t \cdot \text{V}_{\text{d}}^t} \right) \cdot \text{N}_{\text{trip.x}}^t}{\text{Fixed costs} \cdot \text{fuel costs}} \]

\[ \text{N}_{\text{trip.x}}^t = \text{N}_{\text{ship.x}}^t \cdot \frac{\text{K}_{\text{ship}}^t}{\text{d}_{\text{trip}}^t \cdot \text{V}_{\text{d}}^t + \text{L}_{\text{ship}}^t} \]

where \( \text{N}_{\text{ship.x}}^t \) is the number of ships needed for a certain capacity of transport method \( x \), \( f_{\text{ship.x}}^t \) is the fuel need of a ship in l/km, \( p_{\text{fuel}}^t \) is the price of the fuel in €/l, \( d_{\text{ship}}^t \) is the distance by ship from region \( i \) to the port of Rotterdam in km, \( \text{V}_{\text{d}}^t \) is the average velocity of the ship in km/h and \( \text{L}_{\text{ship}}^t \) is the loading and unloading time in hours. Liquefaction and conversion costs of the hydrogen in region \( i \), in €, are calculated in equations (13) and (14), respectively.

\[ \text{LC}_{\text{in}}^t = \frac{\text{CAPEX}_{\text{in}}^t + \text{OPEX}_{\text{in}}^t}{\text{Fixed costs} \cdot \text{electricity costs}} \]
\[ \text{CC}_{\text{in}}^t = \frac{\text{CAPEX}_{\text{in}}^{\text{amm}} + \text{OPEX}_{\text{in}}^{\text{amm}}}{\text{Fixed costs} \cdot \text{electricity costs}} \]

where \( \text{el}_{\text{liq}}^t \) is the electricity input for the liquefaction process in kWh, \( \text{el}_{\text{amm}}^t \) is the electricity input for the conversion to ammonia and \( P_{\text{fuel}}^t \) is the price of electricity in region \( i \) and year \( t \) in €/kWh. The costs of converting hydrogen into ammonia includes the costs of the total Haber-Bosch process as well as the costs of air separation.

The non-location specific inputs for the transport of hydrogen refer to capital and operational expenditures, power consumption of compressors, liquefaction and conversion and the fuel consumption, (un)loading time and average speed of ships. In addition, in the analysis it is assumed that the fuel price for ships is equal for all regions, given that this is a global market. Assumptions on all these inputs can be found in Appendix A.

### Location specific factors transport routes

Location specific factors for hydrogen transport include the costs of electricity and the transport distance, either by pipeline or by ship. The costs for electricity per region are calculated in the same manner as for electrolysis as explained in section 3.1.2.

Assumptions for the transport distance towards the port of Rotterdam by pipeline are based on two criteria. First, pipeline transport is mostly done over land since the costs of construction are considerably lower. Secondly, the transport distance is minimized, to ensure a minimization of construction and operating costs, which are both functions of distance.\(^2\) For transport by ship, only the seaborne transport is considered, neglecting the costs of transportation within that region to the port. All assumptions for distances can be found in Appendix B.

### Levelized costs of hydrogen supply

To construct a merit order of hydrogen supply routes to the Northwest European market from different locations, the levelized costs of hydrogen supply from each selected region are calculated as shown in equation (15).

\[ \text{LCOH}_{\text{i}} = \frac{\text{LCOHP}_{\text{i}}}{1} + \text{LCOHT}_{\text{i}} \]

where the levelized costs of hydrogen supply are the combination of levelized costs of production, accounted for the opportunity costs of transporting the hydrogen to Northwest Europe, and the levelized costs of transport. The opportunity costs are the result of the fact that once a producer in region \( i \) decides to transport his hydrogen to Northwest Europe, the hydrogen that is lost in the transportation cannot be sold anymore, but still has to be produced initially.

