

# INTERNATIONAL APPROACHES TO CLEAN MOLECULES

FIVE CASES ON HYDROGEN

JABBE VAN LEEUWEN

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# TABLE OF CONTENTS

<b>1 INTRODUCTION</b>	<b>9</b>
<b>2 INTEGRATED ENERGY SYSTEM POTENTIAL</b>	<b>11</b>
<b>3 CASE STUDIES</b>	<b>15</b>
CASE 1: H21 NORTH OF ENGLAND (UK)	15
CASE 2: QUEST (CANADA)	18
CASE 3: HYDROGEN ENERGY SUPPLY CHAIN (JAPAN & AUSTRALIA)	21
CASE 4: ENERGIEPARK MAINZ (GERMANY)	25
CASE 5: HÖGANÄS BIOMASS GASIFICATION (SWEDEN)	28
<b>4 INSIGHTS</b>	<b>31</b>
<b>5 CONCLUSION</b>	<b>37</b>

# 1 INTRODUCTION

In the current energy transition, it is becoming increasingly clear that for a successful system transition to a low carbon economy, all aspects of energy supply and demand should be considered as interrelated. As previously argued<sup>1</sup>, a focus predominantly on one 'silo' or aspect of the energy system will fail to achieve an effective, full transition of the energy system. With the transition in the electricity sector underway, and the remarkable cost decreases in renewable power production in wind and solar PV sectors<sup>2</sup>, more attention is being given to the transition of other energy sectors. As a result, more integrated approaches to the transition of the energy system are being considered.

Following this, climate neutral, molecular energy carriers (so called 'clean molecules') are receiving more attention and companies, institutions and governments all over the world are now researching and developing a broad range of clean molecule options and applications. Here, clean molecules are interpreted as molecular energy carriers of which conversion and use do not contribute to anthropogenic climate change. Examples of these include hydrogen ('blue' and 'green'), renewable ammonia, and synthetic crude oil. This wide scope approach allows for the covering of all relevant developments in clean molecules.

It is important to realise that the energy transition is not only a techno-economic challenge, but also the topic of a larger social and political debate with differing world views on where society should be heading, and how it should be organised. As a potential part of the energy transition, clean molecules are debated regarding their foreseen applications and markets, but also on the desired production routes and for their potential role in an international economic context. It is thus remarkable that stakeholders with very diverse backgrounds and interests are now interested in, and working towards the same solution space. Thorough understanding of the dynamics and drivers underlying this convergence is therefore valuable.

At the moment this has led to a myriad of approaches towards clean molecules, with varying technological (e.g. molecule, production, use) and market strategies. Of

1 CIEP (2017) 'Speaking notes: Integrated energy system transition'.

2 BP (2018) 'Statistical Review of World Energy' shows a global average growth rate of 16.2% per annum (2006-2016) for renewable energy consumption (excluding hydroelectricity and nuclear).

these, after long held promises, hydrogen has recently seen a true revival and is now one of the most promising clean molecule options. Therefore, this paper will place its emphasis on hydrogen, by inquiring into the dynamics behind recent developments through a selection of hydrogen projects as case studies. The findings of this paper aim to help improve understanding of the background and drivers of current developments, which could aid in the creation of a more uniform vision on the value and use of clean molecules and the most viable pathway towards implementation.



## 2 INTEGRATED ENERGY SYSTEM POTENTIAL

While clean molecules are not a primary energy source themselves, it is envisioned that they could become a new, additional backbone of an integrated energy system, by acting as an energy carrier. By leveraging several advantageous properties, clean molecules could interconnect production, storage, transport, conversion and use of climate-neutral energy. With this they offer valuable flexibility and optionality to the energy system. The potential backbone function is graphically represented with hydrogen as an example in Figure 1. Although clean molecules are certainly not a universally viable solution, the value proposition is likely strong enough that they can outcompete or outsmart the use of electrons for certain applications due to the multiple demand sectors they could serve.

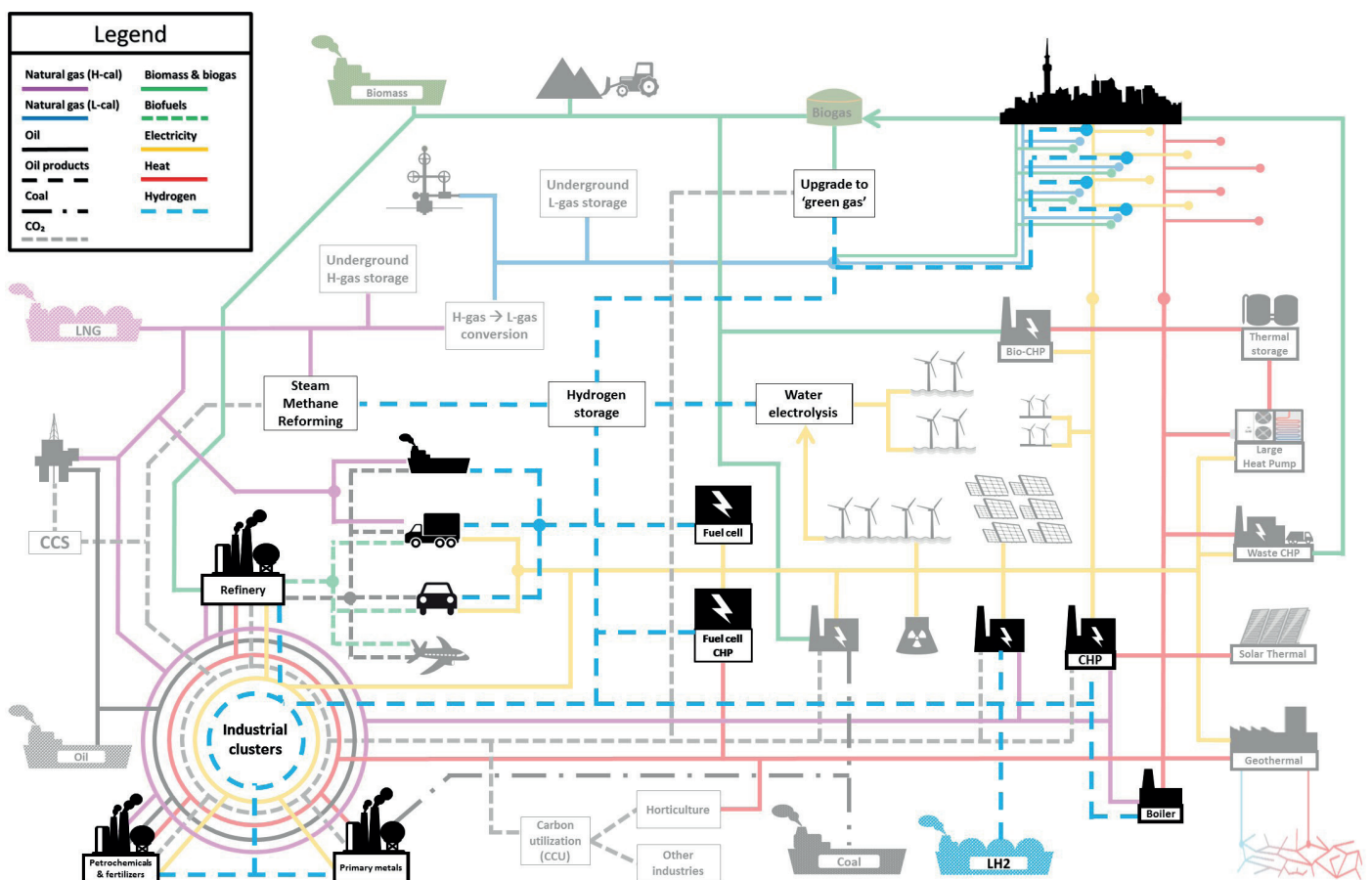


FIGURE 1 – HIGHLIGHTED SYSTEM ROLE OF CLEAN MOLECULES, HERE EXEMPLIFIED BY HYDROGEN. FIGURE ADAPTED FROM CIEP (2017) 'SPEAKING NOTES: INTEGRATED ENERGY SYSTEM TRANSITION'



## PRODUCTION OF CLEAN MOLECULES

A whole range of primary energy sources and technologies can be used for the production of clean molecules.<sup>3</sup> In the electrochemical route, hydrogen is produced by using electricity for electrolysis of water. If the electricity originates from renewable sources, such as wind or solar PV, this hydrogen is often referred to as 'green' hydrogen. Being highly flexible and responsive, electrolysis can be linked to fluctuating power production of renewable energy sources (RES), in effect creating a demand side response and storage of a variable production source. The additional and flexible power demand for electrolysis can be beneficial to the power market as it could increase the absorption capacity of power markets, allowing more renewables to be fed into the system by preventing curtailment and adding demand.<sup>4</sup> Within chemical production routes, in order for clean molecules to be created, fossil primary energy sources are converted and emissions are then captured and stored (CCS). In the case of natural gas reforming to hydrogen in combination with CCS, this hydrogen is often referred to as 'blue' hydrogen. This route might offer new perspectives on existing assets in the transition towards a climate-neutral future.<sup>5</sup> In bio-based routes, a biomass feedstock provides primary energy already in molecular form, which can either be used directly or converted to secondary energy carriers. The most straightforward is the burning of biomass for heat or power generation, however it is also possible to convert biomass to liquid or gaseous energy carriers, as for example biofuels or biogas.<sup>6</sup> Furthermore, photoelectrochemical and solar thermochemistry routes, which hold the promise of increased conversion efficiencies, are also being researched.<sup>7</sup>

## ENERGY TRANSPORT AND STORAGE

From existing experiences and projects it is known that the transport of energy over long distances is generally more economic as molecules through pipelines than as electrons through cables.<sup>8</sup> In addition, molecular energy vectors can be transported over routes where neither a cable nor a pipeline is viable, but is possible by, for example, shipping or road transport. For storage of large energy quantities and over longer periods, molecular storage technologies are regarded technically and

3 The Royal Society (2018) 'Options for producing low-carbon hydrogen at scale'.

4 CIEP (2017) 'Solar PV in a strategic world'.

5 E.g. a techno-economic evaluation of retrofitting CCS on existing SMR plant is researched as case 04-04 in IEAGHG (2017) 'Understanding the cost of retrofitting CO2 capture in an integrated oil refinery, 2017-TR8'.

