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Keywords

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Abstract

The main aim of the ELEGANCY project is to accelerate the deployment of Carbon Capture and Sequestration (CCS) technologies in Europe through H_2-CCS chain networks. 5 country case studies are included as part of WP5. This document provides framework for the different case studies by giving an overview of H_2 purity requirements and H_2 utilization scenarios of the five case studies.

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1 INTRODUCTION

The main aim of the ELEGANCY project is to accelerate the deployment of Carbon Capture and Sequestration (CCS) technologies in Europe through H_2-CCS chain networks. 5 country case studies are included as part of WP5. This document provides framework for the different case studies by giving an overview of H_2 purity requirements and H_2 utilization scenarios of the five case studies.

1.1 Dutch case study

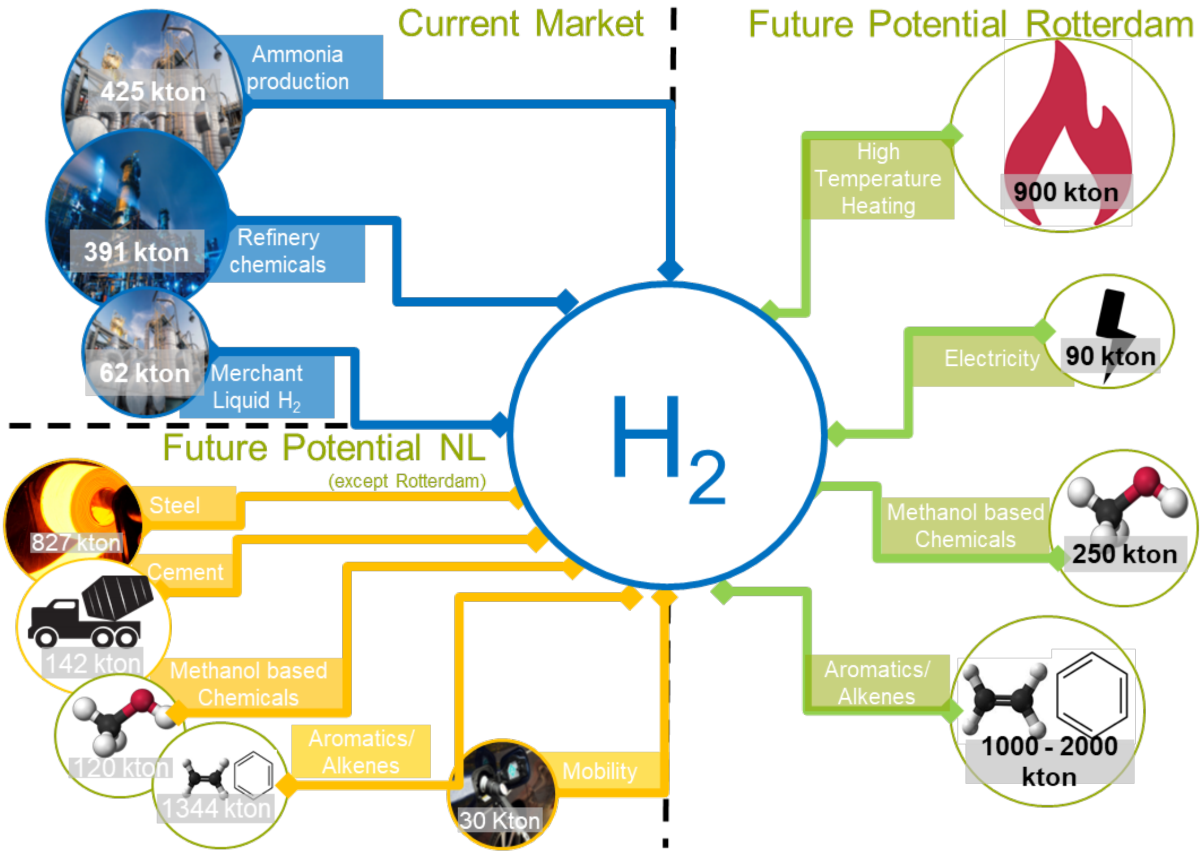


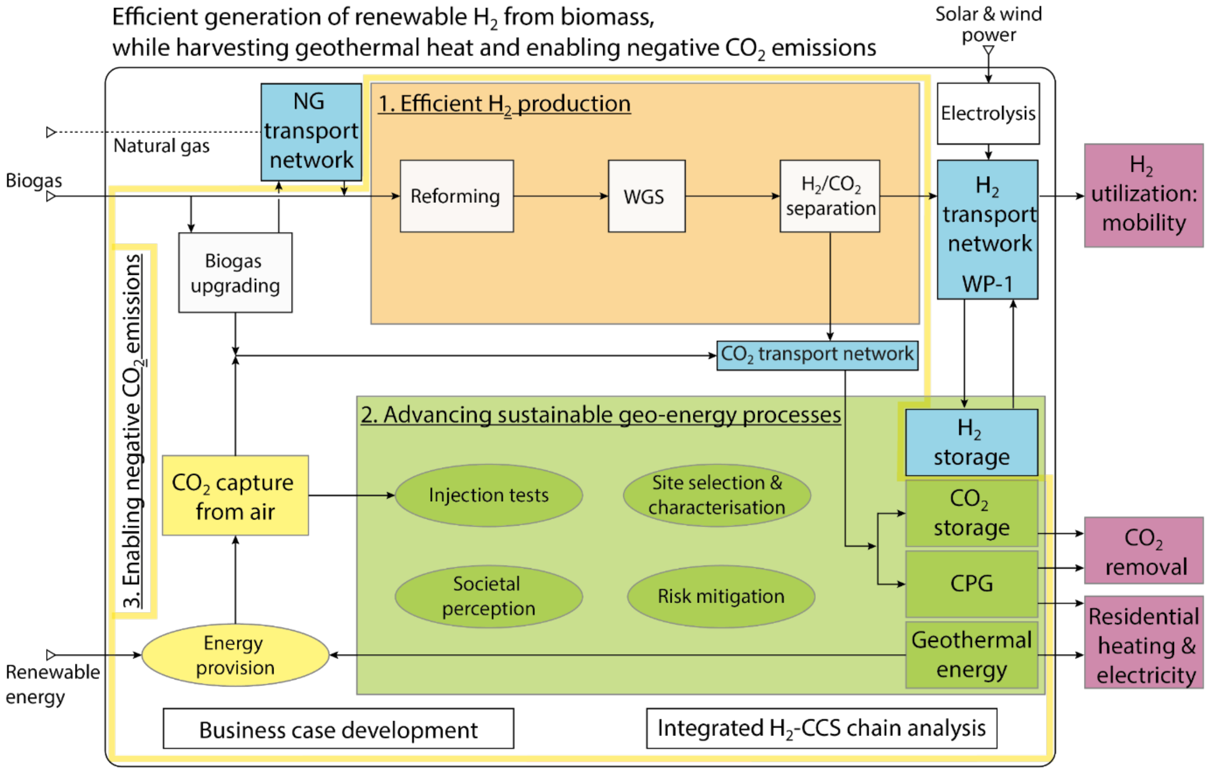
Figure 1.1: Overview of current market and future potential for the requirement of H_2 in the Netherlands, with a particular focus on future potential in the Rotterdam harbor.

Figure 1.1.1 shows the overview of H_2 capacity (Ktonnes/annum) required under the current market conditions in the Netherlands and its future potential in the Netherlands and the Rotterdam harbor. The overview is divided in three parts, 1) The current production of H_2 (mostly via steam methane reforming) in the Netherlands, 2) future potential of H_2 requirement in the Rotterdam petrochemical region and 3) future potential of H_2 requirement in the Netherlands (except Rotterdam). The following section shows the details of the estimated numbers presented in the overview.

ACT ELEGANCY, Project No 271498, has received funding from DETEC (CH), FZJ/PtJ (DE), RVO (NL), Gassnova (NO), BEIS (UK), Gassco AS and Statoil Petroleum AS, and is co-funded by the European Commission under the Horizon 2020 programme, ACT Grant Agreement No 691712.

1.2 Swiss case study

The Swiss case study focuses on decarbonizing the transport sector, which in 2015 accounted for 32% of national CO_2 emissions. It thereby provides an alternative to (fully) electrifying mobility, especially for heavy transport such as Lorries and buses. The case study uses natural gas and organic feedstock as a starting point. Natural gas and biogas will be reformed in a steam reformer with CO_2 capture, applying newly developed VPSA technology for the single cycle purification of hydrogen and CO_2. Solid biomass will be gasified, after which the product gas will be cleaned of contaminants CO_2 and hydrogen will be purified, likely also with the VPSA technology. The value chain is complemented with a full hydrogen and CO_2 transmission network, and hydrogen fuelling stations. To compare with other means of hydrogen production and use, also water electrolysis, and use in the Swiss industry may be included. For CO_2 storage, multiple options will be considered: storage in a saline aquifer in Switzerland; exporting it to countries with high storage capacities in depleted oil and gas fields; putting it to use in so-called CO_2 plume geothermal (CPG) energy generation: simultaneously storing CO_2 and using it as a working fluid for geothermal electricity production cycles. For the latter use scenario, also direct air capture (DAC) of CO_2 will be included. Given this value chain design, the Swiss case study has the opportunity to provide decarbonized fossil based hydrogen, deliver negative emissions when using organic matter as feedstock or when using DAC, and generate carbon free electricity through CPG. Important elements of the Swiss case study also include paving the way for possible future injection tests. They include setting up criteria for site selection, drawing up active plans for risk management, developing sound communication strategies, and identifying permitting needs and barriers.



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1.3 UK case study

The ELEGANCY UK case study informs the practical and cost-effective implementation of H_2 and CCS at large scale for urban low-carbon domestic heating and application to a refinery and petrochemicals industrial site.

Carbon dioxide capture, transport and storage (CCS) was deemed economically feasible at the large-scale planned for 100% H_2 for domestic heating by the H21 Leeds City Gate project. Phases of implementation of H_2 and CCS are envisaged, such as that shown, for illustrative purposes only, in Figure 1.3.1.

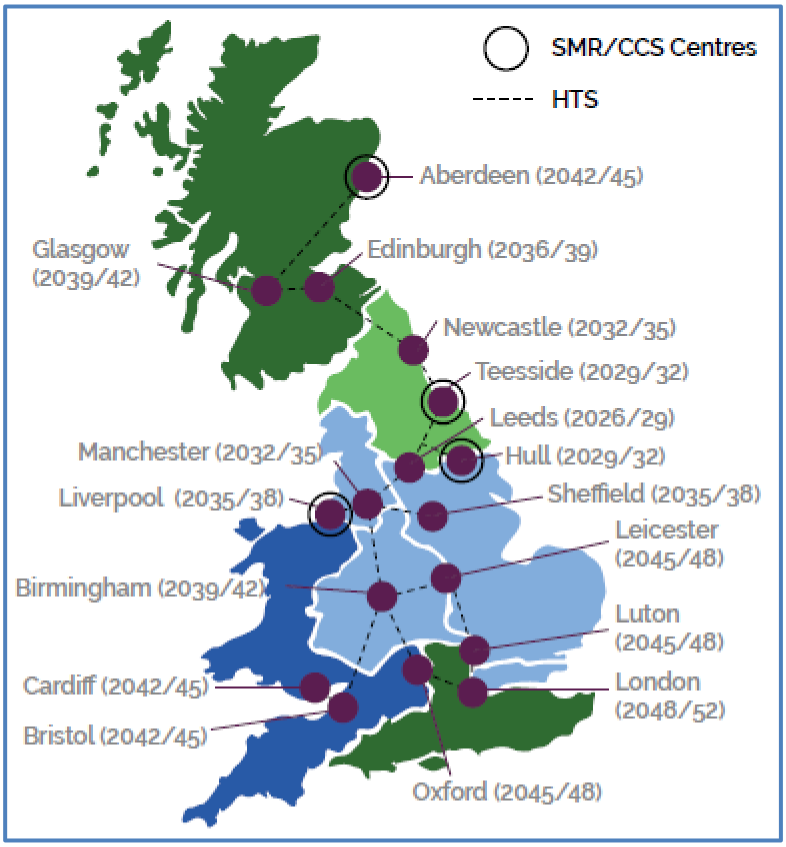

Figure 1.2: UK H21 Rollout – H2 supply large city by city and Hydrogen Transmission System (HTS), from H21 Leeds City Gate report[1] *(2016). CO_2 generated by Steam Methane Reformation (SMR) at CCS centres.*

The H21 Roadmap project gathered evidence to support a decision to implement the first phase of roll-out of 100% H_2 for domestic heating of three large UK cities. The ELEGANCY UK case study undertakes as assessment of the cost-effective CO_2 transport and storage needs for the first phase of roll-out for three UK cities in 2026 to 2032. The ELEGANCY H_2-CCS chain modelling tool is needed to assess the economically feasible delivery of CO_2 transport and storage for the

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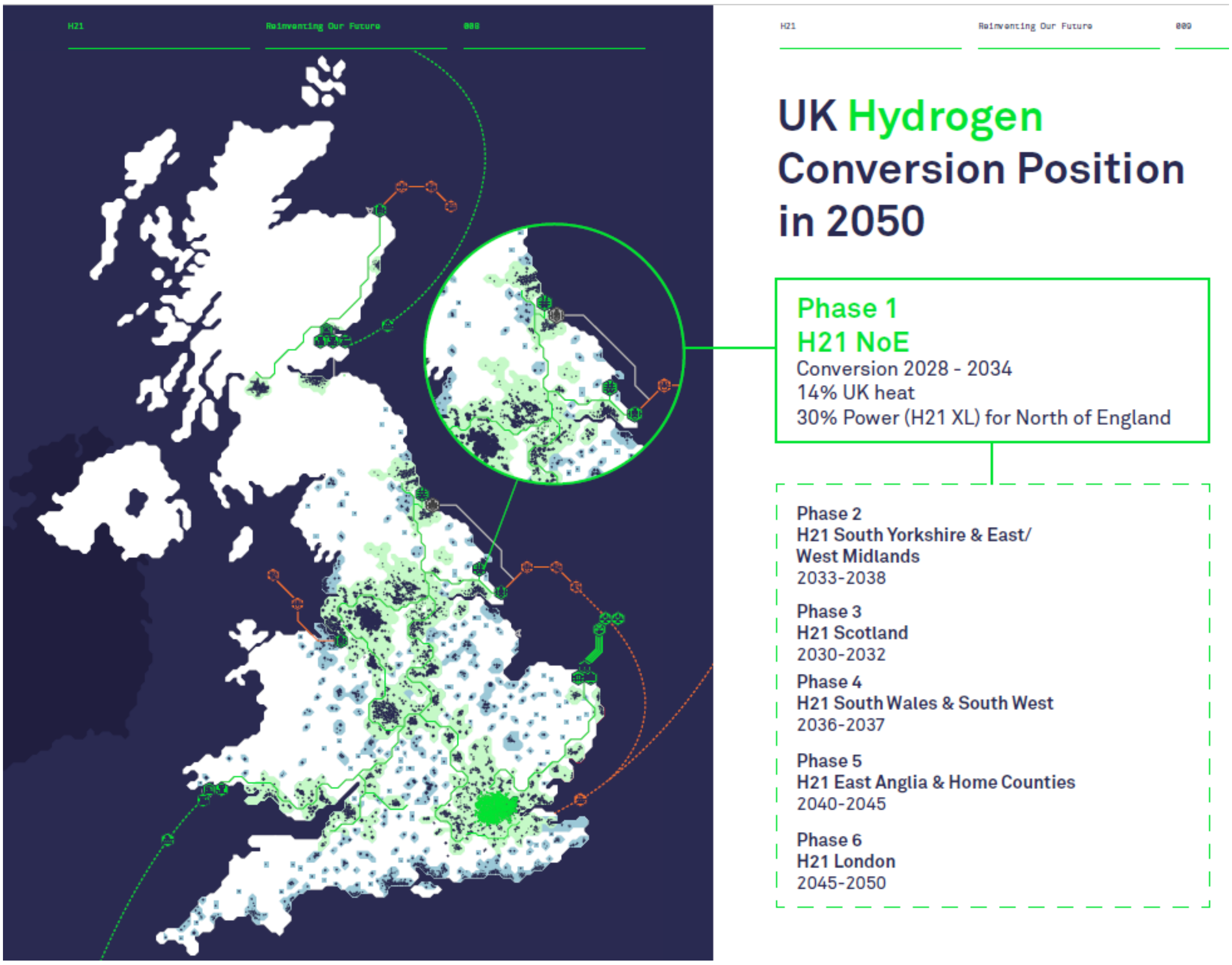
[1] https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf

first and all subsequent phases of implementation in the period 2026 to 2052. Also, to sustain the CO_2 transport and storage network for domestic heating of large cities by 100% hydrogen to 2100. The phased implementation of the H21 Roadmap for city by city roll-out has been taken up by the H21 North of England Project, with public launch of detailed findings in November 2018[2]. H21 North of England report proposes conversion will begin in 2028, with expansion across 3.7 million properties in Leeds, Bradford, Wakefield, York, Huddersfield, Hull, Liverpool, Manchester, Teesside and Newcastle over the following seven years. A six-phase further UK rollout could see 12 million more homes across the rest of the UK converted to hydrogen by 2050.



