Green Hydrogen Infrastructure Rollout: Market Suitability of Chemical Industry in Germany

1,2 Simonas Cerniauskas, 1 Hans Kulekampf, 1 Thomas Grubbe, 1 Martin Robinius and 2 Detlef Stolten.

1 Institute of Techno-economic System Analysis (IEK-3), Forschungszentrum Jülich GmbH, Wilhelm-Johannen-Str., D-52428, Germany
2 Chair for Fuel Cells, RWTH Aachen University, c/o Institute of Techno-economic System Analysis (IEK-3), Forschungszentrum Jülich GmbH, Wilhelm-Johannen-Str., D-52428, Germany

*Corresponding author e-mail: hans.ks91@gmail.com

ABSTRACT
Currently, hydrogen is already broadly adopted in the chemical industry as feedstock. Existing demand, large throughput volumes, and concentrated demand structure make the chemical industry as a promising case for hydrogen infrastructure development. To address the market suitability of the chemical industry for green hydrogen infrastructure development, we have analyzed the supply of three hydrogen markets: ammonia, methanol and refinery product. Relevant geospatially resolved hydrogen demand data is assessed and a plant-specific fossil fuel-based hydrogen cost benchmark is estimated. The market-specific technical green hydrogen potential in the current chemical processes is derived from the literature and by applying a bottom-up process simulation. Furthermore, the economic green hydrogen admixture levels are derived from the historical final product price variations and carbon tax scenarios for the year 2030. Based on these results, a multi-criteria analysis is applied to create a low-cost plant connection sequence and the related cost development of the countrywide green hydrogen infrastructure is analyzed. Our results indicate that the chemical industry offers a fast and low-cost solution for the introduction of green hydrogen infrastructure by 2030 if a carbon tax of 50€/tCO₂ is facilitated.

Keywords: geospatial analysis, hydrogen supply chain, green chemicals, green methanol, green ammonia

INTRODUCTION
The most frequently discussed option of hydrogen infrastructure development is to couple the infrastructure roll-out with the introduction of new hydrogen markets through the adoption of fuel cells and hydrogen turbines. However, such a strategy creates a high level of uncertainty with regards to the sufficient market adoption of both technologies. This uncertainty diminishes the pace of the technology adoption, and thus limits the suitability of these novel markets for hydrogen infrastructure development. This research aims to analyze the implementation of an alternative approach to initiate a wider green hydrogen adoption and accelerate the energy system decarbonization. In this study, we analyze under which conditions existing hydrogen consumer markets in Germany, are suitable to facilitate hydrogen infrastructure development. The scope of the analysis encompasses three hydrogen markets: ammonia, methanol and refinery product. Due to the chemical industry’s geospatial distribution and high overall demand, green hydrogen adoption in this market could offer a promising option to initiate a countrywide green hydrogen infrastructure development and accelerate the energy system decarbonization.

MATERIALS AND METHODS
A broad literature and data review was carried out to determine the structure and geospatial locations of the current hydrogen demand in four German markets: ammonia, methanol, refineries [1]–[7]. For the case of ammonia and methanol, a top-down approach was applied, where each chemical plant was characterized by its output capacity to derive the corresponding hydrogen demand. For the case of merchant chemicals, the net demand was directly obtained from literature sources. In the case of refineries, a bottom-up approach was considered, where each hydrogen-related operational unit was characterized by its processing capacity and a specific hydrogen production/consumption factor. Furthermore, to assess the site-specific natural gas (NG) cost, regionalized network levies are utilized as a proxy for the NG infrastructure cost [8].

In order to assess the cost-competitiveness of green hydrogen supply to the chemical industry, two pathways were accessed. The cost of green hydrogen delivery is calculated with a hydrogen supply chain model [9]–[11]. The model considers various hydrogen supply pathways, including production cost, storage, processing and conditioning, transport, and fueling. The derived hydrogen cost is governed by the geospatial distance between sources and sinks, unit scale as well as required transport capacities and hydrogen quality requirements. To estimate the scale function of on-site steam methane reforming (SMR), an extensive literature review was performed [1]–[13]. The obtained data for various plant capacities was used to fit the scaling function. For estimating the SMR plant variable OPEX, two
approaches were followed. Variable operating costs were derived by using Aspen Plus V8.8 (by AspenTech) from a heat and mass balance of the processes. Fixed operating costs, such as operating labor, maintenance, overhead and catalyst use, were obtained from the literature [16] and defined as 3.5% of the CAPEX.