6 For a comprehensive overview of technological options, see Department of Energy (2016) 'Biomass conversion', DOE/EE-1436.

7 More information, e.g. in E. Karatairi & J.E. Miller (2017) 'Splitting CO2 to produce syngas and hydrocarbon fuels: PEC and STC', DOI: 10.1557/mrs.2017.282.

8 E.g. comparing the NorNed cable (700 MWe, 580 km, 600 m€ project costs) with the Nordstream 2 pipeline (55 BCM/year, 1222 km, 9.5 b€ project costs) transport capacity costs (€\*km-1\*MW-1) are 12x lower for pipelines.

economically as more viable than competing electrochemical options (such as batteries).<sup>9</sup> Adding power conversion technologies, such as power-to-gas, to the energy system could thus open up possibilities for multiday or even seasonal storage of intermittent renewable energy.

## APPLICATIONS OF CLEAN MOLECULES

Clean molecules can be absorbed by different markets for very diverse applications. In industries, clean molecules could be used for heat supply and as feedstock. High temperature heat, for which alternatives to burning molecules are difficult to realise, can be decarbonised by fuel substitution with clean molecules. In case feedstocks in (chemical) industry are replaced (for example hydrogen, ammonia or methanol), not only is production decarbonised, but also the end-of-life disposal of the created products can potentially be climate neutral.

Next to the demand side response role of electrolysis, further stabilisation of the power system can be achieved by using clean molecules in dispatchable power production, for example with fuel cells or hydrogen-fuelled thermal power stations.<sup>10</sup> Since these options are not dependent on weather conditions, they add optionality for maintaining a renewable power supply in periods with unfavourable conditions for wind and solar PV production.

For residential and space heating, existing natural gas distribution networks can potentially be used for clean molecule delivery. It is projected that avoidance of investments in new infrastructure (and avoiding early retirement of assets) and lower cost gas-based applications for end-users are reducing costs by so much, that overall system costs are lower compared to alternative systems.<sup>11</sup>

In the mobility sector, applications such as shipping, heavy transport and aviation set high demands for power delivery, on-board energy storage and propulsion system volume. This makes them thus far unsuitable for direct electricity or direct renewable energy use. With increasing pressures to decarbonise, replacement of current fuels with clean molecules, although currently still expensive, could prove to be one of the few viable solutions.<sup>12</sup>

9 Jülich (2016) 'Comparison of electricity storage options using levelized cost of storage (LCOS) method', DOI: 10.1016/j.apenergy.2016.08.165.

10 News Vattenfall (06-07-2017) 'Vattenfall aims for carbon-free gas power'.

11 Frontier economics (2018) 'The importance of the gas infrastructure for Germany's energy transition'.

12 Cerology (2017) 'What role is there for electrofuel technologies in European transport's low carbon future?' and Agora (2018) 'The future cost of electricity-based synthetic fuels'.

# 3 CASE STUDIES

With possible applications of hydrogen being so diverse and following the current intense interest, there is an enormous number of (research) initiatives and projects.<sup>13</sup> This paper has no intention to be exhaustive or complete. Instead, five cases have been selected which illustrate the variety in applications, stakeholders, drivers and interests. The selected cases consider the application of hydrogen for residential heating (case 1), as feedstock (case 2), for energy transport (case 3), for power market integration (case 4) and for integration with the bio-based economy (case 5).

## CASE 1: H21 NORTH OF ENGLAND (UK)

### HEATING IN THE BUILT ENVIRONMENT

Application of clean molecules for residential heating revolves mostly around the replacement of natural gas, either by synthetic or biogenic methane (biogas) or by hydrogen (blending or complete substitution). The potential repurposing of existing natural gas distribution networks is interesting, as investment in new infrastructure could be avoided. Most hydrogen and synthetic gas projects are still in the research phase<sup>14</sup> with some early commercial results<sup>15</sup>. However, in terms of scalability, they hold great promise and are thus interesting cases. We selected the H21 North of England project as a case study, as it is large scale, receives broad support from network operators, government and commercial partners, and if successful, can serve as a blueprint for a national rollout.

### NATIONAL BACKGROUND

The United Kingdom has a sizeable oil and gas industry, providing relatively high self-sufficiency by producing 80% of its domestic oil demand and 50% of its domestic natural gas demand.<sup>16</sup> For providing heat, natural gas has thus been an attractive choice and now accounts for 87% of total heat demand.<sup>17</sup> At the same time, in 2008, the UK set ambitious targets for GHG reduction with the Climate Change Act

13 A recent review of initiatives involving hydrogen in the Netherlands alone amounted to over a hundred projects TKI Gas (2017) 'Overzicht van Nederlandse waterstofinitiatieven, plannen en toepassingen'.

14 E.g. DNV-GL (2017) 'Verkenning waterstofinfrastructuur'.

15 Hydrogen fuelled CHP for residential use is available from Toshiba: The Pure Hydrogen Fuel Cell System.

16 Data for 2016 from IEA, UK key energy statistics.

17 Data for 2015 from IEA Statistics, Electricity and heat balance.

by aiming for at least 80% reduction in 2050 (base 1990).<sup>18</sup> Decarbonising domestic heat supply is an indispensable part of achieving this target. Of the multiple technology pathways towards this (e.g. electrification, biomass sourced heat networks, and decarbonised gas), studies have indicated that hydrogen is likely to play an important role.<sup>19</sup> Repurposing of existing gas distribution networks for hydrogen is expected to lead to lower system costs compared to solutions which require significant investments in new infrastructure (either for heat or electricity).<sup>20</sup>

## PROJECT DESCRIPTION

This project started in 2016 as the H21 'Leeds City Gate' project, and now with expanded coverage as H21 'North of England', the programme aims to decarbonise domestic heating demand by the use of hydrogen delivered to homes through converted natural gas distribution networks.<sup>21</sup> The proposed conversion area covers 3.8 million meter points (houses), including the cities of Leeds, Manchester, and Liverpool, accounting for 14% of total UK heat demand. With a peak hour demand of 42.2 GW (cold winter conditions) and taking into account (seasonal) fluctuating demand and inter-seasonal storage, a year average demand of 9.7 GW is derived. Since this would require RES capacity being built on a 10-15 times larger scale than current mega projects, it is deemed unlikely that build-up of the required RES capacity is achievable within the timeframe of the project. Therefore, instead of electrolysis using renewable power ('green' hydrogen), Auto Thermal Reforming (ATR) of natural gas coupled with CO<sub>2</sub> storage under the North Sea ('blue' hydrogen) is deemed a more viable option.<sup>22</sup> For transmission, new high and intermediate pressure pipelines will be built, taking into account a 3 times overcapacity to allow for future expansion of the hydrogen economy. These will feed the (repurposed) existing distribution network for final delivery to homes. See Figure 2 for a schematic project overview.

Partnering in H21 are Northern Gas Networks, Cadent (private operators of the northern England, and central England gas distribution networks respectively) and Equinor (Norwegian oil and gas producer). Responsibilities are divided, with Equinor providing hydrogen production, inter-seasonal storage and CO<sub>2</sub> storage, whereas

18 For a comprehensive overview of the UK climate change policy, see Grantham Research Institute on Climate Change and the Environment (2018) '10 years of the UK Climate Change Act'. An important instrument is the Carbon Price Floor (CPF), adopted in 2013 and adding a premium of 18 £/t CO<sub>2</sub> on top of the EU Emission Trading System (ETS). For more on the CPF, see House of Commons Library (2018) 'Briefing paper 05927'.

19 Committee on Climate Change (2018) 'The role of hydrogen in a low-carbon economy'.

20 KPMG (2016) '2050 Energy Scenarios'.

21 H21 North of England project report (2018).

22 H21 North of England project report (2018), section 3.0 'Large scale hydrogen production and storage technologies'.

Northern Gas Networks and Cadent share a 50/50 responsibility for hydrogen transmission and conversion of distribution networks and appliances.