UK Hydrogen Conversion Position in 2050

Phase 1
H21 NoE
Conversion 2028 - 2034
14% UK heat
30% Power (H21 XL) for North of England

Phase 2
H21 South Yorkshire & East/ West Midlands
2033-2038

Phase 3
H21 Scotland
2030-2032

Phase 4
H21 South Wales & South West
2036-2037

Phase 5
H21 East Anglia & Home Counties
2040-2045

Phase 6
H21 London
2045-2050

Figure 1.3 H21 North of England Project phased UK hydrogen conversion[2], circled area of Phase 1 also illustrated in Figure 1.4.

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[2] https://www.northerngasnetworks.co.uk/wp-content/uploads/2018/11/H21-Meeting-UK-Climate-Change-Obligations.pdf

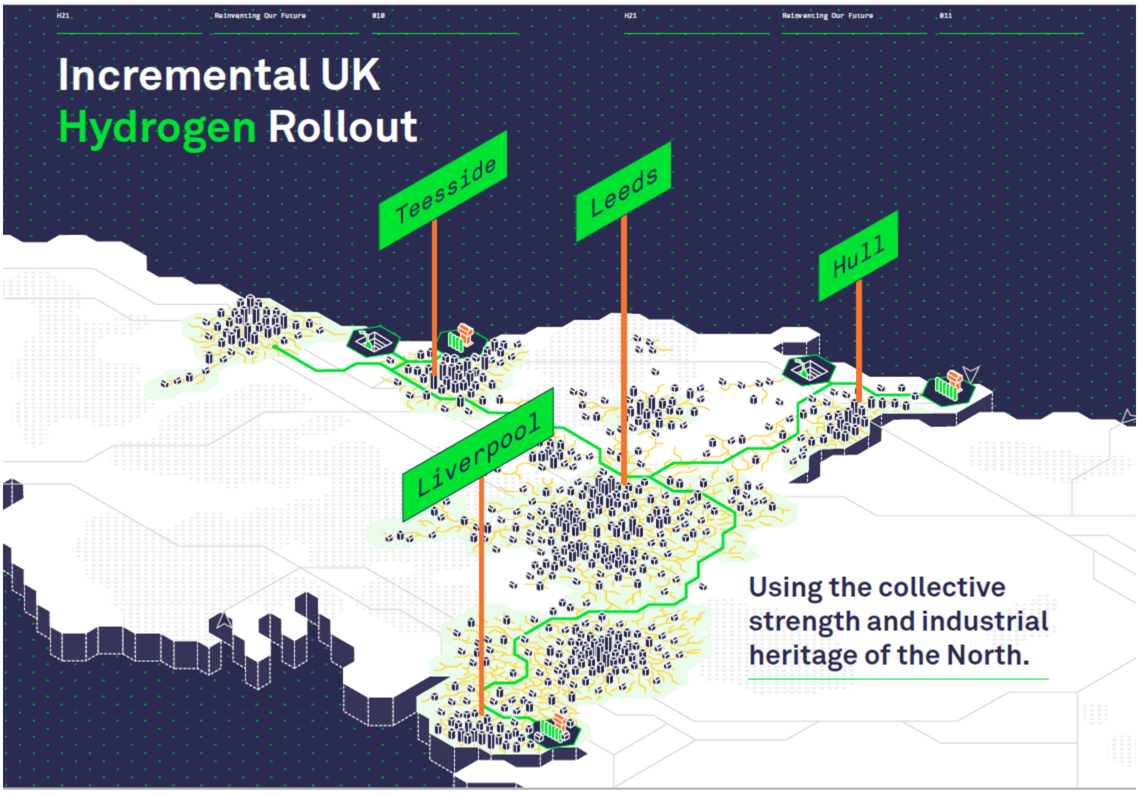

Figure 1.4 H21 North of England Phase 1 conversion to hydrogen for the cities of Leeds, Bradford, Wakefield, York, Huddersfield, Hull, Liverpool, Manchester, Teesside and Newcastle from 2028 to 2034[2].

The UK case study aims to investigate the storage requirements for CO_2 from methane reforming to produce H_2 as planned at the Teesside industry cluster for domestic heating supplied to seven large UK cities. The storage resource required to achieve the H21 North of England ambition is to be assessed. The impact of the variation in CO_2 supply associated with fluctuating seasonal demand for domestic heating will be modelled and compared with existing practise and management of offshore fields used for natural gas storage. The requirement for the H_2-CCS chain modelling tool for the UK case study will inform the practical and cost-effective implementation of a transport and storage network for H_2 and CO_2.
Initial modelling of H_2 reformation assumes CO_2 generation by Steam Methane Reformation (SMR) by Pressure Swing Adsorption (PSA), although more innovative technologies, such as Autothermal Reformation (ATR), introducing greater efficiency and lower cost are assumed in the later phases of implementation.

The CO_2 storage requirement for low-carbon development of the Grangemouth industrial site will be assessed within the context of plans for low-carbon gas in Scotland. The Scottish Energy Policy[3] considers the implementation of H_2 and CCS for low-carbon gas for industrial processes, to power electricity generation and urban domestic heating. Application of the H_2-CCS chain tool at Grangemouth, as a refinery and petrochemicals case study, will assess the spectrum of

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[3] https://www.gov.scot/publications/scottish-energy-strategy-future-energy-scotland-9781788515276/

implementation from CCS on existing industrial sources of CO_2 to H_2-CCS for heating to drive industrial processes.

Business case tools developed in ELEGANCY will be applied to the large scale delivery of H2-CCS in the region encompassing the north-east of England and south-east of Scotland with guidance provided by INEOS and other key stakeholders.

The potential end-usage of hydrogen in the UK, as a low-carbon technology, for existing and potential end-use markets is reviewed in Appendix C: Potential UK hydrogen market sectors.

1.4 German case study

The German case study focuses on the feasibility of a decarbonized gas infrastructure. Therefore, three scenarios will be developed and validated. The first scenario covers a decarbonisation of big industrial CO_2 point sources. As the Norwegian natural gas in this scenario still is delivered to Germany without being decarbonized at its source, the capture of the amount of CO_2 emitted by this natural gas could be the minimal reduction aim of this scenario. The second scenario is focusing on the addition of hydrogen from Norway into the existing natural gas network, the third scenario determines the feasibility of a new separate H2 infrastructure. The results will be evaluated economically and ecologically. All the work in the case study is processed with an interdisciplinary approach, as the technical, economic, social and law aspects flow together in this case study.

1.5 Norwegian case study

The Norwegian case aims to identify and develop a business case for a Norwegian H_2 value chain based primarily on natural gas. For Norway, a key question is whether it is optimal to convert natural gas to H_2 in Norway and export this via new (or converted existing) pipelines, or to export natural gas in existing pipelines for distributed H_2 conversion in Europe and then import the produced CO_2 for storage in the North Sea via a new pipeline for this purpose. The Norwegian case study will additionally evaluate the benefit of converting Norway’s large natural gas resources to H_2 with CCS, primarily to satisfy the expected growth in worldwide demand of H_2 as an energy carrier and additionally to mitigate emissions in off-shore platforms and the transport sector. This case study will also study the possible synergies with the Norwegian full-scale CCS project.

Using the tools developed in WP4 of the project, the Norwegian case study will develop an optimal strategy and infrastructure investment scenario for Norwegian H_2 export and utilization, including the location of H_2 production, CO_2 storage and transport of both gases to/from Continental Europe in synergy with the Norwegian full-scale CCS project.

2 H2 PURITY REQUIREMENTS

The hydrogen purity requirements presented in Table 2-1 are taken from literature[4]. The industrial fuel specification has been updated to better reflect existing practise for H_2 combustion with diluents to minimize NOx emissions. It should be noted that while Table 2-1 provides requirements from an end use perspective, from a transport perspective it is probably better to transport high purity H_2 to reduce unnecessary compression transportation costs and also from corrosion aspects. Additionally, ship transport of H_2 requires 99.99% purity.

Table 2.1: Hydrogen purity requirements

		H_2 purity (min) [%]	Impurity limits (max) [ppm]	Source
Refining		~95	S: low levels	[60], [112]
Ammonia		23-25 (N_2:74-77)	CO_2, CO, H_2O and S: low levels	[5], [38]
PEM fuel cells for automotive purposes		99.97	H_2O:5, HC:2, O_2:5, He:300, N_2+Ar:100, CO_2:2, CO:0.2, S:0.004, NH_3:0.1 H_2O:5, HC:100, O_2:5, He+N_2+Ar:500, CO_2:2, CO:0.5, S:0.01, NH_3:0.1	[105] [23]
PEM fuel cells for stationary purposes[a)]	Cat. 1	50	H_2O:NC, HC:10, O_2:200, N_2+Ar+He:50%, CO:10, S:0.004	[106]
	Cat. 2	50	H_2O:NC, HC:2, O_2:200, N_2+Ar+He:50%, CO:10, S:0.004	[106]
	Cat. 3	99.9	H_2O:NC, HC:2, O_2:50, N_2+Ar+He:0.1%, CO:2, S:0.004	[106]
Gas turbines		Low	Limited amount of Na, K, V and S	[115]
Industrial fuel (e.g. power generation or heat energy source)		99.90[b)]	H_2O:NC, HC:NC, O_2:100, N_2:400, S:10	[104]
		50[c)]	H_2O:NC, HC:NC, CO2, CO: low levels, O_2:100, N_2+Ar+He:50%, S:10	

NC = Not to be condensed, HC = Hydrocarbons on methane basis, S = Sulphur compounds

[a] The categories are defined to meet the standards of different stationary applications

[b] This value is from an ISO standard and is most likely from the supply perspective rather than end-use

[c] A suggested minimum purity from an end use perspective

Detailed H_2 production specifications and technical requirements from a H_2 supplier's perspective are provided in Appendix A.

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[4] Voldsund, Mari, Kristin Jordal, and Rahul Anantharaman. 2016. "Hydrogen Production with CO2 Capture." *International Journal of Hydrogen Energy* 41 (9):4969–92

3 H2 UTILIZATION SCENARIOS

3.1 Dutch Case Study

3.1.1 Current market for H_2 production:

The majority of the production of H_2 in the Netherlands comes from the petrochemical refinery (mainly Rotterdam) and the fertilizer facility of Yara and OCI Nitrogen, totalling an estimated annual production of 900 Ktonnes/annum. Of this, approximately 335 Ktonnes/annum is estimated use for the production of Ammonia (1.9 Mtonnes/annum) at Yara[5] and 324 Ktonnes/annum for the production of refinery chemicals[6,7]. Table 3-1 shows a detailed description of H_2 production facilities in the Rotterdam area. The remaining capacity is covered as production in other petrochemical sites (south NL), NH_3 at OCI, production as liquid H_2 by merchant companies and as side products from refinery processes (eg. ethylene, styrene manufacturing).

Table 3.1: Production capacity of H_2 for the production of refinery chemicals in Rotterdam.

Plant site	Owner	Capacity (Ktonnes/annum)	Process /source	Reference
Botlek	Exxon Chemicals	22	SMR	2) Hycom
Pernis	Air Products	1	SMR	2) Hycom
Pernis	Shell Chemicals	51	SMR	2) Hycom
Rozenburg	Air Liquide	9	SMR	2) Hycom
Rozenburg	Air Liquide	11	ATR	2) Hycom
Rozenburg	Air Products	16	SMR+LH2	2) Hycom
Pernis	Air Liquide	104	SMR	3) Facts and Figures (Port of Rotterdam).
Botlek	Air Products	110	SMR	Website Air Products[8].

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[5] Global production capacities Yara: http://yara.com/about/production_sites/global_production_capacity/

[6] Steinberger-Wilckens, R., Trümper, S.C., Perrin, J. and Maisonnier, G., Industrial surplus hydrogen and markets and production, EU report, Document No.: R2H2001PU., 2007

[7] Facts and Figures Petrochemical Cluster (Port of Rotterdam), www.portofrotterdam.com/nl/lading-industrie/raffinage-en-chemie/facts-figures-brochure

[8] http://www.airproducts.com/Company/news-center/2010/06/0622-air-products-start-met-bouw-nieuwe-waterstoffabriek-in-de-botlek.aspx

3.1.2 Future potential for H_2 production in Rotterdam:

In petrochemical refinery, H_2 can be potentially used in the future for high temperature heating via combustion, electricity production via fuel cells, production of methanol-based chemicals (C_1 chemistry) and furthermore the production of aromatics and alkenes (also via methanol). Figure 3.1.1 shows the estimated future potential of H_2 requirement for the Rotterdam refinery area. Below, the basis of the estimated numbers are explained:

- **High temperature heating** by combustion of H_2 can be used for a significant amount of refinery processes currently using high pressure steam or furnaces. Figure 3.1.2 shows the energy use (PJ/annum) by high temperature processes in the Port of Rotterdam. The energy consumption is estimated based on the production capacity of different refinery processes obtained from the Port of Rotterdam[9]. The current energy demand for such processes in Rotterdam harbour is estimated as 135 PJ/annum which potentially require a H_2 capacity of ~ 0.93 million tonnes/year. Currently, a significant portion of this heat is provided by burning refinery gas from the existing processes. An alternative to the use of refinery gas use can provide a head start for the potential use for H_2.

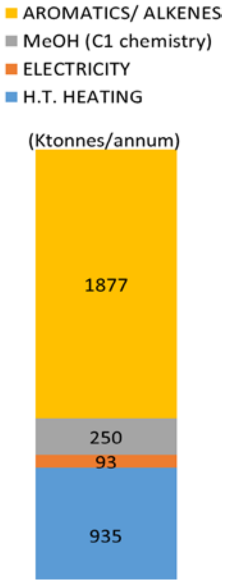

Figure 3.1:An Overview of future potential of H_2 requirement (Ktonnes/annum) in the Rotterdam harbour.

- **Direct electricity use** for the production of chemicals by converting H_2 to electricity with use of fuel cells has the potential for use in the refinery processes. Specifically targeted for high electricity consuming processes such as production of chlorine, poly-urethane and polycarbonate. The electricity requirement for Cl_2 production of 600 Ktonnes/annum[10] in Rotterdam is estimated to use approximately 93 Ktonne of H_2 per annum (depicted in Figure 3.1.1). Additionally, processes with high pressure and high flow rate/ pumping rate such as ethylene oxide, propylene oxide also require large amount of electricity totalling to a capacity estimate of ~ 100 - 200 Ktonnes/ annum. The efficiency of the fuel cell is assumed as 60%.