Table 1. Main techno-economic parameters of the SMR plant

<table>
<thead>
<tr>
<th>CAPEX Scaling Function</th>
<th>OPEX Parameters</th>
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<tr>
<td>CAPEX&lt;sub&gt;ref&lt;/sub&gt; 213.66 Million €</td>
<td>NG consumption ratio – feed 11.52 MJ NG/Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Capacity&lt;sub&gt;ref&lt;/sub&gt; 100,000 Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;/h</td>
<td>NG consumption ratio – fuel SMR Capacity 10,000 (Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;/h) 3.2 MJ NG/Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Scaling factor, n 0.710</td>
<td>Make-up water consumption ratio SMR capacity 10,000 (Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;/h) 0.66 kg H&lt;sub&gt;2&lt;/sub&gt;O/Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>CAPEX&lt;sub&gt;ref&lt;/sub&gt; 990 €/(kg H&lt;sub&gt;2&lt;/sub&gt;/day)</td>
<td>Electricity consumption ratio SMR capacity 1,000 (Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;/h) 0.072 kWh/ Nm&lt;sup&gt;3&lt;/sup&gt; H&lt;sub&gt;2&lt;/sub&gt;</td>
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Techno-economic models of the relevant chemical process were developed to analyze the technical green hydrogen substitution potential and the resulting green chemical cost. For ammonia and methanol, special attention was given on the technical limitation related to the stoichiometric module of each reactor inlet stream. Subsequently, we design a three-step methodology to rank industrial sites regarding their suitability for hydrogen market development. The industrial sites are ranked according to their distance to the renewable energy resources, technical grey hydrogen substitution potential by green hydrogen, and the height of the site-specific grey hydrogen benchmark cost. The derived ranking of the industrial sites is then used to develop a cost-efficient hydrogen infrastructure rollout. The designed roll-out is determined with the aforementioned hydrogen supply chain model. Table 2 provides an overview of the main techno-economic parameters used in this study.

Table 2. Main techno-economic parameters of the techno-economic chemical process models

<table>
<thead>
<tr>
<th>Ammonia</th>
<th>Methanol</th>
<th>Refinery</th>
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<tbody>
<tr>
<td>CAPEX 350 $/t</td>
<td>CAPEX 310 $/t</td>
<td>CAPEX 640 $/t</td>
</tr>
<tr>
<td>Fix OPEX 2.8%</td>
<td>Fix OPEX 3%</td>
<td>Fix OPEX ?</td>
</tr>
<tr>
<td>NG consumption 17 MJ/Nm&lt;sup&gt;3&lt;/sup&gt;H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Heavy residues consumption 0.8 t/M&lt;sub&gt;MeOH&lt;/sub&gt;</td>
<td>x</td>
</tr>
<tr>
<td>Water demand 12.55 kg&lt;sub&gt;H2O&lt;/sub&gt;/kg&lt;sub&gt;H2&lt;/sub&gt;</td>
<td>Fuel demand 0.037 Kg&lt;sub&gt;H2O&lt;/sub&gt;/M&lt;sub&gt;MeOH&lt;/sub&gt;</td>
<td>x</td>
</tr>
<tr>
<td>Electricity demand 0.455 kWh/kg&lt;sub&gt;H2&lt;/sub&gt;</td>
<td>Electricity demand 180 kWh/M&lt;sub&gt;MeOH&lt;/sub&gt;</td>
<td>x</td>
</tr>
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RESULTS AND DISCUSSION

According to our results, displayed in Table 3, green hydrogen substitution potential varies among the three industries. No major technical challenge was found to replace 100% of the hydrogen of ammonia and refineries. Methanol on the other side presents a technical limitation due to the specific amount of CO and CO<sub>2</sub> needed for the reaction inlet. The technical limitation is governed by the type of feedstock and the syngas production technology and was found to be in the range of 45% for methanol. A green hydrogen penetration case was defined as the amount of green hydrogen that can be replaced that equals the cost of the levelized product if a 50 €/tCO<sub>2</sub> tax is applied. The results showed that under this condition, green hydrogen could be substituted between 9-11% for ammonia, 4-6% for methanol and 40 – 100% for refineries. The reason behind a broader range for refineries is that they present different hydrogen balances due to their singularities.