The H21 project is supported by two government funded research programmes. Laboratory testing to collect evidence of safe operation on 100% hydrogen for pipes and equipment is currently ongoing.<sup>23</sup> For this, £8.9 million of public funding has been received from Ofgem, the national regulatory authority for gas and electricity markets in the UK.<sup>24</sup> After completion of the laboratory testing, additional field testing may be conducted for a proposed budget of £4.4 million. In parallel, development of hydrogen-fuelled appliances for heating and cooking is being pursued by the governmental Department for Business, Energy & Industrial Strategy via the £25 million 'Hydrogen for Heat Programme', running from 2017 to 2021.<sup>25</sup>

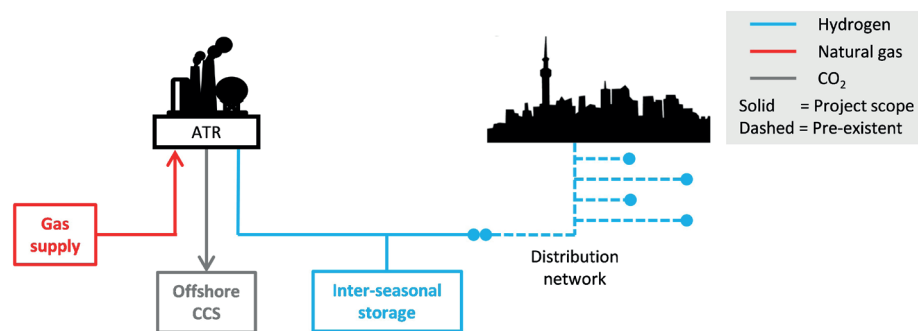


FIGURE 2 – H21 NORTH OF ENGLAND SCHEMATIC PROJECT OVERVIEW

## ENABLING FACTORS AND DRIVERS

The H21 project is gaining traction and is supported because of multiple favourable factors. Firstly, as mentioned above, the repurposing of natural gas grids holds the promise of reduced system transition costs. For a government serving national interests, support for (at least researching) such a solution seems logical. However, the two private network operators partnering in this project are operating in a regulated market under the energy regulator Ofgem, which makes research to repurpose natural gas grids for hydrogen perhaps not a core operation. However, successful implementation of H21 would create future value for the infrastructure assets in the portfolios of these private organisations. Pursuing the repurposing of

23 H21 Network Innovation Competition project description (2017) 'H21 - NIC', project code NGNGN04.

24 Ofgem (2017) 'Network Innovation Competition 2017 Funding Decisions'.

25 Arup & Kiwa Gastec press release (08-11-2018) 'Hydrogen for heat'.

assets could thus increase shareholder value. For Equinor, also a commercial supporting party, a similar consideration of increased future shareholder value can be considered. In a decarbonised future, hydrogen production coupled with CCS can be an option to monetise resources otherwise stranded due to carbon contents.

The second factor is the Iron Mains Replacement Programme (IMRP), which is ongoing independently from H21 or other clean molecule developments. Started in 2002 and to be completed in 2032, ageing cast iron distribution pipes are being replaced by polyethylene (PE) pipes out of concern for failure and the consequences thereof. A positive side effect is that while cast iron pipes are unfit for hydrogen transport due to embrittlement, PE pipes are fit for 100% hydrogen transport. Parts of the network which are not replaced (on average 10% metallic pipelines, fittings, equipment, governors, etc), are thus being tested in the aforementioned laboratory setting.

Thirdly, the north-east coast of England is favourable for blue hydrogen production for multiple reasons. A reliable supply of natural gas is available, due to the area being situated reasonably close to the North Sea gas fields and associated infrastructure. Furthermore, in the subsurface salt layer below Yorkshire, construction of caverns capable of hydrogen storage is possible, allowing for inter-seasonal storage. Both factors allow for a secure supply of energy throughout the year. In addition, adequate CO<sub>2</sub> storage potential is found in three blocks of the nearby, offshore Bunter sandstone aquifer. Alternatively, CO<sub>2</sub> transport to a Norwegian offshore storage location might be possible. This creates cost effective storage opportunities for the 512 Mt CO<sub>2</sub> considered over the lifetime of the H21 project.

## **CASE 2: QUEST (CANADA)**

### **INDUSTRIAL FEEDSTOCKS**

While industrial feedstocks are highly diverse, a general approach to adopt clean molecules seems to emerge around replacing a limited number of elementary building blocks. These elementary building blocks could subsequently be converted to desired (more complex) products. Hydrogen is one of the most elementary feedstocks and already in high demand in several industries.<sup>26</sup> In addition, ammonia production (used as fertiliser or potentially as energy storage) is an active field of

<sup>26</sup> European hydrogen production, infrastructure and demand is surveyed in the Roads2HyCom project.

research, including multiple demonstration and pilot plants.<sup>27</sup> Furthermore, interest exists in climate neutral production of more complex molecules such as methanol and 'synthetic crude'.<sup>28</sup> As a case study, the Quest project (Canada) is selected here, due to its maturity and success (in operation since 2015). Furthermore, this project illustrates new perspectives for existing installations, and shows the wide diversity in applications and visions for clean molecules.

## NATIONAL BACKGROUND

In the national Canadian economy, and especially in Alberta's provincial economy, the oil and gas sector plays an important role. Alberta accounts for 81% of Canada's crude production, with 2.4 million barrels/day of upgraded and non-upgraded bitumen from tar sands.<sup>29</sup> This accounts for 17% of the provincial GDP (it is the largest single sector contribution), with oil and petrochemicals making up 65% of the province's exports.<sup>30</sup>

As extraction and processing of tar sands is energy intensive, Canadian crudes have among the highest GHG footprints of different oil feedstocks.<sup>31</sup> This is reflected in national emission statistics, which shows that the oil and gas sector is the nation's largest emitter, and that tar sands production and upgrading alone account for 9% of the national GHG emissions.<sup>32</sup>

In its Intended Nationally Determined Contribution (INDC) to the Paris Agreement, Canada pledged a 30% emission reduction in 2030 from 2005 levels.<sup>33</sup> The province of Alberta implemented a GHG emission reduction target of 50 Mt below a business-as-usual (BAU) baseline for 2020 and increasing to 200 Mt below BAU in 2050, with a potential limit of 100 Mt GHG emissions for tar sands related activities envisioned in the province's Climate Leadership Plan.

27 Studies such as ISTP (2017) 'Power to Ammonia' or the MoU for joint research between OCP and Fraunhofer IMWS. Demonstration plants are built by Siemens (Green Ammonia Energy Storage Demonstrator, UK) AIST (Fukushima Renewable Energy Laboratory, Japan) and ThyssenKrupp (Hydrogen Utility - H2U, Australia).

28 For example, Carbon Recycling International produces 5 million litre/yr of methanol at the George Olah facility, Iceland and Nordic Blue Crude will start 8000 t/yr production of synthetic crude at Heroya, Norway in 2020.

29 Tar sands are also referred to as oil sands, bituminous sands or crude bitumen.

30 Highlights of the Alberta economy, 2017, Alberta Economic Development and Trade.

31 Carnegie Endowment for International Peace (2015) 'Know your oil'.

32 Data for 2013 from IEA (2015) 'Energy policies review of IEA countries - Canada'.

33 Centre for International Governance Innovation (2018) 'The evolution of Canada's international and domestic climate policy'.



## PROJECT DESCRIPTION

In an effort to decrease the GHG footprint of tar sands, Quest is centred around the carbon capture and storage of emissions from hydrogen production at the Shell Scotford upgrader. At this site, an integrated upgrader and refinery process bitumen from tar sands into products (e.g. diesel, gasoline, jet fuel). Hydrogen is essential for this and is produced on-site by three hydrogen manufacturing units (HMUs), by steam methane reforming (SMR). In the Quest project, 1.2 Mt CO<sub>2</sub> emissions per year (approx. 35% of the total upgrader emissions) from these HMUs are captured by retrofitting amine-based pressure swing adsorption (PSA) units.<sup>34</sup> The captured CO<sub>2</sub> is subsequently processed, transported 65 km by pipeline, and permanently stored 2 km below the surface. A measurement, monitoring and verification programme to ensure safety and containment of the storage is an integral part of the project.

Following the final investment decision to proceed with the Quest project in 2012, operation began in 2015. In the first three years of operation, 3 million tons of CO<sub>2</sub> have been stored, while the project is funded for at least 10 years, with an intended lifetime equal to the remaining life of the Scotford upgrader (approx. 25 years).

Total project costs for construction and the first 10 years of operation are budgeted at C\$1310 million. The largest share (C\$745 million) is funded by the Province of Alberta. The commercial partners of Scotford (60% Shell Canada, 20% Chevron Canada, 20% Marathon Oil Sands Holding) funded C\$445 million, and the national Clean Energy fund contributed C\$120 million.<sup>35</sup>

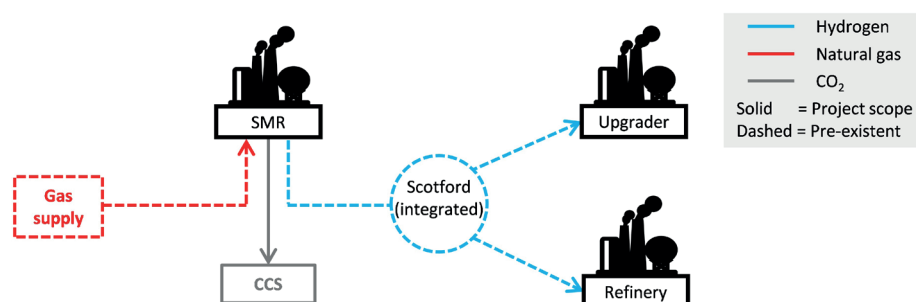


FIGURE 3 – QUEST SCHEMATIC PROJECT OVERVIEW

<sup>34</sup> Quest Carbon Capture and Storage project – Annual summary report 2014.