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[9] See footnote 5

[10] See footnote 5

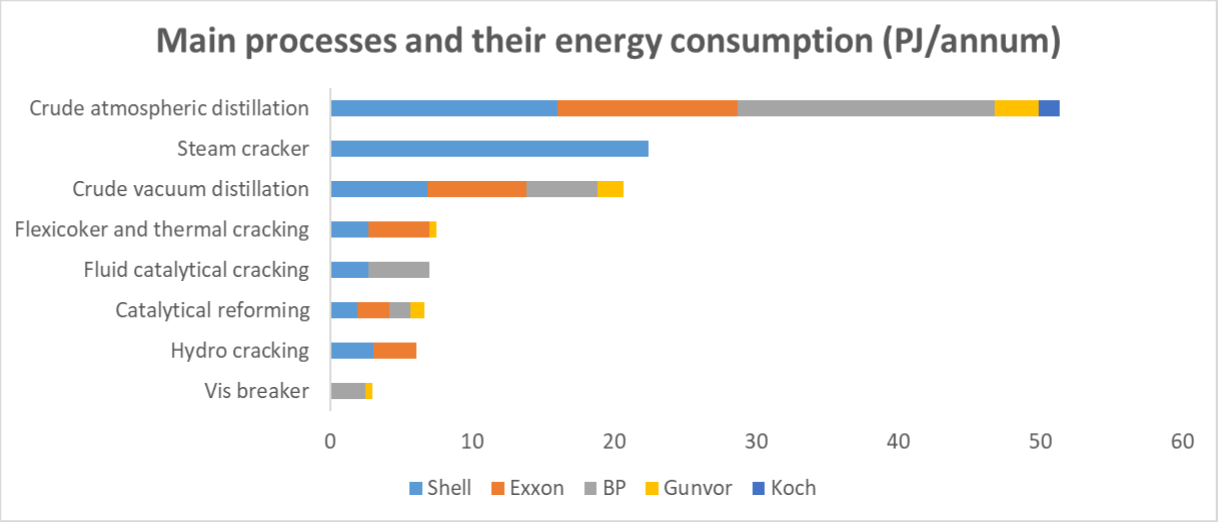

Figure 3.2: Energy use (PJ/annum) by high temperature processes in the Rotterdam harbour.

- **Methanol (MeOH)** is used as a feedstock for the production of di-methyl ether, formaldehyde, methyl (and ethyl) tert butyl ether and polymethyl methacrylate, and can be produced by reacting carbon dioxide with H_2. Figure 3.1.3(a) shows the current production of these chemicals in the Rotterdam harbour[3]. Based on the production capacity of formaldehyde and DME in the Rotterdam harbour[11], potentially 250 Ktonnes/annum of H_2 capacity will be required. Currently, methanol is not produced but imported into the Rotterdam harbour. This capacity can be potentially covered using H_2 and CO_2 as feedstocks.

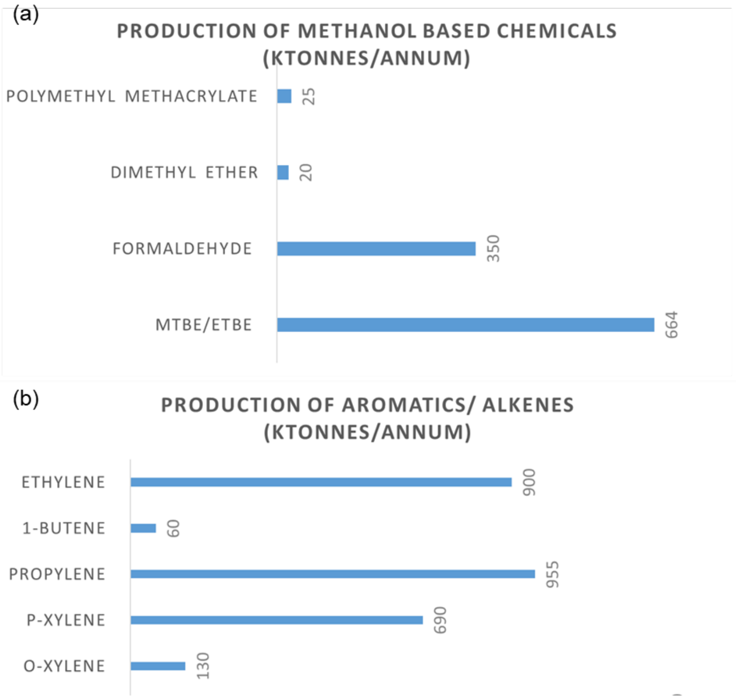

Figure 3.3:(a) The production capacity (Ktonnes/ annum) of methanol based chemicals in the Rotterdam harbour, (b) The production capacity (Ktonnes/ annum) of aromatic/ alkene based chemicals in the Rotterdam harbour.

- **Aromatics and alkenes** can also be produced from methanol. Based on the current capacities of alkenes and aromatics being produced at the Rotterdam harbour[12], an estimated ~1000 -2000 Ktonnes/annum of H_2 can be potentially utilized. This capacity is dependent on the overall production capacity aromatics and alkenes of ~ 4000 Ktonnes/annum. The estimation is based on the combined aromatic and alkene

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[11] See footnote 5

[12] See footnote 5

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process described in literature[13]. Ward et al describes the use of zeolite catalyst for production of hydrocarbons (alkenes, aromatics and alkanes) from methanol. For simplicity of calculations, we have assumed that the alkanes in the product (~12% by weight) are converted to alkenes and aromatics. Furthermore, the variation in H_2 requirement depends on the route used for the production of methanol (via SMR or via CO_2). Figure 3.1.3(b) shows the distribution of production capacity of different aromatics and alkenes produced in Rotterdam. The production of aromatics and alkenes from H_2 (via methanol) is a progressive proposition and is expected to be of potential in far future after the current refinery assets have considerably aged and there is a significant infrastructure for renewable H_2 available.

3.1.3 Future potential for H_2 production in the Netherlands (except Rotterdam):

The industries which have future potential for the consumption of H_2 in the Netherlands include high temperature industries like production of steel and cement, production of chemicals (methanol, ammonia, aromatics and alkenes) and new prospects such as transport and mobility.

- Steel: Tata steel (Ijmuiden) has a production capacity of 7 Mtonnes/annum of steel[14]. H_2 can be potentially used in the production of steel for providing the heat and also for providing a reductive environment. Up to 90% of the total 827 Ktonnes/annum H_2 required is estimated to be used for heating and the rest for reduction of Fe_2O_3 to Fe.
- Cement: The production of cement also requires high temperature processing. For a total production of 7.45 Mtonnes/annum of cement in Netherlands and Belgium[15], an estimated 142 Ktonnes/ annum of H_2 would be potentially required for providing the heat.
- Chemical production: Based on the annual production capacity of 60 Ktonnes each of NH_3 and MeOH, an estimated potential of 120 Ktonnes/ annum of H_2 is potentially required in the north of Netherlands[16].
- Aromatics and Alkenes: Apart from Rotterdam, other locations (eg. Terneuzen and Bergen op Zoom) also are involved in production of alkenes/ aromatics. Based on the ethylene production capacity of ~ 3100

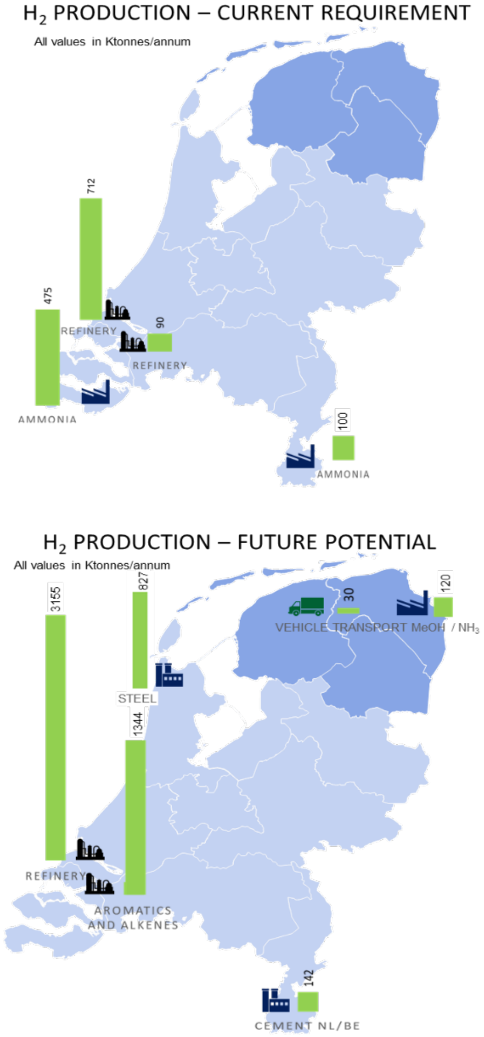

Figure 3.4: Overview of current requirements and future potential of H_2 market in the Netherlands.

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[13] Ward, Tess; Weishaar, Jonathan; Wilkison, Brady; and Ruskowsky, Gabrianna, "Methanol to Aromatics" (2016). *Honors Theses AY 15/16.* Paper 21.

[14] Steel production capacity in Netherlands: https://www.trade.gov/steel/countries/pdfs/2017/q2/exports-dutch.pdf

[15] Cement production: http://www.globalcement.com/magazine/articles/663-cement-in-belgium-and-the-netherlands

[16] See footnote 8

Ktonnes/annum from Sabic and Dow, a potential H_2 production via the methanol route can be estimated as~ 1350 Ktonnes/annum[17].

- Vehicle transport: Based on expectations from Noordelijke Innovation board, for the region of North Holland, an estimated 30 Ktonnes/annum can be potentially used for vehicle transport in the north of Netherlands[18]. A detailed mapping of H_2 use is given in appendix B.

Note that the above list for the H_2 use in the Netherlands, can be extended with additional applications such as heat and electricity use in residential/ commercial buildings, vehicle transport etc. However, to keep the focus of this study towards the industrial case of petrochemical (process) industry in the Rotterdam area, these possibilities are considered out of scope.

3.1.4 Summary

Table 3-2 is based on the original Figure B.1 provided from the Dutch Case study.

Table 3.2: H_2 utilization (in t/y) scenario for Dutch case study.

Sector	Location	Year			
		2017/8	2021	2030	2035
Transport	Northern-Netherlands			30k	
Industry	Rotterdam	400 K	400 - 500 K	400 - 650 K	400 - 800 K
Grid balancing			0 – 45 K	0-90k	0-90 K
Industry	Southern Netherlands	425 K	425 K	425 K	425 K

3.2 Swiss Case Study

3.2.1. Transport Sector

The mobility sector is the one causing the highest greenhouse gas emissions in Switzerland – it contributed 32% of national emissions (including aviation) in 2015 (cf. footnote[19]). It is also the sector with the highest demand of final energy, 36% in 2016, and it is almost entirely depending on oil-based fuels[20]. On top of that, it is the only sector with still growing CO_2 emissions: while these emissions have gone down since 1990 in households, the industry, and the service sector, the emissions of the mobility sector today are about 5% higher than 1990 (cf. footnote[19]). The Swiss power sector hardly generates any CO_2 emissions, since it is largely based on hydropower

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[17] Ethylene production: www.petrochemistry.eu/about-petrochemistry/facts-and-figures/crackers-capacities.html?cgv0c=264

[18] H_2 in north NL: www.deingenieur.nl/uploads/media/5880bffadd9af/Green%20Hydrogen%20Economy%20in%20Northern%20Netherlands.pdf

[19] Treibhausgasinventar der Schweiz. Swiss Federal Office for the Environment, Bern, Switzerland.

[20] Schweizerische Gesamtenergiestatistik 2016. Swiss Federal Office for Energy, Bern, Switzerland.

and nuclear power, contributing 59% and 33% to domestic generation, respectively, in 2016 (cf. footnote[21]).

Using hydrogen in fuel cell vehicles – lorries, buses and passenger vehicles – may be a promising technology option for decarbonizing the transport sector. However, such fuel cell vehicles can only contribute to decarbonization of the transport sector, if hydrogen production does not cause any substantial greenhouse gas (GHG) emissions[22] [23] [24].

Hydrogen market potentials in terms of potential annual demand for the Swiss mobility sector are quantified for today and for 2035. Estimates for today are based on overall mileage by lorries, buses and passenger vehicles in 2015/2016 (latest statistics available), estimates for 2035 on a "most likely" scenario for the development of distances travelled developed by the Swiss Federal Office for Spatial Development ARE[25]. These mileages per vehicle category are linked to vehicle-specific fuel consumption data, which allows for quantification of potential hydrogen demand today and in 2035 in case all vehicles would be equipped with fuel cell power trains.[26] Such a complete penetration of the vehicle market with fuel cell vehicles is likely unrealistic and can therefore only represent an upper boundary of potential hydrogen demand. Any estimate of future penetration rates would, however, be arbitrary. Whether or not fuel cell vehicles will play a major role in the future transport sector depends on many factors related to technology and market development, economic development, consumer behavior, policy and infrastructure development as well as competing technologies such as battery electric vehicles[27]. For the time being, future development of all these factors, their interdependencies within the complete energy system and their effects on the success of fuel cell vehicles cannot be estimated in a reasonable way and there is no reliable model available, which would be able to take into account all those factors and simulate future market penetration of fuel cell vehicles in Switzerland. In the past, projections of new technologies in vehicle markets were most often (far) too optimistic[28] and therefore not very useful. Here, only the maximum annual potential for hydrogen demand at 100% market share of fuel cell vehicles (buses, lorries and passenger vehicles) is provided. However, in the course of the ELEGANCY project, available models covering the Swiss energy and transport sectors will be supplemented with H_2/CCS chain related processes and used for an evaluation of future penetration of fuel cell vehicles considering a variety of boundary conditions.

The calculations have been performed using the following basic parameters:

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[21] Schweizerische Elektrizitätsstatistik 2016. Swiss Federal Office for Energy, Bern, Switzerland.

[22] Bauer *et al*., The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. Applied Energy 157 (2015) 871-883.

[23] Miotti *et al*., Integrated environmental and economic assessment of current and future fuel cell vehicles. International Journal of Life Cycle Assessment (2017) 22:94-110.

[24] Simons and Bauer, A life-cycle perspective on automotive fuel cells. Applied Energy 157 (2015) 884-896.

[25] Zukunft Mobilität Schweiz – UVEK-Orientierungsrahmen 2040. Swiss Federal Office for Spatial Development ARE, Bern, Switzerland.

[26] In reality, hydrogen demand for fuel cell vehicles today is negligible. There are only a handful passenger fuel cell vehicles, a few lorries and buses, operated as "pilot projects".

[27] Wasserstoffmobilität in der Schweiz, «Positionspapier». Swiss Federal Office for Energy, Bern, Switzerland.

[28] McDowall, Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies. Environmental Innovation and Societal Transitions 20 (2016) 48-61.

Energy content hydrogen (LHV): 120 MJ/kg

Energy content diesel: 35.95 MJ/l

Table 3.3: Quantification of hydrogen demand for passenger vehicles, buses and transport vehicles in Switzerland with a fuel cell vehicle share of 100%. Projected consumption rates for 2035 are extracted from the original table given in Appendix B.

Agent	Specific fuel consumption [MJ/km]	Consumption [t/year]
Private cars	1.0	533 000
Buses	8.9	33 200
Light transport	1.5	63 900
Heavy transport (3.5t-7.5t)	1.96	1 750
Heavy transport (7.5t-18t)	2.84	36 700
Heavy transport (18t-26t)	3.88	18 200
Heavy transport (>26t)	5.6	21 200

Overall hydrogen consumption in the Swiss mobility sector

These calculations result in a hypothetical, annual hydrogen demand in the Swiss mobility sector – to be interpreted as an upper boundary – of 7.97E+08 kg hydrogen today and 7.08E+08 kg hydrogen in 2035. The breakdown into passenger vehicles, buses and lorries is shown in Figure 3.2.1.