### Sensitivity analysis

The levelized costs calculation of both production techniques and all three transport methods depend on several assumptions for technical performance and prices. As is shown by the wide variety of inputs and outcomes discussed in the literature review, these assumptions are difficult to precisely estimate as there is a lack of perfect information for all regions, and the future is uncertain as technical developments can lead to other input values. Relevant developments for the production costs include the gas market, renewable electricity

\(^2\) The transport distance over sea by ships is derived from the website https://sea-distances.org/, with the most optimal port of the region as starting point.
production and capital costs of hydrogen production technologies. For hydrogen transport, cost-savings in pipeline transport can be made by refurbishing existing natural gas pipelines, or blending hydrogen in natural gas transport pipelines. While for ammonia transport, additional cost-savings can also be obtained by using the energy as ammonia at destination, avoiding reconversion costs.

To control for these uncertain developments, a sensitivity analysis on those parameters that are less certain is conducted, to construct a range of levelized costs. This sensitivity analysis is performed by constructing two scenarios for the values of the cost components, on top of the baseline assumptions: an ‘innovation’ and ‘stagnation’ scenario. In the ‘innovation’ scenario, it is assumed that the technology has developed, resulting in higher efficiencies and lower costs, whereas in the ‘stagnation’ scenario it is assumed that the development for technologies is stalled, resulting in lower efficiencies and higher costs. In this way, an upper and lower value for the LCOHS of all regions can be determined, with the variety for all assumptions. All values in between construct the range of levelized costs with any given combination of the input variables that are within the boundaries of the scenarios. These ranges are compared to the results of the base assumptions, called ‘base line.’

Next to these ranges based on the different scenarios for the development of technical and economic parameters, this paper analyses the effect of the natural gas price. Natural gas market prices have increased very strongly over the period between July 2021 and September 2022, due to several supply shocks. Import limitations from Russia have in particular caused the European natural gas market price to increase to historically exorbitant levels. To account for these shocks, several demand and supply responses are taken, which makes it not likely for these extreme prices to remain, especially not for a typical lifetime of an SMR plant. However, there is uncertainty about the development of the natural gas prices. Therefore a sensitivity analysis for the future level of the natural gas price is added.

These ranges are created because where several assumptions within a scenario will automatically hold for each region, this does not hold for all the assumptions. For example, when the capital expenditures for an electrolyser system are lower in the innovative scenario, this will hold for each region, as the input is non-country specific. However, the price of renewable electricity for each region can develop differently, with e.g. an innovative scenario in Europe, induced by stringent climate policy, and a stagnation scenario elsewhere, due to a lack of climate policy. Hence, the lower value of the levelized cost ranges depicts a scenario where all values have the assumption associated with the innovative scenario, where the upper value depicts the scenario where all values have the assumption associated with the stagnation scenario. All assumptions for the sensitivity analysis can be found in Appendix C.

Results

The results consist of estimations for the levelized costs of hydrogen production, transport and supply in and from various regions, both through PEM electrolysis and SMR. The paper first focusses on the merit-order of LCOHP in the various regions, with special attention to the breakdown of cost components for the different technologies. Secondly, the focus is on the LCOHT from the different regions to the port of Rotterdam, while identifying the optimal transportation method per region. Third, the LCOHP, the LCOHT of the optimal transport method and the costs of hydrogen loss during transport are combined to construct a merit-order for the LCOHS to the port of Rotterdam. Finally, the results of the performed sensitivity analysis are shown.

Levelized costs of hydrogen production

Fig. 2 depicts the breakdown of the LCOHP of PEM electrolysis for the regions analysed, based on their most efficient renewable energy input. As can be seen, the minimal LCOHP is
found for Morocco, where the most efficient renewable electricity source is wind turbines onshore. The figure also shows that the LCOEP is both dependent on the costs of renewable electricity as well as the utilisation rate of the electrolyser, both influenced by the capacity factor of renewable energy in the region. For example, the lowest fixed costs per unit of hydrogen can be obtained in Rotterdam, where the obtained utilisation rate, based on offshore wind, is the highest. However, the LCOE of this energy source in this region is higher than the LCOE obtained in other regions by other energy sources, making the energy costs per unit of hydrogen the highest. In this case, the beneficial effect of a higher capacity factor (higher utilisation and lower LCOE), does not offset the negative effect of spatial conditions.