<sup>35</sup> CCS funding agreement – Quest project, Alberta and Shell Canada, 31-05-2011 and CEF investment page <https://www.nrcan.gc.ca/energy/funding/cef/18168>.

## ENABLING FACTORS AND DRIVERS

The fact that the provincial government is covering the largest share (57%) of the project budget reflects the importance of the (tar sands) oil industry, the value of the oil produced, and the importance of exports to the provincial economy in relation to the project budget. It is notable that considerable commercial funding has been granted, despite the lack of direct financial incentives (as e.g. a carbon tax or trading scheme would provide) and despite weak domestic climate policy in place at the time of the final investment decision.<sup>36</sup>

The willingness to contribute to carbon emission reductions can be understood by the considerable public concerns on the environmental footprint of tar sands and the resulting fierce public debates on the desirability of tar sands exploitation.<sup>37</sup> Given both the large economic impact and the large oil sand reserves, public acceptance of the tar sand industry is important for the province's economic stability. Acknowledgement of these concerns and (partly) addressing them with the reduction of GHG footprints, in this case through the introduction of carbon neutral hydrogen, is thus a rational response to improve public perception and prolong the social license to operate for the tar sands industries.

## CASE 3: HYDROGEN ENERGY SUPPLY CHAIN (JAPAN & AUSTRALIA)

### ENERGY TRANSPORT AND TRADE

As some clean molecule forms are substitutes for existing commodities, transportation technologies for these already exist and are in common use. For example, ammonia shipping is common practice in liquefied petroleum gas (LPG) carriers and methane is shipped globally as liquefied natural gas (LNG). For other kinds of clean molecules, such as hydrogen, the same multitude of transport options are not yet available. Research on hydrogen transportation options is most actively pushed by the Japanese government, operationalised in the cross-ministerial Strategic Innovation Promotion Program (SIP) 'Energy carriers' program. As part of this, a demonstration project for organic hydride transport<sup>38</sup> as well as a pilot for liquid hydrogen transport are being developed. The liquified hydrogen transport

36 Centre for International Governance Innovation (2018) 'The evolution of Canada's international and domestic climate policy'.

37 Resistance is both domestic, for example The Globe and Mail (09-04-2015) 'Environmental groups take aim at Alberta oil sands emissions', and foreign, as exemplified by the EU's 'Fuel Quality Directive', which threatened but eventually allowed for tar sands crudes, e.g. Financial Times (04-10-2014) 'EU oil sands ruling set to irk Canada'.

38 Chiyoda corporation (27-07-2017) 'The world's first global hydrogen supply chain demonstration project'

pilot 'Hydrogen Energy Supply Chain' (HESC) poses an interesting case, as it encompasses a complete supply chain and is a collaboration between the Australian and Japanese governments. If proven successful, the developed transport technology holds global potential.

## NATIONAL BACKGROUNDS

As a developed, industrialised country with scarce domestic energy sources, Japan has a high dependency on energy imports, making energy security of supply an ongoing concern.<sup>39</sup> Following the Paris Agreement, Japan has committed itself to reduce GHG emissions by 26% in 2030 and 80% in 2050 (base 2013) with the 'Plan for Global Warming Countermeasures'.<sup>40</sup> Yet, after the Fukushima nuclear accident, LNG and coal imports skyrocketed, increasing both energy import dependency as well as CO<sub>2</sub> emissions. The particular challenge for Japan is thus to maintain energy security and imports, while decarbonising the energy system. The government has identified the creation of a 'hydrogen society', in which hydrogen is established as a secondary energy structure coexisting alongside energy structures for electricity and heat, as a means to achieve this challenge.<sup>41</sup> In this vision, hydrogen is sourced globally and transported to Japan using transport technologies developed in the 'Energy Carrier' program. While this is highly ambitious, the now thriving LNG market is proof that Japan is capable of helping to create new, global energy markets.<sup>42</sup>

Meanwhile, endowed with extensive natural resources, Australia is a large exporter of coal and natural gas with strong trade relations with Japan.<sup>43</sup> These energy exports are an important contributor to Australia's economy. However, in a world pushing for decarbonisation, concerns exist about the future prospects for the export of coal and natural gas. As an adaptation strategy, researchers and governmental institutions have laid out a hydrogen roadmap for Australia to, 'secure its position in the emerging market for low and zero emissions energy using both its fossil-fuel reserves and its enormous capability to produce renewable electricity'.<sup>44</sup>

The effects of shifting energy supply are already felt in the Latrobe Valley, Victoria, where extensive lignite deposits are present. Previously used locally for power

39 In 2015, net energy imports accounted for 95% of TPES. IEA (2017) 'World energy balances'

40 Ministry of the Environment (2017) 'Annual report on the environment in Japan 2017'

41 Ministry of Economy, Trade and Industry (2017) 'Basic hydrogen strategy'.

42 For a brief history of the LNG market, including Japans role in this, see British Chamber of Commerce Singapore (2014) 'LNG 50 – A brief history of LNG'

43 32% of coal exports are destined for Japan, where they account for 64% of Japan's coal imports. Data for 2016 from IEA, Australia key energy statistics

44 Commonwealth of Australia (2018) 'Hydrogen for Australia's future'

production, the prohibitively high costs of upgrading an ageing power plant fleet have resulted in a series of closures.<sup>45</sup> As lignite has limited uses, due to the risks of self-combustion and a low energy density, the adjacent lignite mines are being closed in conjunction with the power plants. With local communities and economies highly dependent on the mines and the power plants, the impact on the region is severe, prompting the state government to respond with a A\$266 million 'Latrobe Valley Economic Development' support package.

## PROJECT DESCRIPTION

The aim of the HESC project is to develop and pilot technology to 'safely and efficiently produce and transport clean hydrogen from Victoria's Latrobe Valley to Japan'.<sup>46</sup> In the Latrobe Valley, hydrogen will be produced by lignite gasification. The produced hydrogen will be transported to the Port of Hastings, where it is liquefied (at -253 °C) and loaded onto a liquid hydrogen carrier vessel for transport to Kobe, Japan. There, the liquid hydrogen will be unloaded, stored and regasified for delivery to customers.

Four deliveries are planned during the one year pilot phase (2020-2021). Depending on the degree of success, commercialisation will be decided upon in the early 2020s. During the pilot phase, CO<sub>2</sub> emissions will be compensated, while for later phases the intention is to join the CarbonNet CCS project of the national and Victorian governments. This project aims to store CO<sub>2</sub> in the Gippsland Basin offshore gas fields near the Latrobe valley, which have a vast 20 Gt storage potential.

The HESC project is divided into Japanese and Australian funded portions. The Japanese portion is organised under the government's New Energy and Industrial Technology Development Organization (NEDO) as the HySTRA collective, consisting of Kawasaki Heavy Industries (KHI), Shell, Iwatani and J-Power.<sup>47</sup> Responsibilities are divided among the partners in Japan as follows: lignite gasification (J-Power on the AGL Loy Yang site, based on coal gasification experience), LH<sub>2</sub> transport (Shell and KHI, design and construction of a 2500 m<sup>3</sup> LH<sub>2</sub> carrier vessel)<sup>48</sup>, and port infrastructure including regasification (Iwatani). The Australian portion is coordinated by Hydrogen Engineering Australia and consists of KHI, J-Power, Iwatani, Marubeni and AGL.<sup>49</sup>

45 ABC News (24-03-2017) 'Hazelwood won't be the last of Latrobe Valley's coal-fired power stations to close'

46 Hydrogen Energy Supply Chain, retrieved 11-10-2018 from <https://hydrogenenergysupplychain.com/>.

47 HySTRA, retrieved 11-10-2018 from <http://www.hystra.or.jp/>.

48 Kawasaki Heavy Industries (04-04-2017) 'Introduction to a Liquefied Hydrogen Carrier for a Pilot Hydrogen Energy Supply Chain (HESC) project in Japan'.

49 Reuters (12-04-2018) 'Australia's AGL to host coal-to-liquid hydrogen export trial for Japan's Kawasaki Heavy'.

Their responsibilities are hydrogen purification, transportation to the Port of Hastings, liquefaction and loading infrastructure. The total HESC project budget is A\$496 million, to which both the Australian federal government and Victoria government contribute A\$50 million while the remainder is covered by Japanese funds.