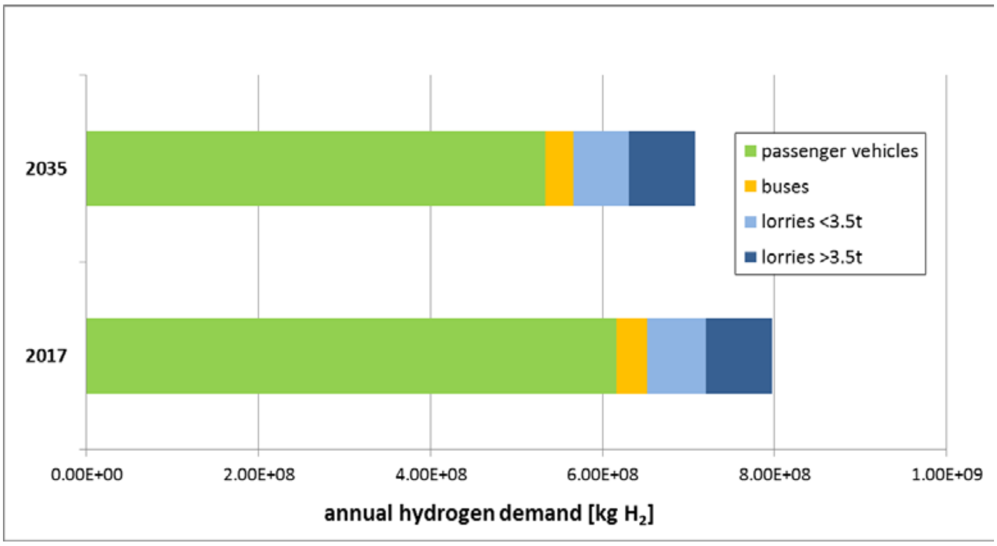

Figure 3.5: Annual hydrogen demand in the Swiss mobility sector with 100% fuel cell vehicles.

3.2.2 Summary

Table 3.4: H2 utilization (in t/y) scenario for Swiss case study

Sector	Location	Year			
		2017/8	2021	2030	2035
Transport	Switzerland	797k			708k

3.3 UK Case Study

3.3.1 Ambitions for the wider deployment of H_2 as an energy carrier

Hydrogen for domestic and industrial heating is included within the 2017 UK Clean Growth Strategy[29] and the Energy Strategy for Scotland[3]. However, there is no explicit provision of volumes of H_2 production for low-carbon heating, domestic or commercial, or for transport which comprise 13% and 24% of UK emissions, respectively. Although H_2 use or complete electrification are assumed as options, the proportions and their likelihood are not given. More recent publications by the UK Climate Change Committee[30, 31, 32], have indicated that a mix of all low-carbon energy sources will be needed for the UK to achieve net-zero greenhouse gas emissions by 2050 and in Scotland by 2045[33] announced in May 2019.

Analysis by the CCC[31] assesses how the UK and its devolved nations will meet the challenge of reaching net-zero greenhouse gas (GHG) emissions by 2050. The CCC consider:

> ‘It is impossible to predict the exact mix of technologies and behaviours that will best meet the challenge of reaching net-zero GHG emissions, but our analysis [in this report] gives an improved understanding of what a sensible mix might look like’

The CCC illustrate scenarios for the 2020s, 2030s and 2010s (Figure 3.6) and the measures, taken together, would reduce UK emissions by 95-96% by 2050. The scenarios illustrated, relevant to the ELEGANCY H_2 and CCS research, include development of a hydrogen economy, carbon capture and storage in industry and extensive electrification:

- The CCC envisage the development of a hydrogen economy to service demands for some industrial processes, for energy-dense applications in long-distance heavy-goods vehicles and ships, and for electricity and heating in peak periods. By 2050, a new low-carbon industry is needed with UK hydrogen production capacity of comparable size to the UK's current fleet of gas-fired power stations.

- CCS is a regarded by the CCC as a necessity not an option to achieve the UK net-zero target by 2050. Implementation of CCS is foreseen in industry, with bioenergy (for GHG removal from the atmosphere), and very likely for hydrogen and electricity production. The scenarios involve aggregate annual capture and storage of 75-175 Mt CO_2 in 2050, which would require a major CO_2 transport and storage infrastructure servicing at least five industrial clusters and with some CO_2 transported by ships or heavy goods vehicles.

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[29] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf

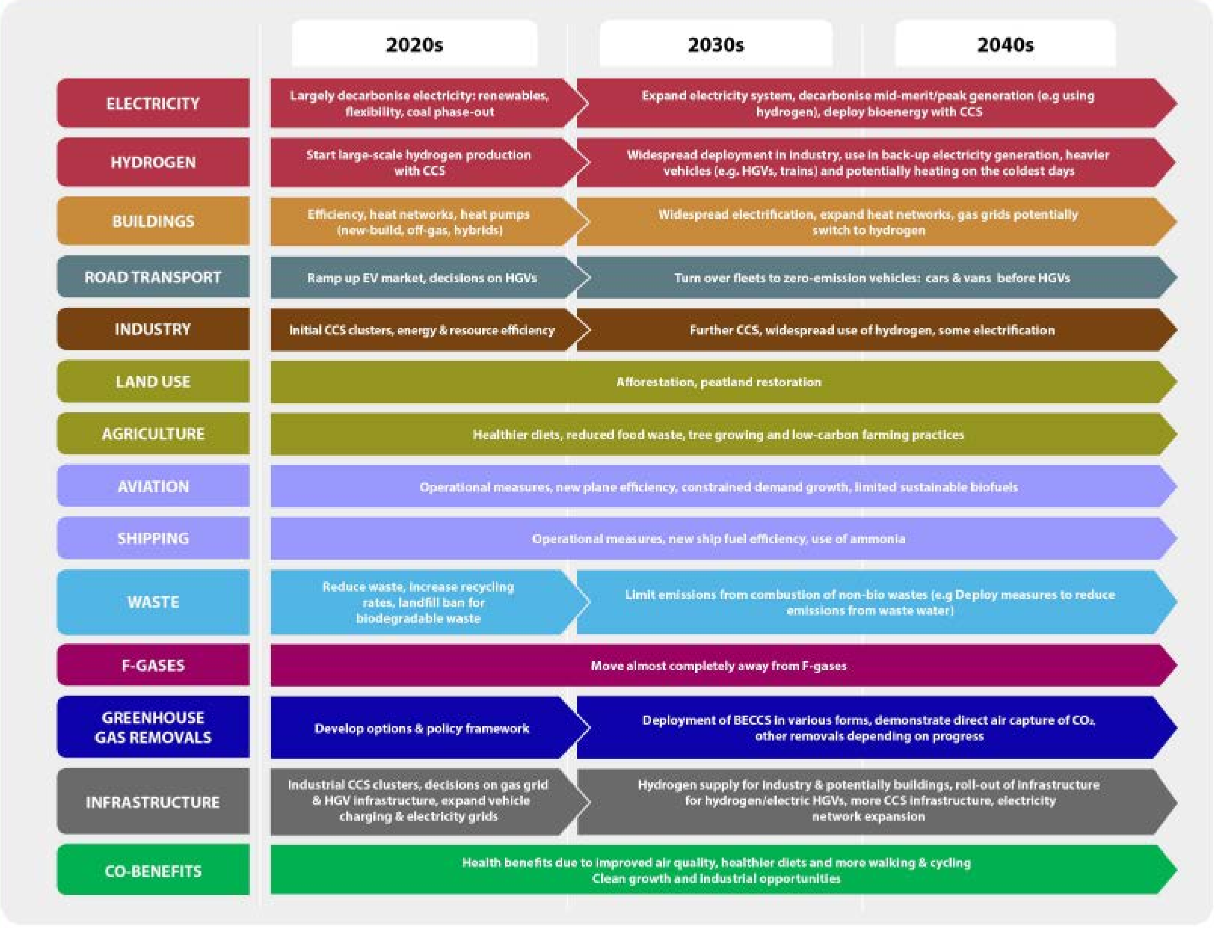
[30] CCC, January 2018. An independent assessment of the UK’s Clean Growth Strategy. 84 pages. Available from https://www.theccc.org.uk/publications/

[31] CCC, June 2016. A Strategic Approach to Carbon Capture and Storage. https://www.theccc.org.uk/wp-content/uploads/2016/07/Letter-to-Rt-Hon-Amber-Rudd-CCS.pdf

[32] https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf

[33] https://www.gov.scot/news/reaching-net-zero/

- Extensive electrification, particularly of transport and heating, supported by a major expansion of renewable and other low-carbon power generation. The scenarios involve around a doubling of electricity demand, with all power produced from low-carbon sources (compared to 50% today).



	2020s	2030s	2040s
ELECTRICITY	Largely decarbonise electricity: renewables, flexibility, coal phase-out	Expand electricity system, decarbonise mid-merit/peak generation (e.g using hydrogen), deploy bioenergy with CCS	
HYDROGEN	Start large-scale hydrogen production with CCS	Widespread deployment in industry, use in back-up electricity generation, heavier vehicles (e.g. HGVs, trains) and potentially heating on the coldest days	
BUILDINGS	Efficiency, heat networks, heat pumps (new-build, off-gas, hybrids)	Widespread electrification, expand heat networks, gas grids potentially switch to hydrogen	
ROAD TRANSPORT	Ramp up EV market, decisions on HGVs	Turn over fleets to zero-emission vehicles: cars & vans before HGVs	
INDUSTRY	Initial CCS clusters, energy & resource efficiency	Further CCS, widespread use of hydrogen, some electrification	
LAND USE	Afforestation, peatland restoration		
AGRICULTURE	Healthier diets, reduced food waste, tree growing and low-carbon farming practices		
AVIATION	Operational measures, new plane efficiency, constrained demand growth, limited sustainable biofuels		
SHIPPING	Operational measures, new ship fuel efficiency, use of ammonia		
WASTE	Reduce waste, increase recycling rates, landfill ban for biodegradable waste	Limit emissions from combustion of non-bio wastes (e.g Deploy measures to reduce emissions from waste water)	
F-GASES	Move almost completely away from F-gases		
GREENHOUSE GAS REMOVALS	Develop options & policy framework	Deployment of BECCS in various forms, demonstrate direct air capture of CO_2, other removals depending on progress	
INFRASTRUCTURE	Industrial CCS clusters, decisions on gas grid & HGV infrastructure, expand vehicle charging & electricity grids	Hydrogen supply for industry & potentially buildings, roll-out of infrastructure for hydrogen/electric HGVs, more CCS infrastructure, electricity network expansion	
CO-BENEFITS	Health benefits due to improved air quality, healthier diets and more walking & cycling Clean growth and industrial opportunities		

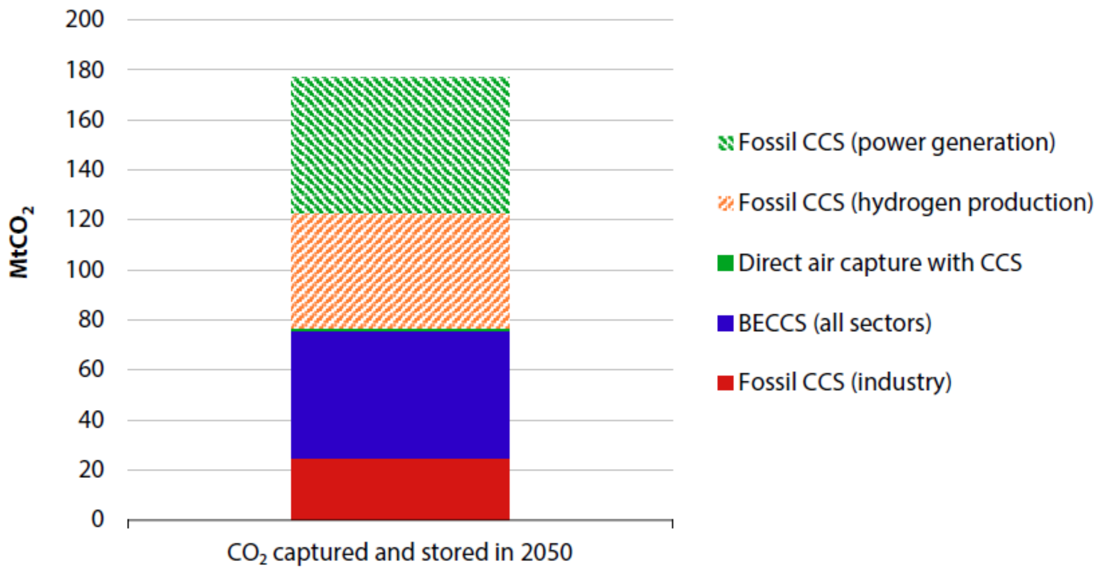
Source: CCC analysis.
Notes: CCS = carbon capture and storage. EV = electric vehicle. BECCS = bioenergy with CCS.

Figure 3.6 UK net-zero Greenhouse Gas scenario, from CCC, May 2019[32]*. CCC, Climate Change Committee. F-Gases, fluorinated gases.*

The UK net-zero ambition includes commencement of large-scale hydrogen production in the 2020s and its widespread deployment in industry, use in back-up electricity generation, heavier vehicles, and heating on the coldest days (Figure 3.6). The Scottish Energy Strategy[3] has developed two indicative scenarios for the energy system in 2050: low-carbon electricity; hydrogen. Both could meet the demand for energy across the industry, services and transport sectors. Scotland's energy system in 2050 is unlikely to match either but include aspects of both.

The ambitions for net-zero emissions in the UK is by 2050 and Scotland in 2045 and includes all sectors without distinction of proportion by end uses. In the case of the most challenging deep emissions reduction the CCC envisage up to 175 million tonnes annual CO_2 captured and stored.

Approximately 100 million tonnes of the envisaged annual volume of CO_2 captured and stored is from the reformation of H_2 and generation of electrical power from fossil fuels (Figure 3.7).



Source: CCC analysis.

Notes: 1. The volumes shown here for CO_2 captured and stored for fossil CCS are based on the production of 148 TWh of electricity from gas CCS plants and 225 TWh of hydrogen from advanced gas reforming plants (see Chapter 2 of the accompanying Technical Report). However, as stated in that chapter, it is not possible to foresee the exact generation/production mix in 2050. Hence we denote these blocks in the chart with shading.

2. 'BECCS (all sectors)' covers the burning of biomass (including agricultural and forestry residues), waste wood, biomethane/biogas and the biogenic part of municipal and commercial and industrial waste (MSW/C&IW) in industry and for power generation, plus CO_2 captured and stored from the production of biofuels for aviation and burning in homes (bioLPG in off-gas hybrid heat pumps).

3. Fossil CCS for power generation and industry covers burning of fossil fuels, plus the non-biogenic part (46% of the total) of MSW/C&IW.

Figure 3.7 Total CO_2 captured and stored in the UK most challenging emissions reduction (Further Ambition) scenario in 2050 of the CCC[31]

3.3.1.1 Transport sector

The ambition to reduce emissions from the UK transport sector is evident from government strategies[3, 29] and research and development of low-carbon transport. There are a number of operational projects within UK cities, most notably in the city of Aberdeen[34] which operates a fleet of ten buses[35], with 15 more on order, a refuse lorry and road sweeper and 21 cars. There are two refuelling station in Aberdeen with capacity for 350 and 700 bar refuelling for large vehicles, vans and cars. The hydrogen used is from ‘green’ sources, wind- and solar-powered generation. Other UK cities have plans for transport based on hydrogen from large-scale reformation of hydrogen, such as in Leeds, including cars, buses, trains and even planes in their

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[34] http://www.h2aberdeen.com/

[35] http://www.h2aberdeen.com/home/H2-Aberdeen-hydrogen-bus.aspx

decarbonisation aspirations[36]. However, development of operational hydrogen fuel-cell powered vehicles is not solely confined to urban areas. The Orkney Islands, Scotland, has operated five vehicles since 2017[37]. Pilot projects for hydrogen-powered shipping are also in operation in the Orkney Islands as part of a hydrogen-based economy. The HySeas[38] programme of research projects have culminated in the construction and testing of a hydrogen fuel-cell powered vehicle and passenger ferry.