Fig. 3 shows the breakdown of the LCOEP for SMR with CCS technology. One can see that, compared to PEM electrolysis, there now is an additional cost of carbon. Given the uniform European natural gas prices in Norway and Rotterdam, one sees that the energy costs are similar. The carbon costs are slightly lower in Norway, given the lower costs of storing carbon, resulting in a lower LCOHP as well (see Fig. 4).

When the LCOHP of both techniques is combined, the merit-order of production per region is obtained, depicted in Fig. 4. Comparing the two techniques, it becomes clear that the high costs of energy for the SMR with CCS technology does lead to a higher LCOHP than for the case of electrolysis production in Morocco. For the other regions, where the energy costs are higher for electrolysis, this does not hold.

**Levelized costs of hydrogen transport**

As described before, the LCOHT determined per region is based on the minimum LCOHT out of three methods for that technique. The LCOHT per method per region is determined...
by multiple factors as energy prices, fixed costs and distance between production location and location of destination. The influence of distance on the LCOHT for the different transport methods, ceteris paribus, is shown in Fig. 5.

As can be seen in Fig. 5, both shipping methods, as liquid hydrogen and ammonia, have high upfront costs independent of distance, related to liquefaction and (re)conversion, respectively. Hence, for smaller distances, transport by pipelines is more efficient than shipping hydrogen. However, as the distance increases, the costs of pipeline transport increase at a faster rate than with the transport as liquid hydrogen or ammonia. This is even more the case when the pipelines are offshore. As can be seen, at a certain distance, there is a change in the most efficient transport method. The exact distance where this ‘tipping point’ occurs differs per production location (energy costs and ratio on- and off-shore pipelines), but generally this is only at large intercontinental distances over 10,000 km.

When applying the country specific information of the regions of interest, the minimalized LCOHT per region from transporting hydrogen to the port of Rotterdam is obtained, depicted in Fig. 6. As becomes clear from the picture, distance is the most important explanatory variable for the merit order of the LCOHT. One can also observe that, as Fig. 5 also suggested, the most efficient transport method changes from pipeline transport to ammonia shipment for the distance over

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**Fig. 5** – Comparison levelized transport costs for different transport methods, dependent on distance between production location and location of destination. The calculations are based on the base line assumptions as specified in Appendices A and B.

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**Fig. 6** – Levelized costs of transport and losses of hydrogen transport to Rotterdam, from various regions. The calculations are based on the base line assumptions as specified in Appendices A and B.
intercontinental distances. In the calculations of this paper, this happens for the transport from Chile and Australia. For the case of Norway, one sees that the LCOHT of the SMR technique is slightly lower than the PEM electrolysis technique, although the transport method is similar. This is due to the higher costs of the hydrogen lost during transport, prompted by the higher LCOHP for that hydrogen production technique.

By combining the LCOHP and LCOHT as in equation (15), the LCOHS to the port of Rotterdam from different regions and by different production techniques is obtained. Ranking all the regions from lowest to the highest LCOHS results in the merit order. Fig. 7 depicts the merit-order of LCOHS of only low-carbon hydrogen from renewable electricity. It shows that, for this technology, importing hydrogen from Morocco is the lowest-cost source of hydrogen for the Northwest European hydrogen market, with an LCOHS of just below 4 €/kg. The costs of the hydrogen transport are more than offset by the more efficient production circumstances if we compare this to the costs of the production of hydrogen by electrolysis in Rotterdam itself. Although spatial conditions for hydrogen production from renewable electricity are relatively favourable in both Australia and Chile, the large distances incur high transport costs, making import to Europe uncompetitive.