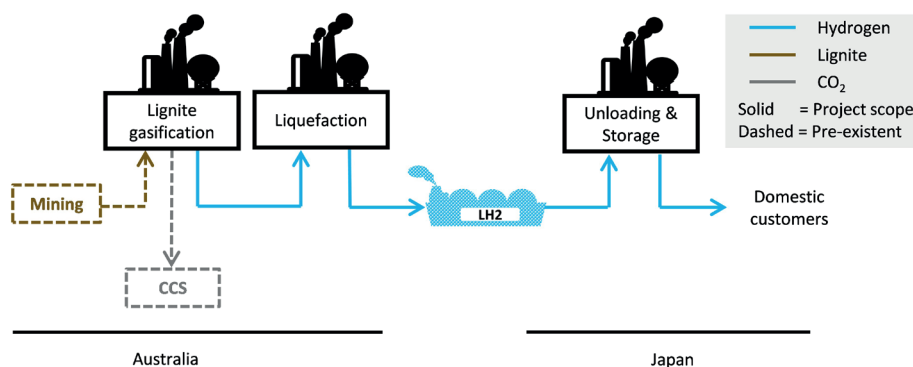


FIGURE 4 – HYDROGEN ENERGY SUPPLY CHAIN SCHEMATIC OVERVIEW

### ENABLING FACTORS AND DRIVERS

Several factors and drivers are coinciding in the HESC project, providing a strong project base. From an international trade perspective, both Australia and Japan can benefit from this project. For Japan, collaboration with an existing and reliable trade partner like Australia on the import of decarbonised energy is attractive, both for climate reasons as well as for security of supply reasons. For Australia, this project is attractive to secure decarbonised energy export options as a hedge against current energy exports. In addition, Australia can potentially benefit from a first mover's advantage in the international hydrogen market. This should also be understood from the domestic viewpoint that such new economic development can be offered to regions presently struggling with industrial decline.

Considering the complex technology required to be developed, Japan boasts industrial companies with the scale, capabilities and experiences required. Through the experience of, for example, KHI with liquid hydrogen rocket fuel storage and LNG shipbuilding, the extensive know-how of J-Power in gasification and the fact that Iwatani is already operating liquefaction plants, project risks are reduced. Moreover, the security of supply position is strengthened further as these are Japanese domestic companies. The clustered occurrence of extensive lignite deposits, large CO<sub>2</sub> storage potential, and the vicinity of seaports around the Latrobe valley is unique and highly favourable. Finally, the closures of the Latrobe Valley power plants are effectively making the lignite deposits stranded resources, freeing them up for other applications at low opportunity costs.

## CASE 4: ENERGIEPARK MAINZ (GERMANY)

### SECTOR COUPLING

As clean molecules could facilitate the integration of high shares of RES in the power system, the substantial increase in RES capacity has stimulated interest in power-to-product (PtX) technologies. Hydrogen production by electrolysis of water receives the most interest, including possible subsequent conversion into methane. As this interconnects the power, gas, and industry sectors, it is also named sector integration.

As a case study for this application of clean molecules, the German Energiepark Mainz project is selected as it is mature, involves relatively high power with large gas volumes, and it is conducted by a diverse consortium, showcasing the interests associated with power-to-gas (PtG).

### NATIONAL CONTEXT

After the 2010 implementation, the 'Energiewende' has gripped the German electricity sector in the move towards renewable power generation. The results are tangible, as in 2016 31% of total power production was by renewable sources (a 12 percent point increase over 2010).<sup>50</sup> This is the result of a rapid build-up of renewable power generation capacity, spurred by governmental support via fixed feed-in tariffs. The base of this is legislation targeting an 80-95% GHG emission reduction by 2050 (base 1990) and a phase out of nuclear power plants by 2022.<sup>51</sup>

However, with increasing renewable generation capacity, some negative aspects of RES have also become more apparent.<sup>52</sup> With new wind power production mostly located in the windy north, where power absorption is relatively low, and large power demand in the south, grid expansion became vital to connect new production with demand. Public resistance to these grid expansions is causing bottlenecks for supply meeting demand. Furthermore, the combination of high renewable production and inflexible lignite-based production is more frequently leading to negative power prices in low demand moments, deteriorating the business cases for (renewable) power producers.<sup>53</sup>

50 Data for 2016 from IEA German key energy statistics.

51 IEA (2013) 'Energy policies of IEA countries, Germany, 2013 review'.

52 CIEP (2014) 'The energiewende and Germany's industrial policy', chapter 3.1.

53 Since negative prices in Germany were first noted on Sunday, 8 May 2016, the situation has become more common and is increasingly occurring. Also see Bloomberg (06-08-2018) 'Power Worth Less Than Zero Spreads as Green Energy Floods the Grid'.

From these concerns, the concept of integrating energy sectors (in German referred to as 'Sektorkopplung') to stabilise the power market and accelerate decarbonisation of sectors other than power has gained attention. The conversion of power to hydrogen by electrolysis of water is a popular option for this. As electrolyzers are not yet an incumbent technology, a number of power-to-gas pilots and demonstrations are being conducted to advance development.<sup>54</sup>

## PROJECT DESCRIPTION

The Energiepark Mainz project is set up to achieve multiple targets. Firstly, the potential of PtG technology as flexible power demand for reduction of fluctuations and congestion in the power grid caused by variable generation (in this case by wind turbines) is being demonstrated. Secondly, the project is being used as a technology demonstrator for a proton exchange membrane (PEM) electrolyser and hydrogen processing and handling technology. Thirdly, scholarly research on management and operating modes is being conducted for identification of the most economically attractive PtG business models.<sup>55</sup>

Three Siemens PEM electrolyzers constitute the central equipment in the Energiepark Mainz project, with a combined capacity of 6 MW<sub>e</sub> (peak, 15 minutes) or 4 MW<sub>e</sub> (continuous operation) and an output of 1,000 nm<sup>3</sup>/h. The produced hydrogen is subsequently purified, dehumidified and compressed for storage at 8 MPa. The hydrogen is then either injected into the natural gas grid (max. 10%<sub>vol</sub> H<sub>2</sub>) or further purified (up to 99.999%), dehumidified and compressed to 22.5 MPa for tube trailer delivery to industrial customers.

Following the final investment decision in 2013 and opening in 2015, the project has run for a year and is now finalised.<sup>56</sup> The project budget over this period totalled €17 million, 50% of which was covered by the national government's Bundesministerium für Wirtschaft und Energie (BMWi). The other half was covered by the project partners Siemens AG (21%), Mainzer Stadtwerke AG (14%), Linde Gas Deutschland (12%) and the RheinMain University of Applied Sciences (3%). Responsibilities were divided over the various parties, with Linde overseeing the plant design, construction, operation and certification, Siemens delivering the PEM electrolyzers, Mainzer Stadtwerke for site preparation and communications and the RheinMain University of Applied Sciences guiding scholarly research and publications.

54 For an up-to-date overview, see <http://www.powertogas.info/power-to-gas/pilotprojekte-im-ueberblick/>.

55 Kopp et al. (2017) 'Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis', DOI: 10.1016/j.ijhydene.2016.12.145.

56 'Energiepark Mainz Elektrolyse-Wasserstoff als Energiespeicher und -vektor, gemeinsamer Schlussbericht' (2017) DOI: 10.2314/GBV:1002770254.



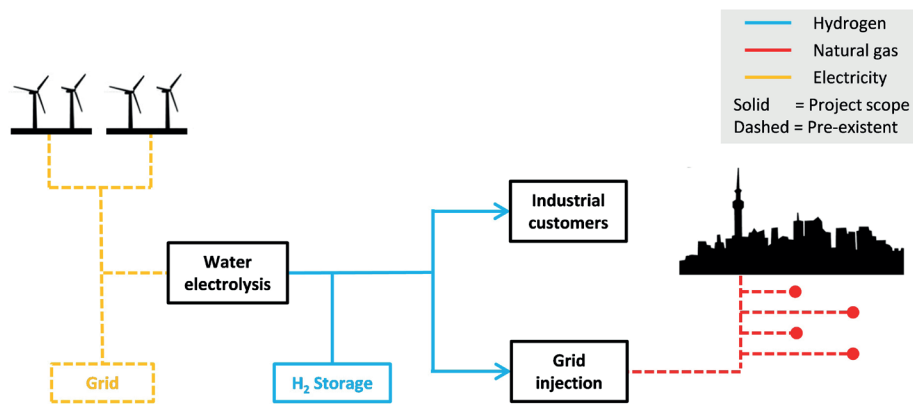


FIGURE 5 – ENERGIEPARK MAINZ SCHEMATIC OVERVIEW

### ENABLING FACTORS AND DRIVERS

The different backgrounds of project members demonstrate the broad interest for hydrogen, with governmental, industrial and utility partners joining efforts. For the industrial partners, Siemens and Linde, one incentive to participate is gaining knowhow and experience with hydrogen plants and equipment. Pay-offs are already tangible, with improvements to plant design, the granting of hydrogen plant certifications, and a next generation of electrolyzers with updated double-digit capacity on the market.<sup>57</sup> Also, the timely seizing of market share in emerging sectors, such as hydrogen, is attractive in anticipation of growth. Sector entry through participation in pilots and demonstrations is one way to achieve this.