Hydrogen fuel cell-based air transport is a component of the strategy for decarbonisation in Scotland where the HyFlyer project is investigating decarbonisation of medium range small passenger propeller aircraft[39]. The demonstration of aircraft flight out of Orkney will be powered with electric motors, hydrogen fuel cells and gas storage.

3.3.1.2 Residential/community sector

Residential and commercial heating, including space heating, water heating, cooking applications are the some of the main consumers of energy in the domestic sector. Currently, approximately 270 TWh of heat required annually by the UK residential sector is supplied using natural gas[40]. Under the assumption that all of the natural gas heating infrastructure will be converted to H_2 by 2050, the demand for hydrogen at 2050 can be approximated as eight million tonnes. A non-domestic heating demand of approximately 150 TWh could increase the requirement for H_2.

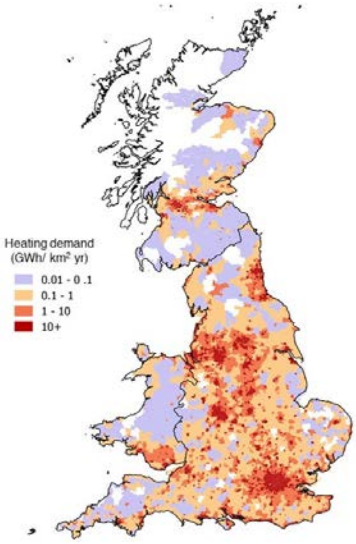

Figure 3.8 Geographical distribution of domestic and non-domestic heating demand supplied using natural gas in 2016.

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[36] https://www.northerngasnetworks.co.uk/2018/11/23/hydrogen-blueprint-unveiled-to-make-over-3-7-million-homes-near-emission-free-by-2034/

[37] https://www.bbc.com/future/article/20190327-the-tiny-islands-leading-the-way-in-hydrogen-power

[38] https://www.hyseas3.eu/

[39] http://www.emec.org.uk/press-release-hyflyer-zero-emission-aircraft-flight-tests-set-for-orkney/

[40] https://www.gov.uk/government/collections/sub-national-gas-consumption-data

Large-scale reformation of methane for hydrogen to add the national gas supply grid is the predominant planned implementation of hydrogen to reduce emissions across the UK. These have focused on the economies of scale at urban conurbations also on the benefit to regional communities. The H21 North of England project plans 100% conversion to hydrogen of seven cities[2] and Cadent**Error! Bookmark not defined.** plans to blend hydrogen with natural gas for Liverpool and Manchester. Whereas for the Aberdeen Hydrogen Vision the Scottish Gas Network (SGN) Hydrogen 100 pilot project could provide 300 new houses with hydrogen-powered heating from methane reformation and CCS at the Acorn offshore site. Project Cavendish is assessing the feasibility of a hydrogen production plant at the Isle of Grain power station41, Kent, to use hydrogen for transport and heating in the London area. The CO2 produced is planned for offshore geological storage with shipping to the Acorn project site.

Off-grid development of hydrogen for domestic heating of isolated or rural communities is under investigation, as a component of the BIG HIT project[42].

3.3.2 Objectives of the UK case study, H21 North of England and Grangemouth case study

The technical focus of the UK case study is to quantify the output of CO_2 from H_2 reformation at Teesside for the H21 projects. Firstly, for the implementation of the first phase of 100% H2 supply for three large UK cities, e.g. Leeds, Kingston Upon Hull and Greater Teesside area[1]. Secondly, to anticipate wider implementation including the seven cities envisaged by H21 North of England project.

Importantly, to quantify the ramp up to the annual volumes of CO_2 captured for the years 2029 to 2035 estimated for the first phase of implementation and beyond 2055 for the longer term. Annual demand is estimated as 1.5 Mt in 2029, increasing to 3.37 Mt from 2032 onwards for phase 1 implementation (Table Table 3.7). However, there is no indication of ramp up associated with the implementation of infrastructure and phased connection of households to the H2 gas supply for the first three cities and subsequent cities.

Table 3.5 Annual volumes of CO_2 captured for phase 1 of H21 Leeds City Gate

	CO_2 captured, million tonnes per year						
Leeds (roll-out 2026-2029)	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Teesside – Greater Area (roll-out 2029-2032)				1.28	1.28	1.28	1.28
Kingston Upon Hull – City				0.59	0.59	0.59	0.59

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[41] https://www.power-technology.com/projects/isleofgrain/

[42] https://www.bighit.eu/

(roll-out 2029-2032)							
Annual CO_2 storage demand at completion of each roll-out stage (Mt)	1.5	1.5	1.5	3.37	3.37	3.37	3.37
	2029	2030	2031	2032	2033	2034	2035

The commercial and policy focus of the UK case study will apply the business model and business case development and assessment methodology developed in ELEGANCY Work Package 3 (WP3). This part of the case study will review the H21 North of England report, highlight gaps and priorities for further work in the business case definition, consider the design of public/private business models, and recommend measures for implementation using practical investment solutions. The study will identify the key risks and barriers to investment in the H2-CCS integrated value chain in the northeast of England and southeast of Scotland. It will suggest ways to overcome these so that the time to market for CCS on a component, system and business-case level can be reduced.

The case study will assess the implications to seasonal variations in domestic heating demand on the supply and volume of CO_2 from H_2 generation to the transport network and storage site. Seasonal variations in heating demand are well known to energy providers but the effect on CO2 supply and storage provision is not yet known. The time-scale and the upper and lower limits of the variation need to be understood to assess the storage capacity and impact on CO2 injectivity. The implications of H_2 reformation operational constraints on CO2 supply and so transport and storage will be assessed. In addition to variations due to seasonal demand the steam methane reformation during operation is a continual process but there is planned intermittency for annual maintenance during the summer months. The variation is important to assess the impact on the geomechanical stability of the storage strata.

An essential component of the case study is analysis of the most cost-effective, but also practical, transport and storage network. Only this will make the large-scale implementation of domestic heating by H_2 and CCS economically feasible for large cities in the UK.
The storage demands, if any, for hydrogen in order to supply periods of peak demand during the winter months will be assessed. The current storage capacity, in the form of salt caverns may not be sufficient for hydrogen as it is for natural gas.

The potential for emissions reduction in the chemicals industry using H2-CCS value chain, will be assessed by consideration of the UK refinery and petrochemicals plant to Grangemouth. In particular, which pathway allows for greatest emissions reduction at lowest cost? Perhaps a CCS-only option or a H_2–only option or a combination of both into a H2-CCS solution.

Components in the H_2/CO_2 value chain

The case study with lay out the components required for the implementation of the H_2 with CCS value chain for large UK cities and also industrial sites. The components required will be developed in the ELEGANCY WP4 H2 and CCS chain tool. Those components are anticipated to include:

- H2 feedstocks – natural gas, petroleum, etc.
- H_2 production & CO_2 separation: Initially, SMR with PSA and MDEA for CO_2 capture.

- Development and implementation of SMR with SEWGS, SMW with advanced PSA etc
- CO_2 transport – pipeline
- CO_2 storage – geological reservoirs

Requirements for the H2-CCS Chain Tool
Examples of likely requirements are to:

1. Understand the supply of CO_2 generated by methane reformation to produce H_2 for transport and geological storage, in additional to that planned from other industrial sources.
2. Model the effect of uncertainty in infrastructure development and storage provision.
3. Incorporate components for a ‘business as usual’ scenario, i.e. industrial growth for an energy supply solely by complete electrification, plus scenarios of increasing domestic and commercial heating by H_2 and CCS.
4. Assess the effect of scale in the component models of a CO_2 transport and storage network to achieve the cost reductions required for domestic heating by H_2 in large UK cities to be economically viable.
5. Present performance metrics that are relevant to the industrial sector.

3.4 German Case Study

Hydrogen can play a key role in the future energy system and transportation system by providing options for decarbonisation in combination with fuel cells. Decarbonisation is, without any doubt, necessary for the development towards a sustainable economy and society, as well as for fulfilling the ambitious climate goals. Political initiatives set the pace by fostering research in related fields and developing strategic road maps for implementation on a national and international level. Therefore, German initiatives on H_2 provide a first reference point for analysing the potential of hydrogen and related developments.

In Germany, the government supports the development of hydrogen and fuel cell technology primarily within the *National Innovation Programme for Hydrogen and Fuel Cell Technology* (NIP) (German: Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie). In 2006, the *NIP* was launched as a cross-departmental 10-year program by the Federal Ministry of Transport and Digital Infrastructure (BMVI) in cooperation with Germany’s industry and academia[43] [44]. From 2007 to 2016, the government and industry partners have invested 1.4 billion euros in hydrogen and fuel cell projects with the aim to promote the market preparation of products and application based on hydrogen and fuel cell technology (phase I). Half of the funding volume was provided by the Federal Ministry of Transport and Digital Infrastructure and the Federal Ministry for Economic Affairs and Energy (BMVI), while the rest was provided by participating industry partners. The federal government decided to prolong the support by adopting the *NIP* from 2016 to 2026, aiming at boosting the market

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[43] BMVI, National Programme of Innovation for Hydrogen and Fuel Cell Technology, The future of mobility is electric, 2016 [2017-12-20] http://www.bmvi.de/SharedDocs/EN/Dossier/Electric-Mobility-Sector/top-04-fuel-cell-technology.html

[44] BMVI, Nationales Innovationsprogramm Wasserstoff und Brennstoffzellentechnologie, n.d., [2027-12-12] http://www.bmvi.de/SharedDocs/DE/Artikel/G/nationales-innovationsprogramm-wasserstoff-und-brennstoffzellentechnologie-nip.html?nn=36210

maturity of hydrogen and fuel cell technologies (phase II)[45]. In order to simultaneously advance the numerous hydrogen and fuel cell product and application options and to address the specific market requirements, the *NIP* is divided into the three program areas, ‘Transport and Hydrogen Infrastructure’, ‘Stationary Energy Supply’, and ‘Special Market’, cf. footnote[46]. The *National Organization for Hydrogen and Fuel Cell Technology GmbH* (NOW - Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie GmbH) was established in 2008 and is in charge of coordinating and managing the *NIP*. In addition, *NOW* is responsible for the Electromobility Model Regions programme and actively supports the BMVI in developing the Mobility and Fuel Strategy as well as implementing the Directive 2014/94/EU on the development of alternative fuels infrastructure (CPT)[47].

In this context, German hydrogen mobility initiatives is mentioned as an example of a sector specific initiative with great importance. In 2002, the *Clean Energy Partnership* (CEP) was established in Germany with the aim to develop an automotive hydrogen economy in Germany by creating a hydrogen infrastructure supply network. For this purpose, the industry consortium *CEP* planned to build 50 filling-stations between 2012 and 2016. The *CEP* is considered a major lighthouse project of the *NIP* and is supervised by *NOW*.

In 2017, the industry initiative *H_2 Mobility Deutschland* (weblink in footnote[48]) took over the *CEP’*s filling stations as a new operator and will further expand the nation-wide filling-station infrastructure. *CEP* will continue to play an important role as independent network that aims at the further development of technologies and standards. The H_2 Mobility Deutschland GmbH & Co. KG was founded in 2015 as a joint venture between the six *CEP* partners Air Liquide, OMV, Daimler, Linde, Shell and Total. To coordinate the development within the automobile industry, BMW, Honda, Toyota, Hyundai and Volkswagen became associated partners as well as the *NOW*[49].

In the first project phase, the *H_2 mobility roadmap* highlights the construction of initially 100 refuelling stations by 2018/ 2019 unconditionally, irrespectively of the actual number of hydrogen-powered vehicles on the road. These refuelling stations are planned to be set up in eight main urban areas (Berlin, Hamburg, Rhine-Ruhr, Frankfurt, Nuremberg, Stuttgart, Munich and Leipzig/Halle) as well as along the connecting motorways and highways. In the second phase, a maximum of 400 refuelling stations is planned to be built by 2023, depending on the number of fuel cell vehicles registered. Financial support for the majority of the first 100 refuelling stations is provided amongst other by the *NIP* and the European Commission in the *Fuel Cells and Hydrogen Joint Undertaking* (FCH-JU).

By this means, the so-called chicken-or-the-egg problem related to the question what comes first, fuel cell vehicle or hydrogen refuelling stations, was addressed in Germany[50]. Evaluating this development towards hydrogen as the potential future emission-free fuel, it is hardly possible to

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[45] NOW Electric Mobility with Hydrogen and Fuel Cells – State of development and market introduction in the area of passenger vehicles in Germany, online available https://www.now-gmbh.de/content/7-service/4-publikationen/4-nip-wasserstoff-und-brennstoffzellentechnologie/electric-mobility-with-hydrogen-2017_en_310817.pdf

[46] BAN (Bundesanzeiger), BAnz AT 29.09.2016 B4, 2016 [2017-12-19] online available https://www.bundesanzeiger.de/ebanzwww/contentloader?state.action=genericsearch_loadpublicationpdf&session.sessionid=d2e2531d5e41198e7f1f267722ab549e&fts_search_list.destHistoryId=24565&fts_search_list.selected=2bad2cda0e013441&state.filename=BAnz%20AT%2029.09.2016%20B4

[47] NOW, Tasks, n.d. [2017-12-20] https://www.now-gmbh.de/en/about-now/aufgaben

[48] www.h2-mobility.de

[49] CEP, Hydrogen - what kept us moving 2002–2016, 2016, online available https://www.now-gmbh.de/content/7-service/4-publikationen/4-nip-wasserstoff-und-brennstoffzellentechnologie/cep_abschlussdokumentation_en.pdf

[50] See footnote 45, p. 28-29

deny that “Germany is a trailblazer and pioneer in this field”, as stated by Alexander Dobrindt, the former federal minister of transport and digital infrastructure[51].

3.4.1 Determination of hydrogen demands for 2035

In the following, the procedure for determining the H_2 demands in the sectors industry, mobility and heating is described as it was performed in the final design for the German case study (see deliverable D5.5.3[52] for all final results).

3.4.1.1 Industry

For the subcategory of hydrogen producing and consuming industry, the industrial hydrogen production from the Roads2HyCom study is used and the production rates from the "merchant" and "captive" sectors are determined[53]. For this purpose, a constant production quantity up to 2035 is assumed for those industrial sectors which consume or produce relevant quantities of hydrogen[54]. This results in a hydrogen demand of 14.95 billion Nm^3/a or 44.8 TWh/a for the hydrogen producing and using sectors of the industrial sector. The study looked at 46 company locations and added up the figures for several companies in a NUTS 3 region. The production rates of the "by-product" sector are not considered, as these are produced during a process in combination with other products. The CO_2 savings by the use of blue hydrogen amount to 93%, compared with grey hydrogen there are also monetary savings of 25%.

For the steel industry, first the plans of the steel producers were analysed. For example, Thyssenkrupp plans to inject hydrogen into the blast furnace starting in 2020 and to replace the blast furnace process by electric arc furnaces with H_2 direct reduction between 2025 and 2050[55]. For the German case study it is assumed that by 2035, 50% of the blast furnaces will already have been replaced, and the other half will be injecting hydrogen instead of coal into the blast furnace process.

The injection process requires 131 m^3 of H_2 per tonne of pig iron, achieving CO_2 savings[56] of up to 19%. An annual quantity of 6.13 TWh/a is thus required for hydrogen injection at 50% of the blast furnace sites. Compared to coal injection, the injection costs are reduced by 50%.

Almost 2400 MJ or 785 Nm^3 of hydrogen are required per ton of crude steel for direct H_2 reduction[57]. This means that if 50% of the existing blast furnaces are converted in 2035, the hydrogen demand will be 36.76 TWh/a. When all blast furnaces have been converted by 2050, the hydrogen demand will be 73.52 TWh/a. The CO_2 savings amount to more than 80% when comparing the mass and fuel balance before and after the conversion[40]. The material and energy costs (without investments) will decrease by 3% compared to the blast furnace route.