Table 3. Levelized cost of chemical products and cost-competitive green hydrogen substitution potential for different scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Natural gas cost</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt; Tax (€/t)</th>
<th>Ammonia (€/t)</th>
<th>Methanol (€/t)</th>
<th>Refinery (€/t)</th>
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<tbody>
<tr>
<td>2020</td>
<td>X</td>
<td>0</td>
<td>370</td>
<td>260</td>
<td>490</td>
</tr>
<tr>
<td>2030</td>
<td>X</td>
<td>0</td>
<td>420</td>
<td>320</td>
<td>620</td>
</tr>
<tr>
<td>2030</td>
<td>X</td>
<td>50</td>
<td>540</td>
<td>360</td>
<td>830</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Ammonia</th>
<th>Methanol</th>
<th>Refinery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green H&lt;sub&gt;2&lt;/sub&gt; reference cost</td>
<td>5 €/kg</td>
<td>5 €/kg</td>
<td>5 €/kg</td>
</tr>
<tr>
<td>Green H&lt;sub&gt;2&lt;/sub&gt; substitution potential</td>
<td>100%</td>
<td>45%</td>
<td>100%</td>
</tr>
<tr>
<td>Green H&lt;sub&gt;2&lt;/sub&gt; penetration case at 50 €/tCO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>9-11%</td>
<td>4-6%</td>
<td>40 – 100%</td>
</tr>
</tbody>
</table>

Based on the derived technical and economic data, we apply our methodology to identify promising industrial sites and their connection sequence to the green hydrogen infrastructure. The resulting cost development of a green hydrogen supply chain is displayed in Fig. 1. Small overall hydrogen required to reach stable hydrogen cost level indicates
improving infrastructure scale effects and rapid infrastructure cost reduction. Thus, in order to reach the low-cost infrastructure system, less than 5% of the current total hydrogen demand needs to be substituted by the green hydrogen. Furthermore, it has to be pointed out that each connected chemical plant substitutes only the cost-competitive amount of green hydrogen, provided in Table 3. Therefore, even a small substitution of SMR with green hydrogen is sufficient for countrywide development of green hydrogen infrastructure. However, the comparison of different levelized cost of electricity (LCOE), used for green hydrogen production, to the benchmark SMR cost indicates that the challenge of low-cost hydrogen production is significantly higher than the associated delivery infrastructure development. In the case of Germany, this finding highlights the benefits of low-cost renewable hydrogen production in the wind-rich North German regions over the onsite hydrogen production at the chemical plant.

Fig. 1. Green hydrogen cost development and site-specific SMR benchmark cost at 50 €/tCO2

CONCLUSIONS

In this work, we show that green hydrogen has a high technical substitution potential in the selected chemical industry markets. Current hydrogen demand in ammonia and refineries can be substituted by up to 100% with green hydrogen. In the case of methanol CO and CO2 process requirements allow a substitution by up to 45%. We have identified the most promising industrial sites and associated rollout pathways that can facilitate the hydrogen infrastructure development with less than 5% of current hydrogen demand. Our results show that green hydrogen can cost-competitively substitute up to 100% of SMR in refineries, making this market very attractive for initial green hydrogen adoption and infrastructure development. However, due to the anticipated electrification of the transport sector, the relative importance of the refineries is expected to diminish after 2030. Thus, despite smaller economic green hydrogen potentials in ammonia and methanol before 2030, the relative stability of these markets will play an essential role in long-term green hydrogen infrastructure development.

ACKNOWLEDGMENT

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NOMENCLATURE

CAPEX Capital expenditures
CO2 Carbon dioxide
CO Carbon monoxide
NG Natural gas
LCOE Levelized Cost of Electricity
SMR Steam Methane Reforming
OPEX Operation expenditures

Subscripts

ref Reference
REFERENCES