For Mainzer Stadtwerke, the local operator of electricity and natural gas distribution networks, commercial interests are comparable to those of Northern Gas (see the H21 case), as new value can be created for existing infrastructure assets. As the company is wholly owned by the city of Mainz, the public interest of energy transition cost optimisation can be considered an additional driver.

Next to the public transition cost aspect, inclusion of hydrogen in the energy system could increase the RES absorption capacity and thus contribute to achieving the 'Energiewende' targets. In addition, this would potentially allow further increases in domestic energy production, which is attractive from an energy security point of view and an incentive to participate for the national government. Having conducted industrial policy through energy policy before<sup>58</sup>, the positioning of German industrial and manufacturing companies in the potentially large, global market for hydrogen can be considered an important driver for the national government as well. All these factors make it attractive for the national government to participate in the project.

<sup>57</sup> Siemens Sylyzer 300 data sheet.

<sup>58</sup> CIEP (2014) 'The energiewende and Germany's industrial policy'.

## CASE 5: HÖGANÄS BIOMASS GASIFICATION (SWEDEN)

### BIO-BASED ROUTE

While burning biomass for power or heat generation is common practice, biomass conversion into clean molecules may hold some distinctive advantages. For example, liquid biofuels (e.g. bio-ethanol or biodiesel) are already in use as drop-in replacements for fossil transport fuels. Recently, interest in using bio-based clean molecules for other purposes has been growing. For example, the presence of carbon in biomass can pose an advantage for processes and products that depend on embedded carbon by nature. In these cases, biomass converted to clean molecules can act as an energy carrier as well as a carbon source. This is especially interesting for the chemical industry, for which biomass conversion to clean molecules might constitute one possible pathway towards a more sustainable energy and feedstock consumption.<sup>59</sup> One approach to this is the gasification of solid or liquid biomass, yielding a gas mixture composed of mainly hydrogen and carbon monoxide (also called synthesis gas or syngas). As syngas produced from fossil resources is already a common feedstock in the industry, bio-based syngas could serve as a direct replacement. Biomass gasification is being pursued by many actors through research, projects and commercial operations.<sup>60</sup> Of these, the Höganäs biomass gasification project in Sweden is a recent and successful illustration of gasification technology.

### NATIONAL CONTEXT

Currently, Sweden already consumes a significant amount of clean molecules in the form of woody biomass, particularly in the (paper) industry, and for district heating, accounting for a 25% contribution to national primary energy consumption.<sup>61</sup> In addition, nuclear energy provides 32% of Sweden's primary energy consumption. Carbon-based fossil fuels supply a relatively modest 28%, predominantly as transportation fuels, since heating oil has been successfully phased out. While the energy intensity of Sweden's economy is relatively high, the result of the current energy mix is a low emission intensity (about a third of the OECD average, both per capita and per GDP PPP).<sup>62</sup>

59 For example, bio-based feedstocks are identified as one pathway towards a renewable chemical industry in VNCI (2018) 'Chemistry for climate: Acting on the need for speed'.

60 Examples are the Swedish GoBiGas project (while technically successful, mothballed due to economics), the To-Syn-Fuel project aimed at converting sewer sludge to fuels and hydrogen, and the ambition to create a bio-based chemical industry cluster at Chemport in The Netherlands.

61 Swedish Energy Agency (2018) 'Energy in Sweden – Facts and figures 2018', 2016 data.

62 Data for 2016 from IEA key world energy statistics.

Against this background, the governmental targets for future GHG emissions are among the most ambitious in the world. In 2017, a climate policy framework and the 'Climate Act' were adopted, as national implementation of the Paris Agreement. According to this act, 'by 2045 Sweden is to have zero net emissions of greenhouse gasses into the atmosphere'.<sup>63</sup>

There is thus a need to displace fossil transportation fuels as well as the minor flows of coal and natural gas now used in industry. Focussing on these last two flows, coal is only used in the coking and steel industry, while 40% of natural gas is used as industry feedstock. In this respect, clean molecules are attractive alternatives for coal replacement in steelmaking<sup>64</sup>, for generation of high temperature heat by burning, or as feedstock.

## PROJECT DESCRIPTION

The Höganäs biomass gasification project is centered around a 6 MW<sub>th</sub> biomass gasification plant. In this plant, biomass from forest residues is gasified into syngas, which consists of 60 vol% hydrogen, 25 vol% carbon monoxide and the rest made up of CO<sub>2</sub> and CH<sub>4</sub>.<sup>65</sup> The gasification plant is built and developed by Cortus Energy, incorporating their proprietary WoodRoll gasification process and technology. Subsequently, the syngas is used at the adjacent Höganäs AB metal powder production site, where it replaces natural gas in a furnace. This fuel shift reduces the greenhouse gas emissions of the furnace by 60%, resulting in 10 kiloton CO<sub>2</sub> savings per year when the plant operates at full capacity, equivalent to 3% of the total plant emissions. Construction commenced in November 2017 and the gasification plant was inaugurated in June 2018.

Total investment is 'in the order of SEK 100 million', funded in part by contributions from the Swedish Environmental Protection Agency's 'Climate leap' fund (SEK 36.3 million) and the Swedish Energy Agency (SEK 7.9 million).<sup>66</sup> The remaining funds are provided by Cortus Energy, owner and operator of the plant, by issuing new shares. The total value of issued shares is in the range of SEK 33-65 million, however other projects under development are also covered by this capitalisation.<sup>67</sup>

63 Government offices of Sweden, Ministry of the Environment and Energy (2017) 'The Swedish climate policy framework'.

64 United in the HYBRIT project, the Swedish-Finnish steelmaking company SSAB, Swedish mining company LKAB and Swedish power company Vattenfall are investigating iron ore reduction in steel using hydrogen instead of coking coal. Construction of a SEK 1.4 billion pilot plant has started, with SEK 528 million funded by the Swedish Energy Agency.

65 Cortus Energy presentation slides 9th International Seminar on Gasification (19-10-2016).

66 Cortus Energy news releases (21-05-2018, 6-12-2016, 23-11-2016).

67 Cortus Energy investor information (24-09-2018).

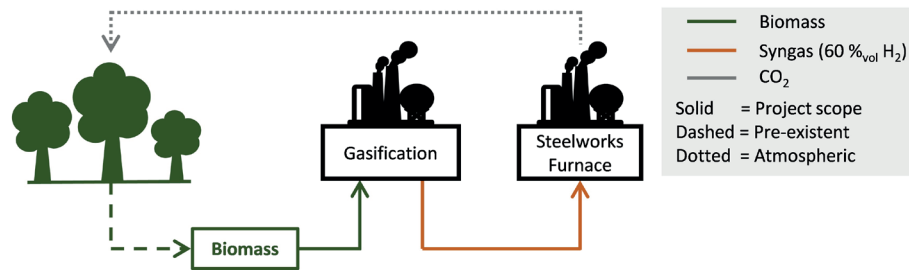


FIGURE 6 – HÖGANÄS BIOMASS GASIFICATION PROJECT OVERVIEW

### ENABLING FACTORS AND DRIVERS

With a large forestry and paper industry, Sweden is rich in biomass and forest residues. Already supplying a large part of the energy mix, the availability and existing supply chains allow for a relatively easy addition of new demand. Furthermore, utilisation of forest residues does not compete with food production, an often-discussed potential negative side effect of biomass use for energy production.

A key factor in creating support for this project is that decarbonisation methods for the generation of high temperature heat are very limited. Burning of clean molecules is one of the few proven carbon neutral technologies currently available for high temperature heat generation. Moreover, the use of syngas constitutes a fuel replacement which does not require changes to the industrial furnace equipment, allowing for fast and cost-effective change.

There is international interest in using the gasification technology applied in this project for different applications. In Japan and the United States, projects are proposed with the intention to use the produced syngas for electricity generation. In France, the creation of a renewable supply of hydrogen is aimed for by hydrogen extraction and purification from the syngas. It is important to note that this versatility is not limited to the specific, proprietary biomass gasification technology used in this project, but rather it is associated with the properties of syngas.

As a demonstration project, realisation of the Höganäs biomass gasification project depended on governmental support. However, successful capitalisation by share issuing indicates an almost mature development phase, with manageable risks and sufficient investors' appetite. In part, this can be attributed to the broad market perspectives from the new applications and existing demand for syngas, and by extension of this, to the potential of biomass gasification.

## 4 INSIGHTS

Each project already consists of interesting developments, yet as a collective set they show the true potential of clean molecules.

One can think of, for example, a future perspective in which hydrogen is used alongside electricity or other energy sources and carriers in a more deeply integrated energy system for heating, industry or many other purposes. Final distribution to customers might take place through repurposed grids, opted for in consideration of the most cost-effective energy transition. The hydrogen supplied could be produced using electrolysis, in part domestically to help absorb RES power production, in part imported when demand exceeds supply. As liquefied hydrogen vessels become a viable option, they will unlock areas with high production potential but remote from demand centres, such as deserts (PV) or plains (wind turbines). After having helped to create a hydrogen market through competitive and large-scale production in the period leading to such a future perspective, bio-based and blue hydrogen production capacity could continue to provide value as a hedge against price, security of supply or other concerns.