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[51] See footnote 45, p.5

[52] https://www.sintef.no/globalassets/project/elegancy/deliverables/elegancy_d5.5.3_co2_h2_infrastructure_germany.pdf

[53] ROADS2HYCOM (ED.): *DELIVERABLE 2.1 AND 2.1a “European Hydrogen Infrastructure Atlas” and “Industrial Excess Hydrogen Analysis” - PART II: Industrial surplus hydrogen and markets and production*. 2007.

[54] MINISTERIUM FÜR WIRTSCHAFT, INNOVATION, DIGITALISIERUNG UND ENERGIE DES LANDES NORDRHEIN-WESTFALEN (ED.): *Wasserstoffstudie Nordrhein-Westfalen*. 2019.

[55] THYSSENKRUPP AG (ED.): *Zwei Technologiepfade – ein Ziel*. In: Compact Steel 01, pp. 14-15. 2019.

[56] DVS MEDIA GMBH (ED.): *Wasserstoff statt Kohle für eine klimafreundliche Stahlproduktion*. In: STAHL+TECHNIK 6, pp. 74-74. 2019.

[57] WEIGEL, M.: *Ganzheitliche Bewertung zukünftig verfügbarer primärer Stahlherstellungsverfahren*. 2014.

In the existing electric arc furnaces, the natural gas demand of 48 kWh per tonne of steel will be replaced by hydrogen, which corresponds[58] to a hydrogen demand of 16 Nm³. For all sites combined, this means a hydrogen demand of 0.6 TWh/a. Emissions caused by the use of natural gas are avoided by 89%, but energy costs increase by 86% in relation to natural gas costs.

In total, the steel industry will have a hydrogen demand of 43.5 TWh/a in 2035, while the demand for the whole industry sector will be 88.3 TWh/a. By using hydrogen, a total of 41.73 $MtCO_2/a$ can be avoided. The distribution of the industrial demand is shown in Figure 3.6, with a distinct industrial hydrogen cluster formation emerging.

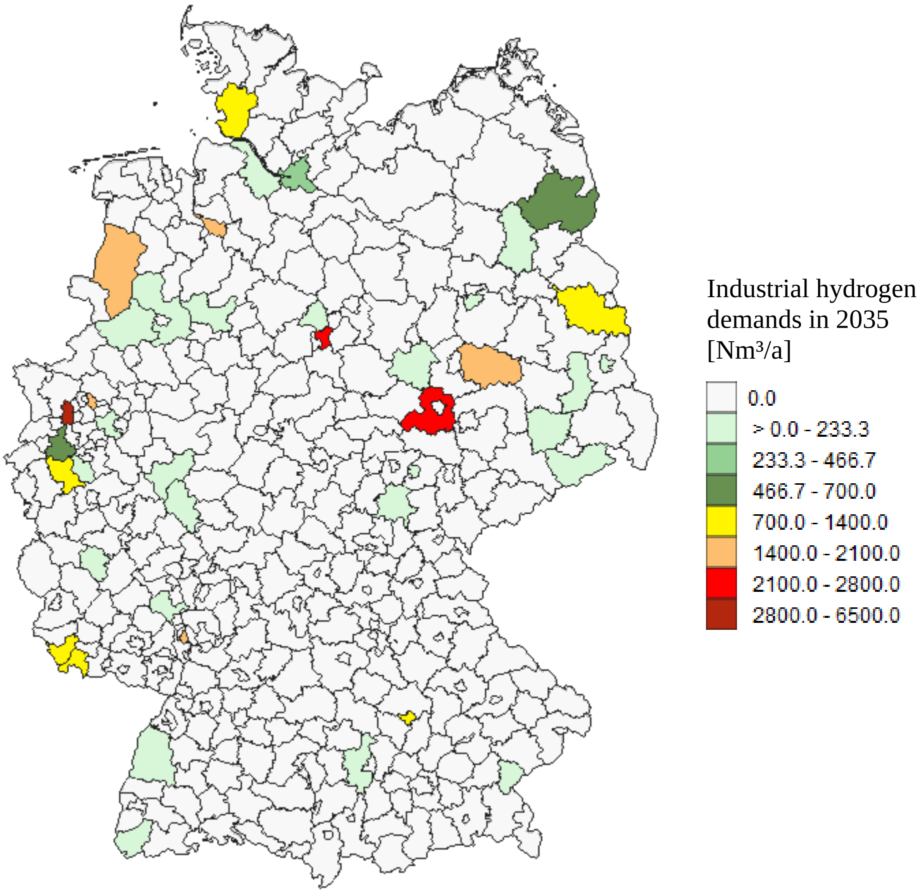

Figure 3.9: Industrial hydrogen demands in 2035.

3.4.1.2 Mobility

In the mobility sector, a distribution factor is determined for hydrogen-powered cars, buses, trains and trucks, each based on specific localised data. This includes current fleet numbers, mileage/passenger volume, fuel consumption, share of diesel vehicles, population density, government subsidies, GDP and consumer income in the region. Using forecast data from a meta-analysis and the respective calculation factors, a distribution is made at NUTS3 level.

For fuel cell passenger cars (FCEV), data from 15 studies was initially evaluated by means of a meta-study to produce a trend function. For the year 2035, this results in an FCEV share of 8.85%

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[58] NAVIGANT (ED.): *Energiewende in der Industrie - Branchensteckbrief der Eisen- und Stahlindustrie*. 2020.

of the total passenger car fleet of 43.5 million vehicles. This value is allocated to the districts using a local distribution factor. The factor is made up of 25% from the proportion of mileage in the district in relation to the total mileage, whereby for FCEVs only mileage above the average of 15,365 kilometres per year and vehicle are considered. An innovation factor is included in the calculation by 40%, which puts the average per capita income in the district in relation to the maximum per capita income. To 25% it is taken into account whether hydrogen filling stations already exist in the district today. The last 10% of the distribution factor takes into account the distribution of taxis among the districts. A value of 0.81 MJ/km is assumed for the H_2 consumption of cars. Thus, a total of 91.8 billion km/a are achieved with FCEVs, for which 20.7 TWh/a of hydrogen are needed. This leads to CO_2 savings of 97% compared to diesel passenger cars while reducing energy costs by 77%.

For buses, an increase in total mileage of 10.5% has been calculated by 2035, which corresponds to 2.57 billion vehicle kilometres. At the end of 2019 there were about 150 FCEV buses in Germany. A value of 900 is assumed for the predicted share of fuel cell buses in 2035, which corresponds to 2% of the total number of buses[59]. With an average mileage of 57,085 km per vehicle and year and a consumption of 10.27 MJ/km, this results in a hydrogen demand of 0.14 TWh/a. This value is again distributed across the districts using a distribution factor that takes into account 30% population density, 10% GDP, 20% federal financial assistance for local public transport and 40% existing FCEV buses. The hydrogen buses save 93% of the emissions of diesel buses and reduce energy costs by 47%.

For public transport trains, the first step is to determine the share of diesel-powered railcars in 2035, all of which are to be replaced by fuel cell (FC) trains. According to [60], 15% of the mileage in 2030 will be achieved with diesel traction, which corresponds to 114.6 million train kilometres and is also assumed as the value for 2035. Based on local data on the mileage of trains in the NUTS 3 regions and the fuel station sites of the German railways, the mileage calculated for FC trains is distributed locally. With an energy consumption of 27.7 MJ/km, this results in a hydrogen demand for public transport trains of 0.9 TWh/a in 2035. The CO_2 savings compared to diesel trains are 97% and energy costs are reduced by 76%.

Since, due to lack of available data, rail freight transport can only be distributed at national level and not to the individual NUTS 3 regions, and since the replacement of all diesel vehicles (5.74% of total transport performance) results in a demand for H_2 of only 0.4 TWh/a, this share is further neglected.

In the case of truck freight transport, a meta-study on the forecast market share of fuel cell trucks is being carried out first. For 2035, the values of 20% share in the 3.5-7.5t size class and 2% in the 7.5-12t size class are determined from this. This results in a total hydrogen truck fleet of 61,800 in 2035, which, given a total of 2.8 billion vehicle kilometres per year and an average consumption of 3.59 and 6.66 MJ/km respectively, will lead to a hydrogen demand of 2.92 TWh/a in 2035. Hydrogen trucks will reduce CO_2 emissions by 95% compared to diesel trucks and energy costs

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[59] PROGNOS AG (ED.): *Entwicklung der Energiemärkte – Energiereferenzprognose*. 2014.

[60] BUNDESMINISTERIUM FÜR VERKEHR UND DIGITALE INFRASTRUKTUR (ed.): *Verkehrsverflechtungsprognose* 2030. 2014.

by 62%. Figure 3.7 shows the localised hydrogen demands described above, summarised for the mobility sector.

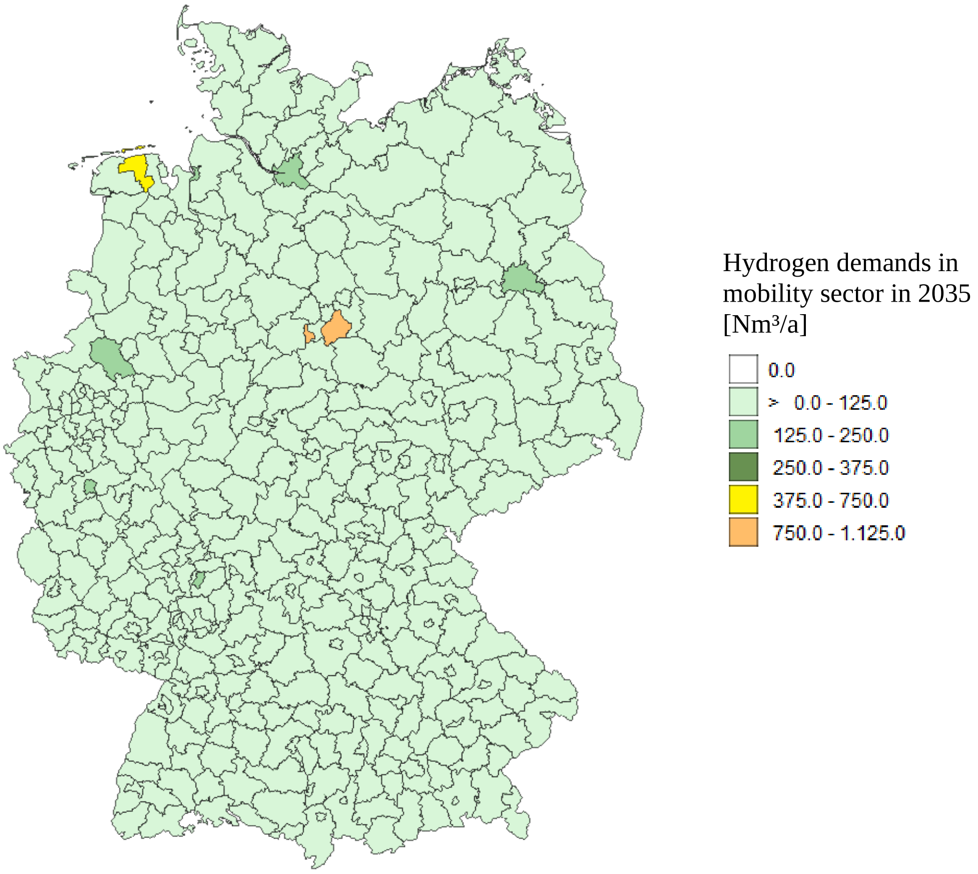

Figure 3.10: Hydrogen demands in mobility in 2035.

3.4.1.3 Heating

For the H_2 demand in the heating sector, the locations of all combined heat and power (CHP) plants are first loaded from a market data register[61] and all plants < 50 kW are sorted out, as the focus is to be on large plants feeding into district heating networks. With an average of 4300 h/a full load hours and heat network losses of 10%, the required amount of hydrogen can be determined assuming that all existing CHPs are replaced by hydrogen CHPs by 2035. With an average lifetime of 15 years, the replacement is necessary up to that point even for very new plants, so that the hydrogen CHPs can be successively added as replacement investments over the next 15 years. The hydrogen demand is determined based on real consumption data of hydrogen CHPs from the manufacturer "2G". Figure 3.8 shows the distribution of the hydrogen demand of the CHP locations added up over the NUTS 3 regions. By switching to hydrogen CHPs, 89% of the CO_2 emissions of the previous natural gas CHPs can be avoided, but the energy costs increase by 86% compared to natural gas CHPs.

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[61] https://www.marktstammdatenregister.de/MaStR

🟥 825.0 - 1100.0

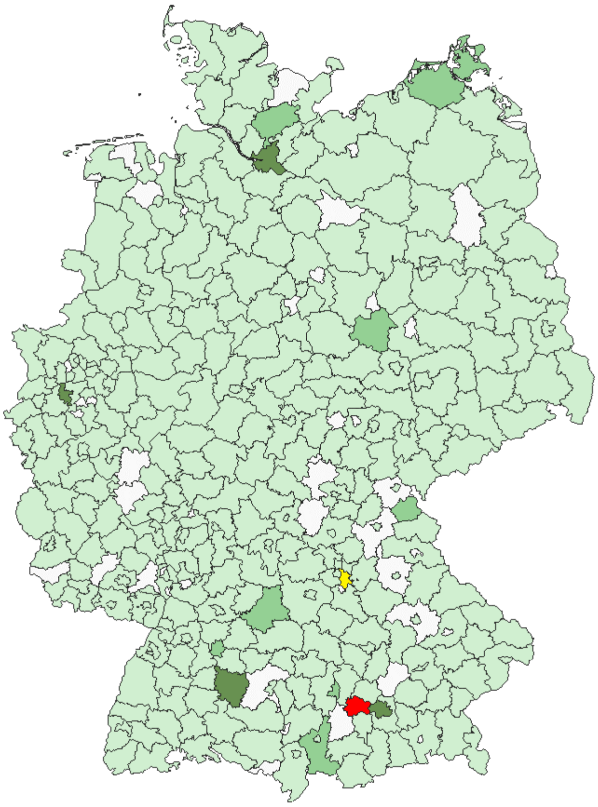

Figure 3.11: Hydrogen demands in heating sector in 2035.

The total sum of all sectors results in hydrogen demands of 140 TWh/a, and based on the data and assumptions used, the demand for the period between 2035 and 2050 is about 280 TWh/a (see Table 3-5). However, the 140 TWh/a calculated for 2035 is not the quantity to be supplied, as each region and city would have to be connected to a hydrogen network as shown in Figure 3.9. But the hotspots shown in this map account for almost half of the total demand, mainly due to the industrial demand located there.

Table 3-6: Summary of the results for the sectoral hydrogen demands.