Fig. 8 shows the merit-order of low-carbon hydrogen supply to the port of Rotterdam with all production and transport technologies considered. From this figure, it becomes clear that the technique of SMR with CCS has an advantage over
PEM electrolysis, even hydrogen through electrolysis is produced in the region with the most favourable spatial conditions. From this figure, it also follows that production in Norway is slightly less efficient because of transportation costs.

**Sensitivity analysis**

**Impact of technical and economic parameters technologies on LCOHS**

By using the assumptions for the scenarios on all production and transportation technologies, a confidence range for the merit order of the LCOHS per region is obtained, as is shown in Fig. 9. One can see that for PEM-electrolysis, the ranges are larger than for SMR with CCS. This results from the higher uncertainty regarding the parameters for this technology. Furthermore, it can be observed that the range is larger for regions with a lower capacity factor and, hence, a lower utilisation of the electrolyser, induced by the lower amount of hydrogen that is produced with the same capital expenditure. A similar change in the capital expenditure, due to innovation or stagnation, is more significant for the levelized costs per unit of hydrogen in regions with less hydrogen production per unit of capital installed.

Besides the effect of the production technology, it can be observed that the influence of the scenarios on the LCOHS and, hence, the range of the sensitivity analysis increases with the distance of transport. This follows from the fact that for pipeline transport, all costs are based on the distance and, hence, for all regions where this method is most suitable, the distance raises the influence of the scenario. Simultaneously, we see that for the shipping transport methods the (re)conversion costs are strongly influenced by the scenarios, independent of the distance, resulting in larger ranges. Since the shipping of ammonia is found to be most suitable for longer distances, this results in a larger range of the LCOHS for regions that have a larger transport distance.

In general, there is much overlap in the ranges in the merit-order for LCOHS, indicating that differences in location specific factors could alter the merit order. However, one must realize that for similar technologies, similar developments are expected across regions. Therefore, an alteration in the merit-order of hydrogen supply is likely to be induced by different developments in electrolysis technology or different transportation methods. It is observed that in an innovative scenario for electrolysis technology, the supply of hydrogen produced with renewable electricity can become competitive with SMR and CCS. This holds for several locations, especially for supply from Morocco. With baseline natural gas prices, hydrogen supplied by ship does not become competitive, even in the most innovative scenario.

**Impact of natural gas wholesale price on LCOHS**

To account for the uncertainty regarding the future natural gas price, and its influence on the LCOHS of hydrogen produced with SMR and CCS, an additional sensitivity analysis is conducted. The results are shown in Fig. 10, where one can see that the natural gas price has a significantly larger impact on the LCOHS of SMR with CCS than the technical and economical parameters in the previous section. For comparison, the base line levelized hydrogen supply costs for PEM-electrolysis, unaffected by the natural gas price, are also shown. In the scenario with low future long-term natural gas prices, the LCOHS of SMR with CCS drops to just above 2 €/kg, making the technology most competitive for both locations. On the other hand, in the scenario with high natural gas prices, the LCOHS rises to almost 6 €/kg, making hydrogen produced with renewables from Morocco, Rotterdam, Saudi Arabia and Norway more competitive than SMR with CCS in the baseline scenario for the technological parameters.

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**Fig. 9** – Range of levelized hydrogen supply costs per country/technology. The calculations for the sensitivity analysis are based on the assumptions in Appendix C.
Conclusions

In this paper, it is analysed to which extent the combination of low-carbon hydrogen production at a favourable location with the most efficient transport method is able to compete with low-carbon hydrogen production in Northwest Europe. To determine the competitiveness of each supply route, the levelized costs of hydrogen supply (LCOHS) is estimated to construct an international merit-order of hydrogen supply. The LCOHS is based on the levelized costs of the most efficient production technology and transportation method in and from each region to the port of Rotterdam, taking into account the costs of hydrogen losses during transport.