When assessing the collective set of cases and the subsequent drivers and enablers, insight is gained into aspects of clean molecules which support their value proposition and increase the probability of a successful hydrogen market, such as the possible future sketched above.

### HIGH VERSATILITY

The cases presented in this paper were selected to showcase the application of hydrogen in different parts of the energy system. Still, as the outlined potential roles have shown, these cases represent only a small fraction of the many potential applications of clean molecules. Moreover, the current cases are focussed on hydrogen alone. Since many more forms of clean molecules exist, each with distinct properties and applications, any of these could add more potential usages, further expanding the versatility.

As the other clean molecule forms often use hydrogen as an intermediate in the production process, the current focus on hydrogen does not have to hinder and be competitive with these forms. If the current developments result in an affordable

and reliable hydrogen supply, other clean molecules might benefit as well, by increasing their competitiveness through decreased production costs.

### PLURIFORM DRIVERS

In each case, the drivers moving the project partners to participate and pursue the development of clean molecules have been identified. When assessing the found drivers as a set, we see they range across (but are not limited to) cost, social license-to-operate, energy security, (regional) economic development and industry policy. Each case is supported by an entwined mix of multiple drivers. Support for clean molecules thus stems from a broad range of drivers from economic, sustainable and strategic backgrounds.

It is notable that the drivers are not the outcome of a 'green and renewable' paradigm alone. Instead, support is broader and is rooted in multiple perspectives. With discourses and values continuously shifting in society, such a favourable regard from multiple perspectives provides clean molecules with a robust base of support. In case certain aspects diminish in relevance or support, other aspects might receive increased or stable support, overall maintaining a value proposition. This increases the likelihood of reaching a mature market stage in a continually changing sector and under turbulent external developments.

### RESILIENT DEVELOPMENT PATHWAY

For clean molecules to mature into a viable option, improvement of the technological and economic readiness levels through successful research, pilots and demonstrations is required. The assessed cases show that for now, all are in part enabled by specific, local favourable conditions (such as carbon storage potential, local economics or stranded resources). This gives insight into why these particular projects are conducted at these specific locations instead of elsewhere. In addition, government support is granted for all the presented cases. As clean molecules are still in the early stages of development, governmental support is considered part of a normal technology development path and not an indication that clean molecules have an intrinsic reliance on local factors or governmental support. In general, with further maturation, reliance on external support should decrease.

For hydrogen projects to get to this point, the assessed cases indicate that longer term visions are supportive of large-scale adoption. In Japan, Australia and the UK, the strategic approaches to hydrogen as an energy import, export and emissions mitigation option, respectively, include timelines up to and beyond 2050. Both the H21 and HESC projects benefit from this and eclipse the other cases in size and

ambition. Coherent, long term commitment to a strategic approach is highly beneficial to give other actors the confidence to engage in hydrogen projects and developments.<sup>68</sup>

As a result of the chosen approach, the elaborated cases are aimed at different applications of clean molecules and therefore are not directly in competition. Instead, each project is competing with other projects not elaborated as cases here or by other solution directions such as electrification or bio-based solutions. As much is still unclear, it is inevitable that some clean projects or applications will fail. However, following the high versatility and pluriform drivers that were found, failure of a single project does not necessarily indicate that clean molecules are an unattractive solution space as a whole. Other actors may continue development or focus might shift to other applications instead of deciding for complete abandonment, creating a resilient development pathway.

Furthermore, it is important to notice that each individual project is supportive of clean molecules as a solution direction through learning and technology transfer. (As an example, think of hydrogen produced using German electrolyzers, transported liquefied in tankers of Japanese design for final use in the built environment of the UK). Through this resilience and mutual strengthening, the development pathway of clean molecules is more robust.

## HYDROGEN MARKET DEVELOPMENT

Moving from general clean molecules to hydrogen as a specific option, it is clear that the market is still in an immature phase of development. While 'grey' hydrogen is a commodity, clean molecule alternatives be they 'blue' or 'green' hydrogen receive much interest, but are not commonly marketed yet. 'Blue' hydrogen is close to large-scale application as demonstration plants have proven the viability and potential production volumes are significant. Current 'green' hydrogen projects show a lower technological readiness level, with small-scale pilots and development still ongoing. This is schematically represented in Figure 7, at the leftmost section of the graph.

In the near future, for both 'blue' and 'green' hydrogen, a decisive moment for reaching the next market phase seems to coincide in the 2020s. Favourable final investment decisions (FIDs) of proposed projects incorporating 'blue' hydrogen (e.g. H21) would push this to a mature, full-scale market phase. For 'green' hydrogen, it is

68 The UK Committee on Climate Change emphasised a stronger need for a strategic approach, stating that "an incremental approach that relies on isolated, piecemeal demonstration projects may lead to hydrogen remaining forever an option 'for the future'." Committee on Climate Change (2018) 'Hydrogen in a low-carbon economy'.



projected that electrolysis equipment in triple digit MW<sub>e</sub> range will become available, moving it out of the pilot phase and into the demonstration scale.<sup>69</sup> At the same time, increasingly stringent climate policies might result in the retrofitting of existing hydrogen production sites with CCS technology (as for example in the Quest project), effectively pushing ‘grey’ hydrogen out of the market in favour of ‘blue’ hydrogen. In addition, the proposed projects that expand the market for hydrogen, to for example domestic heating or mobility, have the potential to significantly increase hydrogen demand. This displacement and market expansion are represented in the centre of Figure 7.

Over a longer timeframe, it is envisioned that cost decreases for renewable power, electrolysis and transport might make ‘green’ hydrogen competitive or may even outcompete ‘blue’ hydrogen.<sup>70</sup> In case this materialises, some replacement of ‘blue’ hydrogen demand is expected, while lower hydrogen costs might also attract additional demand. The blue hydrogen installations could then function as a backup system and hedge for security of supply concerns. The ‘if’, ‘when’, and ‘to what extent’ this will happen remains to be seen, but the potential is real and extensive, and the market is currently moving in this direction. This is indicated by the righthand section of Figure 7, with the yet unclear blue/green ratio displayed as striped.

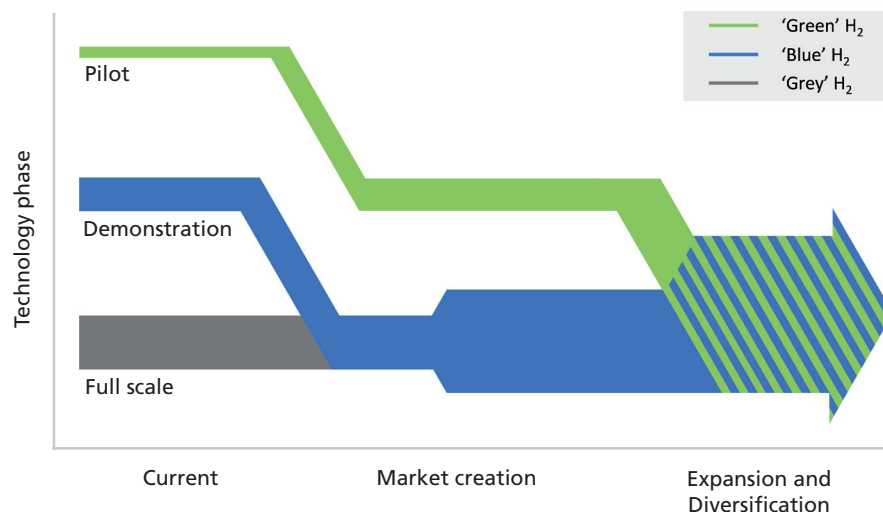


FIGURE 7 – POTENTIAL MARKET TRANSITIONS FOR HYDROGEN

69 100 MWe electrolysis projects are announced by joint ventures of Gasunie/Tennet/Thyssengas (16-10-2018, phased opening by 2022), Port of Amsterdam/Nouryon/Tata Steel (18-10-2018, FID expected in 2021) and Gasunie/Engie (18-10-2018, explorative research).

70 For example, see IRENA (2018) ‘Hydrogen from renewable power’, Agora (2018) ‘The future cost of electricity-based synthetic fuels’ or World Energy Council Germany (2018) ‘International aspects of a power-to-x roadmap’.

## BLUE-GREEN ROUTE

A schism is thus found between the longer-term expectations for 'green' hydrogen as opposed to the shorter-term achievability of 'blue' hydrogen. The desirability of such a 'blue-green' route is the topic of public debate, in which technical and economic arguments are mixed with environmental and political ideals and convictions. Such a debate is strengthening the position of clean molecules if a consensus-based outcome is achieved and broadly supported, and should therefore be kept in the public domain. From the presented cases three root causes for the arguments in favour of the blue-green route can be found.