Sector	**2035 H_2 demands**	**long term estimation**
Mobility	24.4 TWh/a	60 TWh/a
Heating	26.6 TWh/a	100 TWh/a
Industry	89 TWh/a	120 TWh/a
TOTAL	140 TWh/a	280 TWh/a

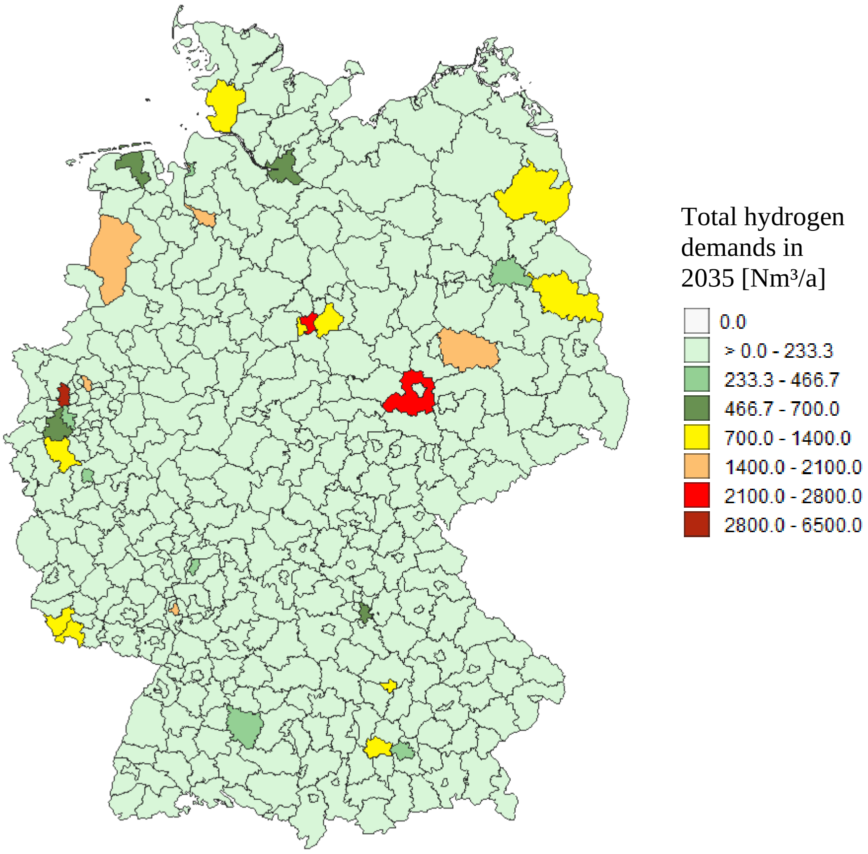

Figure 3.12: Total hydrogen demands for 2035.

The results show that the hotspots are mainly driven by industrial demand, identifying industrial hydrogen demand as the main driver for the establishment of a local hydrogen supply. The mobility and heat sectors are supplied and grow once industrial hydrogen demand has established the necessary infrastructure in a region

3.5 Norwegian Case Study

The following estimates for the Transport sector are rooted in goals for the number of zero-emission transport agents in 2030 set by the most recent governmental transport plan[62]. A hydrogen share of the total number of zero-emission transport agents is set and annual driving lengths, obtained from the statistics bureau[63] are assumed to stay at present levels (as is the ratio of light transport vehicles to private cars, and their total). Hydrogen consumption rates[64] then result in projections for total hydrogen consumption of the individual transport agents. The special case of hydrogen ferries is discussed separately. An estimate for close-proximity shipping hydrogen demand is also offered.

For the Industrial sector, specific details concerning feedstock and fuel are provided, based on present day consumption.

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[62] Nasjonal Transportplan 2018-2029: Grunnlagsdokument

[63] Statistisk Sentralbyrå – www.ssb.no

[64] Norsk Hydrogenforum – www.hydrogen.no

A detailed study for the offshore gas turbines on the Norwegian continental shelf is presented under the Energy sector.

The Residential/community sector is neglected as cheap and environmental friendly electricity for housing is readily available in Norway.

3.5.1 Transport sector

Numbers in Table 3-18 in the format " a/b" refer to scenario I (a) and II (b), respectively. Details are provided below. The column "total fleet" refers to the number of zero-emission agents, with "fleet %" giving the corresponding hydrogen-share.

Table 3.7: *Projected hydrogen consumption in 2030 based on scaled zero-emission transport agents from footnote*[65].

Agent	Fleet %	Total fleet	Total cons. [t/year]
Bus	10/10	8500	2769/2769
Heavy transport	10/25	7500	2655/6638
Light transport	2.0/1.6	496000	1429/1143
Private transport	2.0/1.6	2418000	5991/4793
Taxi	30/30	8200	1434/1434
Ferry	10/20	200	7300/14600
Raumabanen	0/100	1	0/164

The possible contribution from the close-proximity shipping is estimated to 14 000/28 000 t/year, corresponding to 10%/20% hydrogen share, respectively.

Scenarios considered here are "equal-share" (I), based on the assumption that governmental goals in terms of introducing zero-emission technology are achieved by 2030, with the listed hydrogen share compared to other technologies such as biogas, biodiesel and electric-battery drive. The electric-battery drive is assumed to dominate (66%) the ferry sector[66], but we have also applied this to buses and road transport in general. For the private transport, a total number of 62 000/50 000 fuel electric cell vehicles (FECV) is used. It should be noted that similar incentives as for present day battery-driven cars (free parking, free toll roads, etc.) are scheduled for hydrogen cars until 2025 or a number of 50 000 vehicles has been registered.

The alternative considered here (II) is based on a similar utilisation study for Western-Norway[67], which is scaled accordingly for the whole of Norway.

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[65] DNV-GL – Rapportnr. 2016-0931, Rev.1 – www.dnvgl.com

[66] Statens Vegvesen – www.vegvesen.no ("Generell Info om Utviklingskontrakt hydrogen-elektrisk ferje")

[67] See footnote 65

In both cases, the hydrogen consumption rate for road transport is constant, however, averaged quantities from pilot studies in Europe[68]are employed for buses.

A utilisation study for the Raumabanen has been executed[69], which is included here.

For the ferries, one should keep in mind that contracts for many ferry connections are assigned for long time periods (typically 10 years), such that in-phasing of hydrogen ferries could occur later than assumed here.

H_2 utilisation as of now is negligible; the first FCEVs are introduced into the market this year and one transport company is attempting to partially introduce hydrogen fuel into their heavy transport fleet[70]. A pilot hydrogen ferry project, supposed operational in 2021 is underway[71].

Hydrogen fuelling infrastructure is expected to concentrate on the broader Oslo region, with additional stations in the major cities of Bergen, Stavanger and Trondheim. The ferry is supposed to be tested in Western-Norway.

For detailed growth profiles the reader is directed to footnote 69 .

3.5.2 Industrial sector

Presently, hydrogen is employed in considerable scale in ammonia and methanol production. Location specific, the Yara Porsgrunn facility consumes 80 000 t/year and Statoils methanol facility at Tjeldbergodden 130 000 t/year.
The Statoil Mongstad refinery consumes 11 000 t/year.
The TiZir Titanium ilmenite facility in Tyssedal is scheduled to substitute coal with hydrogen in the reduction process, estimated to consume 11 000 t/year[72]. Full-scale operation is set for 2020.

Potential future hydrogen utilisation in the industry is consequently mainly focused on replacing energy today stemming from natural gas (approx. 3000 GWh in 2015). The equivalent hydrogen consumption amounts to 91 000 t/year, distributed throughout Norway.

3.5.3 Energy sector

Assuming offshore gas turbines may be fuelled by hydrogen, annual hydrogen consumption with respect to location emerges and are found in footnote[73]. 1 kg hydrogen has the lower heating value of 120 MJ, and the fuel demand is given from the thermal effect, found from the electric effect divided by the efficiency. A total demand of 664 244 t/year is found, assuming turbines run 85% of continuous operation[74].

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[68] Fuel Cell Electric Buses – www.fuelcellbuses.eu/category/performance-data-0

[69] Tomasgard *et al.*, "Nasjonale rammebetingelser og potensial for hydrogensatsingen i Norge", 2016

[70] ASKO – www.asko.no/nyhetsarkiv/asko-satser-pa-hydrogenteknologi/

[71] See footnote 66

[72] www.sysla.no/gronn/startskudd-for-storskala-hydrogenproduksjon/

[73] www.npd.no/global/norsk/3-publikasjoner/rapporter/oversiktskjema-motorer-og-turbiner.xls

[74] Private conversation with Jens Hetland, who has many years experience with gas turbines and their typical operational regimes

3.5.4 Summary

Table 3.8: H2 utilization (in t/y) scenario for Norwegian case study

Sector	Location	Year			
		2017/8	2021	2030	2035
Transport	Norway			35k/60k	
Industry	Norway	221k		323k	
Energy	Offshore			664k	

3.6 Global H_2 utilization scenario

Table 3.9: Approximate H_2 utilization (in t/y) scenario globally.

Sector	Location	Year			
		2015	2025	2030	2035
Transport	Germany	24	60 000	216 000	515 269
	France	7	22 000	89 000	211 126
	UK	50	30 600	152 000	392 174
	Japan	200	50 000	96 000	256 609
	The US	5	3 168	12 816	30 402

Table 3-20 shows an estimated global H2 utilization scenario within transport, with numbers for 2015, 2025, 2030 and 2035. The numbers for Germany, France and the UK are obtained from the Market outlook for Green Hydrogen by the FP7 project CertifHy[75]. A few missing numbers for these countries were obtained by interpolation. For Japan, the expected number of Fuel Cell Electric Vehicles (FCEVs) in 2017, 2020, and 2030 were collected from Japan's hydrogen strategy[76]. The relation between the number of FCEVs and the corresponding amount of hydrogen in tons (approximately 0.12) was obtained from CertifHy's Market outlook for Green Hydrogen and applied to the Japanese case. For the United States, only the anticipated number of FCEVs sold in 2017 was found[77]. This was converted into tons H_2 by using the same conversion rate (0.12). And the remaining US numbers were found by using the same growth rate as France - the most conservative growth rate of the other countries on the list.

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[75] Hinicio, Daniel Fraile (2015). Market outlook for Green Hydrogen. FP7 project CertifHy.

[76] Hydrogen strategy, December 2017, Cabinet Secretariat (In Japanese).

[77] https://www.statista.com/statistics/416677/sales-of-fuel-cell-electric-vehicles-in-the-united-states/

APPENDIX A

This appendix provides H_2 purity specifications as provided by H_2 supplier

Technical requirements

For the application of H2 in the German industry sector, the standard grade classifications to describe the purity of gases are used. The grade classifications for hydrogen go from 3.0 (99.9 % H_2) to 7.0 (99.99999 %), as it can be seen in Table A-1.

Table A-1 Purity grade classifications for H_2. Cf. footnote[78]

Hydrogen* label	Purity	O_2*	N_2*	CO / CO_2*	Hydro-carbons*	Humidity* (H_2O)
3.0 gaseous, compressed	99.9 Vol.-%	≤ 50	≤ 500			≤ 100
3.8 gaseous, compressed	99.98 Vol.-%	≤ 10	≤ 200			≤ 20
5.0 liquid	99.999 Vol.-%	≤ 2	≤ 3		≤ 0.5	≤ 5
5.0 gaseous, compressed	99.999 Vol.-%	≤ 2	≤ 3		≤ 0.5	≤ 5
5.3 gaseous, compressed	99.9993 Vol.-%	≤ 1	≤ 3		≤ 0.2	≤ 2
5.5 ECD gaseous, compressed	99.9995 Vol.-%	≤ 1		≤ 0.5	≤ 0.1	≤ 1
6.0 liquid "LI-PUR"	99.9999 Vol.-%	≤ 0.2	≤ 0.2	≤ 0.1	≤ 0.1	≤ 0.5
6.0 gaseous, compressed	99.9999 Vol.-%	≤ 0.5	≤ 0.5	≤ 0.1	≤ 0.1	≤ 0.5
7.0 gaseous, compressed	99.99999 Vol.-%	≤ 0.03		≤ 0.03	≤ 0.03	≤ 0.05

*: values are mole fractions

As Table A-2 shows, most industry applications are requiring a purity grade of 3.0, but some special applications, as for example the gas chromatography, need higher purity grades.

Table A-2: H_2 purity requirements for industrial applications [79] [80]

INDUSTRY APPLICATION	H_2 Purity
Ammonia production	3.0
Combustion gas and inert gas for glass production	5.0, 6.0
Fuel	3.0
Gas chromatography	5.5 ECD
Gas conditioning	3.0

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[78] Linde AG. Reingase in Druckbehältern. [2018-01-10]; https://produkte.linde-gase.de/reingase_in_druckbehaltern.

[79] Westfalen AG. Auf einen Blick: Alle Gase. [2018-01-10]; https://www.westfalen-ag.de/geschaeftskunden/auf-einen-blick-alle-gase.html

[80] Linde AG. Wasserstoff ECD 5.5. [2018-01-10]; https://produkte.linde-gase.de/db_neu/wasserstoff_ecd.pdf

Hydration crude oil refining	3.0
Hydration or reduction of petrochemical products	3.0 / 5.0 / 6.0
Metal production	3.0 / 5.0 / 6.0
Petrochemical products	3.0 / 5.0 / 6.0
Reducing inert gas	3.0
Reducing inert gas for soldering in continous furncaces	3.0 to 5.0
Reduction processes	3.0
Synthesis of amonia, hydrogen chloride and methanol	3.0 / 5.0 / 6.0

The purity for mobility applications is being affected by the standardisations for H_2 filling stations and the standardizations for fuel cells in mobility applications. The H_2 filling stations (in Germany) actually supply a purity of 5.0 (cf. footnote[81]) at pressures of 350 or 700 bar. Additionally, a drafted DIN standard (DIN EN 17124 E) is listing the limiting characteristics for PEM fuel cells in mobility applications, as it can be seen in Table A-3. The minimum mole fraction of hydrogen is stated as 99.97 % (3.7), which is below the actual purity at H_2 filling stations (5.0).

Table A-3: Directory of limiting characteristics for PEM FC[82].

DIN EN 17124:2017-09 (E) — Directory of limiting characteristics PEM FC	
Constituent	Characteristics
Hydrogen fuel index (minimum mole fraction)[a]	99.97%
Total non-hydrogen gases	300 µmol/mol
Maximum concentration of individual contaminants	
Water (H_2O)	5 µmol/mol
Total hydrocarbons[b] (Excluding Methane)	2 µmol/mol
Methane (CH_4)	100 µmol/mol
Oxygen (O_2)	5 µmol/mol
Helium (He)	300 µmol/mol
Nitrogen (N_2)	300 µmol/mol
Argon (Ar)	300 µmol/mol
Carbon dioxide (CO_2)	2 µmol/mol
Carbon monoxide (CO)[c]	0.2 µmol/mol
Total sulfur compounds (H_2S basis)	0.004 µmol/mol
Formaldehyde (HCHO)[c]	0.2 µmol/mol
Formic acid (HCOOH)[c]	0.2 µmol/mol

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[81] Lehmann J, Luschtinetz T. Wasserstoff und Brennstoffzellen. Berlin, et al.: Springer. 2014.

[82] Deutsches Institut für Normung (DIN). DIN EN 17124:2017-09 (E), 2017.

Ammonia (NH_3)	0.1 µmol/mol
Total halogenated compoundsd (Halogenate ion basis)	0.05 µmol/mol
Maximum particulates concentration	1 mg/kg
For the constituents that are additive, such as total hydrocarbons and total sulfur compounds, the sum of the constituents shall be less than or equal to the acceptable limit.	
[a]: The hydrogen fuel index is determined by substracting the "total non-hydrogen gases" in this table, expressed in mole percent, from 100 mol percent. [b]: Total hydrocarbons include oxygenated organic species. Total hydrocarbons shall be measured on a carbon basis (µmolC/mol). [c]: Total of CO, HCHO, HCOOH shall not exceed 0.2 µmol/mol [d]: Total halogenated compounds include, for example, hydrogen chloride (HCl), and organic halides (R-X). Species will be checked according Quality Assurance.	

For the use of hydrogen in fuel cells in general, type-specific purity requirements have to be considered. As it can be seen in Table A-4, low temperature fuel cells (PEMFC, PAFC, DMFC) have higher purity requirements than the high temperature fuel cells (SOFC, MCFC).

Table A-4: Type-specific purity requirements for fuel cells.[83] [84] [85]

FUEL CELLS	Purity of H_2 / fuel	CO	CH_2O	CH_3OH	CO_2 compa-tible	N_2	NH_3	Cl	S	Applications
PEMFC	min. 99.97 (3.7); Fuel: H_2, methanol	< 10-110 ppm	< 0.5 %	< 0.5 %	yes					Mobilty, home supply
DMFC	Fuel: methanol									Mobility
PAFC	Fuel: H_2	< 1 %		< 500 ppm	yes	< 4%	< 0.2 ppm	< 1 ppm	< 1 ppm	Heating plants
SOFC	Fuel: H_2, CO	compatible			yes			< 1 ppm	< 1 ppm	Power plants, heating plants, home supply
MCFC	Fuel: H_2, CO	compatible			yes			< 1 ppm	< 1 ppm	Power plants, heating plants

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[83] Weindorf W, Bünger U, et al. Verfahren zur Reinigung von Wasserstoff aus der Erdgasdampfreformierung für den Einsatz in Brennstoffzellen. [2018-01-10]; https://www.netinform.de/GW/files/pdf/BWK.pdf

[84] Fischedick, et al. SHELL hydrogen study. 2017.