It is found that the production of hydrogen using renewable electricity has the lowest costs in Morocco. This lowest production costs also holds when it is compared with hydrogen produced with Steam Methane reforming (SMR) combined with Carbon Capturing and Storage (CCS). The other regions for hydrogen production with electrolysis, however, have higher production costs than SMR and CCS. This result is contrasting with the findings of other papers, as we do not find a structural higher production cost for electrolysis. This can be fully explained by the higher energy costs for SMR, being natural gas, which have strongly increased since this other literature was published.

This paper also finds that hydrogen transport costs are strongly related to distance, with pipeline transport being most efficient for distances below 10,000 km. For the analysed routes of intercontinental distances, Australia and Chile, transport as ammonia was found to be the most competitive, although with significantly higher costs. The high estimated levelized costs of hydrogen transport (LCOHT) for large distances form a constraint on internationally trade, potentially being a driver for global price differences. Hence, rather than a global hydrogen market with one uniform price, it can be expected that regional hydrogen markets with independent prices will develop similar to what is the situation in the natural gas market.

For the supply of low carbon hydrogen, hydrogen produced locally, through SMR with CCS, is estimated as most competitive, with an LCOHS of just under 3.5 €/kg. If one only considers PEM, supply from Morocco is more efficient than production in Europe, with levelized supply costs of slightly above 3.5 €/kg. Overall, in the baseline, the LCOHS of hydrogen produced with electrolysis is in the range of 3.6–7.3 €/kg, which is 1.1–2.1 times as high as SMR with CCS.

The outcomes of an optimized supply route are in the range as found by other literature [15,8], although this paper does not obtain similar supply costs with the use of liquid or ammonia transport. In contrast to others, this paper does not focus on one supply route or one production or transportation technology, but rather searches for the optimal production and transportation mode for each supply route. This enables one to make an appropriate estimation of the economic feasibility of importing low-carbon hydrogen to Rotterdam.

In the sensitivity analysis, an ‘innovation’ and an ‘stagnation’ scenario for all assumptions were constructed, resulting in lower and higher cost components, respectively. In this way, an uncertainty bandwidth was determined for the production, transport and supply costs for all regions to control for uncertainties in development of technologies for hydrogen production and transport. Moreover, an analysis on the influence of the natural gas market is performed. It is found that an alteration in the merit-order of hydrogen supply can be induced by developments in electrolysis technology, capacity factors of renewable electricity or transportation methods. In an innovative scenario for electrolysis
technology, the supply of hydrogen produced with renewable electricity from various locations can be competitive with SMR and CCS. Additionally, it is found that, when long-term gas prices remain high, importing hydrogen produced with renewable electricity from various locations is more competitive.

It is important to remark that some factors that could influence the levelized costs of hydrogen supply are not taken into account in this study. First, the costs and capacity factor of renewable electricity input are based on the direct coupling to a single generation type. An analysis of integration of wind and solar could result in a higher assumed capacity factor which lowers the hydrogen production costs. Therefore, in future research it could be valuable to determine the potential of integration of wind and solar on raising the capacity factors. Second, it is assumed that all prices are allocatively efficient, so only based on (marginal) costs, with well-functioning competitive hydrogen markets. If, however, one supply route is optimal and markets are not competitive, it can be expected that this supplier will demand a higher price. This paper focussed on the PEM electrolyser technique, but there are other promising electrolysis techniques, such as Solid Oxide Electrolyser Cell (SOEC) technique. In further research these types of technologies should be taken into account in order to fully assess the economic potential of electrolysis.

Concluding, when the international wholesale gas price will return back to the historical low level of about 25 euro/MWh, then it is most efficient to produce low-carbon hydrogen through SMR and CCS. It may, however, be more feasible that this gas price remains much higher than that level, in which case it is most efficient to supply low-carbon hydrogen to the Northwest European market by importing it from Morocco where it is produced through PEM-electrolysis.

Declaration of competing interest

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

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Appendix A. Supplementary data

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REFERENCES