Firstly, at current technology readiness levels, green hydrogen technology is not comparable yet on production volumes to blue hydrogen production. Whereas blue hydrogen production technology is well-known, proven and available on an industrial scale, electrolysis equipment has not reached this phase yet (here assuming PEM electrolysis technology will be the most widely used). Production volume capabilities reflect this, with blue hydrogen production volumes being multitudes of green hydrogen.<sup>71</sup> In case electrolysis equipment is directly coupled with RES power production, the capacity factor of RES generation will be an additional bottleneck for production volumes. While blue hydrogen production can be run almost non-stop, green hydrogen production is then limited by the capacity factor of the RES power supply.<sup>72</sup>

Secondly, assessing energy availability only, the RES power required as primary energy for green hydrogen is currently available in limited quantity. For example, if the current European hydrogen demand is to be met by green hydrogen, this would require over half of the current European renewable electricity production.<sup>73</sup> Furthermore, there is competition for the available RES energy with the power market, which is also pushing for decarbonisation. Large scale green hydrogen production should thus go hand-in-hand with significant additional rollout of renewable power production, for which the pace of capacity additions might run into constraints in terms of, for instance, availability of qualified personnel, production locations or lengthy legislative procedures. In comparison, the natural

71 For example, a typical blue hydrogen plant is capable of producing 100,000 nm<sup>3</sup> H<sub>2</sub> per hour (IEAGHG Technical report 2017-02), while the equipment used in Energiepark Mainz is limited at 1,000 nm<sup>3</sup> H<sub>2</sub>/h and the next generation PEM electrolyzers (Siemens Silyzer 300) is moving to 22,000 nm<sup>3</sup> H<sub>2</sub>/h.

72 IEAGHG Technical report 2017-02 assumes a 95% capacity factor for blue hydrogen, while, differing with location and RES source, RES power production may be limited to 25%-60% capacity factor.

73 Based on 92.1 bn m<sup>3</sup> H<sub>2</sub> demand in Europe (Roads2HyCom, 2007), 50 kWh/kh H<sub>2</sub> electrolysis electricity demand and 715.1 TWh renewable electricity generated (BP Statistical Review, 2018), green hydrogen production would absorb 58% of current renewable power production.

gas required for blue hydrogen production can be delivered by robust supply systems with ample supply.

Thirdly, the cost of green hydrogen is, among other things and including both factors above, currently higher than the cost of blue hydrogen.<sup>74</sup> As competitiveness with other decarbonisation options, potentially helped by government support schemes is required for market creation, cost is an important aspect. For green hydrogen, the requirement of governmental support would potentially be too large to be socially and politically acceptable. Therefore, blue hydrogen might be a more realistic option for market creation.

Until green hydrogen is available at sufficiently large volumes at competitive costs, there are thus rational arguments to opt for blue hydrogen in order to create a climate neutral hydrogen market and abate emissions on a short term. At the same time, green hydrogen technology is under development and is expected to become competitive at some point in the future. At that moment, since hydrogen is only a molecule, green hydrogen can join the market and complement or possibly even outcompete blue hydrogen production methods.

<sup>74</sup> Exact costs are dependent on many variables. For the costs impact of some and a comparison between green and blue hydrogen costs, see TKI Nieuw Gas (2018) 'Hydrogen roadmap' – Appendix 3.

## 5 CONCLUSION

Within the very broad spectrum of clean molecules, most developments currently involve hydrogen. Still, this is a broad subject and many different approaches and pathways are being advocated and pursued. In this paper, five hydrogen projects are used as case studies to give insights into the dynamics and drivers behind the development of a hydrogen market. The lessons and insights from the cases can be applied to strengthen the development path.

The diversity of the assessed projects showcases the versatility of clean molecules and the subsequent diversity in applications. As the roles and position of hydrogen in the energy system are, at this stage of development, still unclear, research and development in all directions of the solution space for hydrogen might turn out to be viable. Moreover, since hydrogen can be used as a fundamental building block for other, more complex clean molecules, the versatility can reach beyond direct applications. With a well-supplied and competitive hydrogen market, other (hydrogen based) clean molecule forms might become viable to serve sectors or applications hydrogen cannot, for example through longer hydrocarbon fuels or feedstocks.

By virtue of their versatility, clean molecules attract a wide range of stakeholders. These stakeholders can be driven by economic, environmental or national-strategic considerations. Moreover, the drivers are not stemming from a single paradigm, as shown by the Quest and Energiepark Mainz cases. Both the wide set of drivers and the validity of these from multiple paradigms is increasing the probability of enduring support in dynamic markets and social and political discourses by a shifting set of stakeholders.

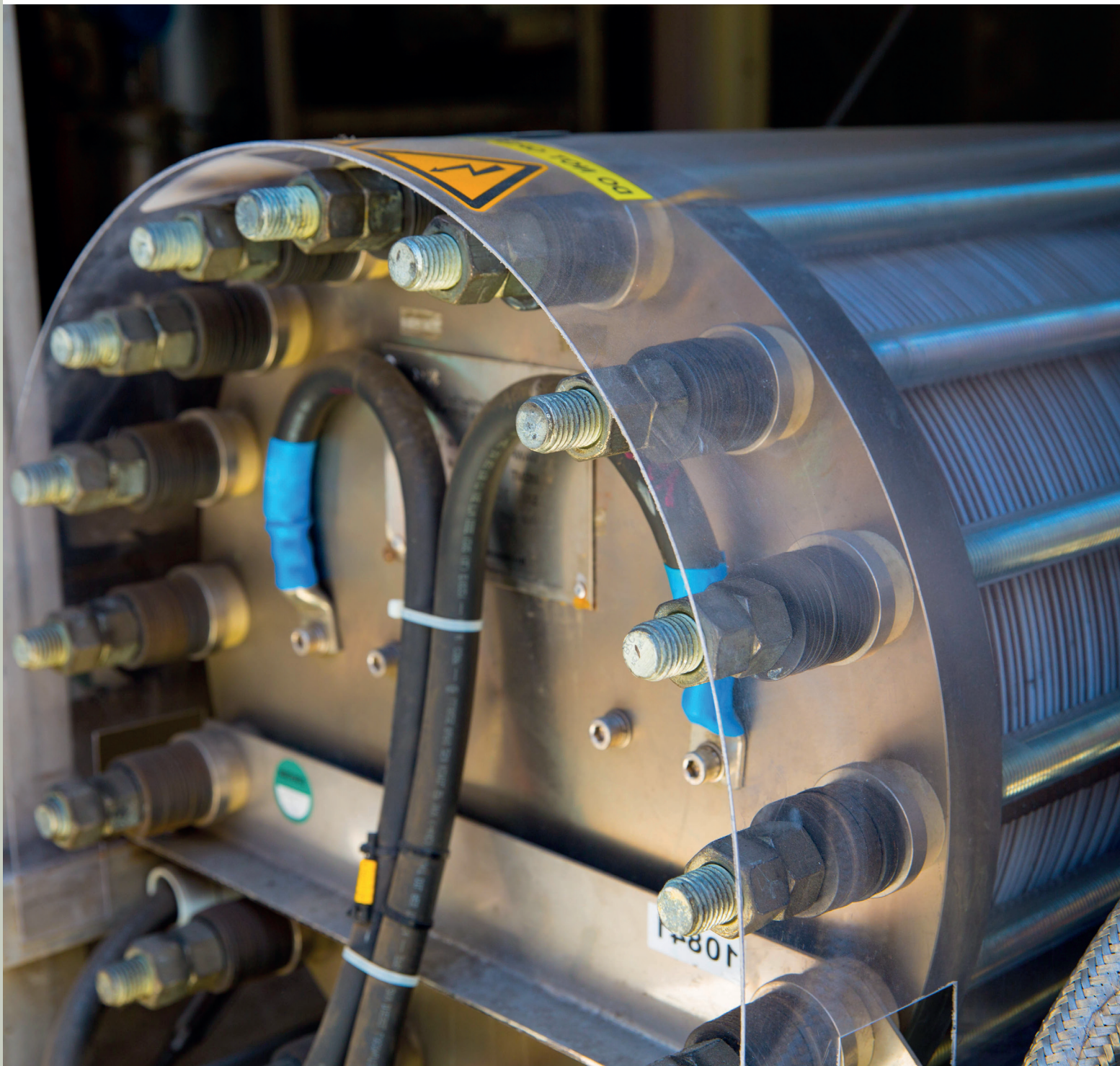
With the high number of projects being developed for different applications by pluriform stakeholders, driven by diverse interests from multiple paradigms, the development pathway of clean molecules as a whole is given a certain resilience. While not all initiatives will succeed, the success of individual projects can benefit the clean molecule proposition as a whole and so create a positive feedback to other projects. This has a positive effect on the likelihood of clean molecules reaching a mature market phase.

At the current technological readiness level, blue hydrogen can be produced in large volumes at a (more) competitive cost, while green hydrogen still requires further development of electrolysis equipment and increases in RES production capacity. For now, blue hydrogen has an appeal for use in market creation. If the market reaches maturity, it could receive hydrogen from alternative production methods, such as green hydrogen (potentially via imports). Depending on developments in for example, costs, technological capabilities, or customer preferences, a ratio between different sources of hydrogen, for example green, blue, imports or domestic production, will then result from this market behaviour.

For now, an integrated energy system with hydrogen as an important energy carrier to connect sectors, achieve a cost optimal energy transition, allow energy storage, and (international) transport remains an uncertain proposition. However, it is encouraging that, despite a lack of (international) coordination or of a clear image of an integrated system, different parts of such a system are being developed autonomously. Ultimately, all these elements could fit together and help in creating such a bright future.







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