[85] Eichlseder H, Klell M. Wasserstoff in der Fahrzeugtechnik. Wiesbaden: Springer Vieweg. 2012.

APPENDIX B

B. 1 Original input from the Dutch Case Study

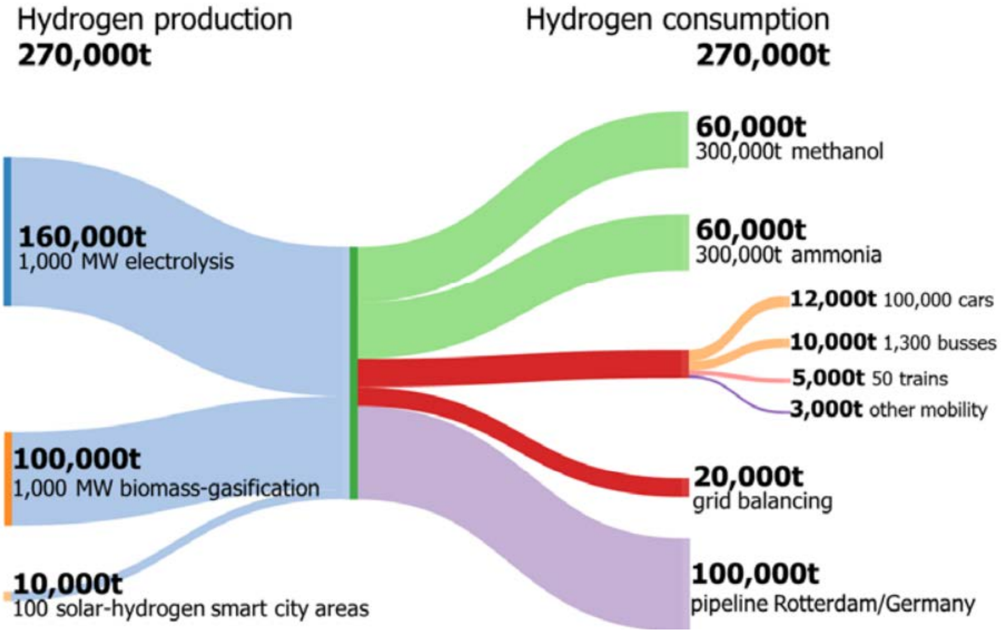

Figure 0.1: Green hydrogen economy mass flows estimated for the north of Netherlands[9].

B. 2 Original tables from the Swiss Case Study

Table 0.1: Quantification of hydrogen demand for passenger vehicles in Switzerland with a fuel cell vehicle share of 100%.

passenger vehicles		**2016**	source	**2035**	source
total transport demand	km	5.77E+10	BFS (2017a)	6.40E+10	Estimate, based on ARE (2017)
specific fuel consumption	MJ/km	1.28	Cox et al. (2017)	1.00	Cox et al. (2017)
total H_2 consumption	MJ	7.39E+10	*calculated*	6.40E+10	*calculated*
total H_2 consumption	kg	6.16E+08	*calculated*	5.33E+08	*calculated*

Table 0.2: Quantification of hydrogen demand for buses in Switzerland with a fuel cell vehicle share of 100%.

buses		**2015**	source	**2035**	source
total transport demand	km	4.03E+08	BFS (2017a)	4.47E+08	Estimate, based on ARE (2017)
specific fuel consumption	MJ/km	10.60	Cox et al. (2017)	8.90	Cox et al. (2017)
total H_2 consumption	MJ	4.28E+09	*calculated*	3.98E+09	*calculated*

total H_2 consumption	kg	3.56E+07	*calculated*	3.32E+07	*calculated*

Table 0.3: Quantification of hydrogen demand for lorries in Switzerland with a fuel cell vehicle share of 100%.

lorries		**2015**	source	**2035**	source
<3.5t					
total transport demand	km	4.27E+09	BFS (2017a)	5.11E+09	Estimate, based on ARE (2017)
specific fuel consumption	MJ/km	1.92	Estimate, based on Cox et al. (2017)	1.5	Estimate, based on Cox et al. (2017)
total H_2 consumption	MJ	8.20E+09	*calculated*	7.67E+09	*calculated*
total H_2 consumption	kg	6.83E+07	*calculated*	6.39E+07	*calculated*
3.5-7.5t					
total transport demand	km	8.94E+07	BFS (2017a)	1.07E+08	Estimate, based on ARE (2017)
specific fuel consumption	MJ/km	2.34	Estimate, based on Cox et al. (2017) and ecoinvent (2018)	1.96	Estimate, based on Cox et al. (2017) and ecoinvent (2018)
total H_2 consumption	MJ	2.09E+08	*calculated*	2.10E+06	*calculated*
total H_2 consumption	kg	1.74E+06	*calculated*	1.75E+06	*calculated*
7.5-18t					
total transport demand	km	1.30E+09	BFS (2017a)	1.55E+09	Estimate, based on ARE (2017)
specific fuel consumption	MJ/km	3.38	Estimate, based on Cox et al. (2017) and ecoinvent (2018)	2.84	Estimate, based on Cox et al. (2017) and ecoinvent (2018)
total H_2 consumption	MJ	4.38E+09	*calculated*	4.41E+09	*calculated*
total H_2 consumption	kg	3.65E+07	*calculated*	3.67E+07	*calculated*
18-26t					
total transport demand	km	4.69E+08	BFS (2017a)	5.62E+08	Estimate, based on ARE (2017)
specific fuel consumption	MJ/km	4.62	Estimate, based on Cox et al. (2017) and ecoinvent (2018)	3.88	Estimate, based on Cox et al. (2017) and ecoinvent (2018)
total H_2 consumption	MJ	2.17E+09	*calculated*	2.18E+09	*calculated*
total H_2 consumption	kg	1.81E+07	*calculated*	1.82E+07	*calculated*
>26t					
total transport demand	km	3.80E+08	BFS (2017a)	4.55E+08	Estimate, based on ARE (2017)
specific fuel consumption	MJ/km	6.67	Estimate, based on Cox et al. (2017) and ecoinvent (2018)	5.60	Estimate, based on Cox et al. (2017) and ecoinvent (2018)
total H_2 consumption	MJ	2.53E+09	*calculated*	2.55E+09	*calculated*
total H_2 consumption	kg	2.11E+07	*calculated*	2.12E+07	*calculated*

Original references from the Swiss case study referred to in the original tables above:

ARE (2017). Zukunft Mobilität Schweiz – UVEK-Orientierungsrahmen 2040. Swiss Federal Office for Spatial Development ARE, Bern, Switzerland.

BFS (2017a). Statistik Personenverkehr Schweiz. Swiss Federal Office for Statistics, Bern, Switzerland.

Cox et al. (2017). Environmental assessment of current and future urban buses with different energy sources. EVS 30, Stuttgart, Germany, October 9-11, 2017.

Ecoinvent (2018) The ecoinvent database, version v3.4, www.ecoinvent.org.

4 APPENDIX C: Potential UK hydrogen market sectors

This appendix presents a brief background to the existing and potential end-use markets for hydrogen (H_2) in the UK. Hydrogen can be produced with low gas emissions from a number of sources and used in a broad range of applications. Based on the E4Tech/Element Energy report "Hydrogen and Fuel Cells: Opportunities for Growth" published in November 2016[86] and commissioned by a number of UK and Scottish Government bodies, the main sectors for hydrogen deployment for the UK are:

a. Conversion of the gas network to hydrogen to provide low carbon heating (combined with large-scale hydrogen production by reforming natural gas and carbon capture and storage to achieve energy system transformation at scale);
b. Hydrogen in the transport sector for decarbonisation and improving the air quality;
c. Conversion of electricity into hydrogen, power-to-fuel and power-to-gas, also known as power-to-X, to store excess renewable electricity at times of lower demand and to help grid management and facilitate a greater penetration of energy generated from renewable sources;
d. Fuel Cell Combined Heat and Power (CHP) for improving energy efficiency in small-scale applications, including portable electrical power from fuel cells.

The impact and benefits of the development and integration of hydrogen into the UK energy system increase significantly with joint and coordinated development of those sectors, as part of a whole energy system. For example, a greater penetration of hydrogen vehicles would be significantly facilitated when utilising a hydrogen production and distribution infrastructure implemented for the gas network conversion instead of requiring a new separate infrastructure.

C.1 Decentralised heat and power

C.1.1 Domestic and commercial heating

In the UK, domestic and commercial heating account for 25% of total emissions and in order to meet international commitments on CO_2 emissions, the UK will need to decarbonise the supply of heat and electricity. This will mean that natural gas, which is used for heating in over 85% of homes, will have to be replaced with either a decarbonised gas, or an electric-heating option with minimum disruption[87] . There are 21 million homes with central heating and hot water from natural gas-fired boilers and a further 2 million commercial boilers[88]. The demand for heating is characterised by significant intra-day and inter-seasonal variation requiring an energy supply with substantial flexibility.

The UK benefits from a gas transmission network where a substantial part has been replaced with modern polyethylene pipes, which can operate safely with high blends of hydrogen and therefore significantly reducing the cost of any infrastructure upgrades. The UK can also make use of existing proven geological underground natural gas storage structures (salt caverns, aquifers,

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[86] E4Tech and Element Energy, Hydrogen and Fuel Cells: Opportunities for Growth: A Roadmap for the UK, 2016

[87] Energy Research Partnership, Potential Role of Hydrogen in the UK Energy System, 2016

[88] Dodds, P. E. and Hawkes, A. (Eds.) The role of hydrogen and fuel cells in providing affordable, secure low-carbon heat. H2FC SUPERGEN, London, UK, 2014

depleted gas fields) at the multi-terawatt hour (TWh) -scale. In addition, the UK has the prior experience of a large-scale network conversion when town gas was replaced by natural gas during the 1960s-80s following the discovery of North Sea gas.

Hydrogen could be used to decarbonise the overall gas system, either by blending it (up to 20%) or 100% replacement of natural gas. According to E4Tech, 60% of the energy required by domestic, commercial and industrial heat users could be supplied by hydrogen through conversion of the gas distribution network by 2050[89] . The resulting saving in emissions would be 1.5-2.2 Mt CO_2/year for a city the size of Leeds, if hydrogen is produced by electrolysis or from reforming natural gas with carbon capture and storage (CCS) to remove emissions. The roadmap developed by E4Tech/Element Energy envisages the conversion of a first city by 2025 along with the construction of a Steam Methane Reformer (SMR) as part of CCS deployment in the 2020-2025 period.

The gas network conversion would represent the backbone for further integration of renewables through “power-to-X” (see C.3), local energy efficient production of electricity in fuel cell CHPs (see C.1.2 and deployment of hydrogen fuelled vehicles (see C.2) increasing the total hydrogen market potential significantly through coordinated system development. A transformation at large scale will require major strategic energy system decisions at least 5 years ahead of any conversion and it must be noted that those decisions will need to be aligned with the roll out of large-scale hydrogen production (and carbon capture and storage if methane reforming is used).

C.1.2 Smaller scale stationary applications

Hydrogen can also be used in stationary fuel cells at scales of electricity generation from kilowatt to megawatt (kW_e to MW_e). This includes systems that generate both power and heat with high electrical efficiencies for the residential/commercial sector and decentralised power solutions (mainly in off-grid areas or for uninterruptible/backup power supply). Fuel Cell CHP can offer an attractive bridging solution to zero emissions heating as the technology fuelled with natural gas is readily available and can be later decarbonised fully through the use of hydrogen with minor modifications. The technology also offers economic opportunities for UK manufacturing companies to launch new products or partner with global companies to scale-up production and deployment.

Micro- and mini-CHP systems (<20 kW_e) are being rolled out through subsidised programmes. Japan leads the global market through the Enefarm programme which aims to install over 1 million systems by 2020. In Europe, EU-funded programmes (Enefield, Callux, and PACE) aim to install systems in the low thousands by 2020. Comparatively, full scale commercial penetration is estimated to require 10,000 units/manufacturer per year. The E4Tech roadmap expects circa one thousand small-scale units and >10 MW_e capacity of large fuel cells installed in the UK by 2020, increasing to ten thousand small-scale units and >100 MW_e capacity of large fuel cells by 2025.

There is potential for fuel cell use in portable and specialist situations, but this is relatively minor compared to the other applications being considered in the UK case study.

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[89] E4tech for Committee on Climate Change: Scenarios for deployment of hydrogen in meeting carbon budgets, October 2015, https://www.theccc.org.uk/publication/e4tech-for-ccc-scenarios-for-deployment-of-hydrogen-in-contributing-to-meeting-carbon-budgets, accessed 13th April 2018

C.2 Transport

Hydrogen fuel cells can be used in a range of transport applications. Their benefits include providing improved air quality and decarbonised transport with no operational compromise for the users. Hydrogen fuel cell vehicles have similar refuelling characteristics and distance ranges to conventional vehicles, therefore offering a real alternative to Battery Electric Vehicles (BEV). In the UK, significant economic benefits could also be derived from local vehicle technology development and manufacturing given the contribution of the car industry to the UK manufacturing sector.

C.2.1 Road: primarily passenger cars, industrial trucks and buses

Since 2013, when Hyundai's first production vehicles became available, the number of hydrogen fuel cell electric vehicles (HFCEVs) in use has been growing. Honda and Hyundai delivered in total just over 2,200 vehicles in 2016 and global manufacturers are readying to manufacture tens of thousands of vehicles by 2020. Buses and other commercial vehicle fleets operating locally with a central home depot are well suited for the early stages of commercialisation. The UK has two of the largest refuelling stations (by volume) in Europe serving the bus fleets in London and Aberdeen, and further plans to expand the current number of locations. Achieving affordability is estimated to require production of hundreds of thousands per year for passenger cars and hundreds to thousands per year for buses and heavier vehicles[90] making the latter an attractive early stage proposition to build infrastructure.

The risks related to committing investment in large-scale HFCEV production and the roll-out of a hydrogen delivery/refuelling infrastructure are currently considered to be the two main barriers to the large-scale introduction of hydrogen, rather than technology development. This is especially so in the face of competition from BEVs and the uncertainty in the consumer response and uptake of HFCEVs. It is envisaged that the early refuelling stations will use on-site hydrogen from electrolysis as this is the most cost effective for low volumes of hydrogen. Centralised hydrogen production and infrastructure can be used in the long term as demand grows above 10,000s vehicles beyond 2020-2025. Targeted programmes are necessary to support the growth of refuelling infrastructure alongside the deployment of new vehicles, therefore creating an early market and demand for hydrogen for infrastructure development. This aims for the establishment of an early fleet of thousands of vehicles by 2020 and 30 refuelling stations. There are already a number of UK and European programmes in place to support hydrogen-fuelled vehicles: UK H_2Mobility, Hydrogen for Transport Programme (HTP), the JIVE and MEHRLIN European Collaborative projects, HyFive.

Subsequently, the E4Tech scenario for successful deployment in the UK estimates that tens of thousands of vehicles could be in operation by 2025 with over 150 stations and that by 2050, as much as 30% of the road transport market could be fuelled by hydrogen.

C.2.2 Other applications

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[90] UK H_2Mobility Members, UK H_2Mobility Phase 1 Results, April 2013

Marine applications are at an early stage of trial and no commercial-scale hydrogen-powered vessel exists. Rail applications are currently at demonstration stage in light rail applications and locomotives. Aviation applications are at a demonstration stage.

C.3 Power-to-Fuel and Power-to-Gas (Power-to-X)

With the increasing share of intermittent renewable energy in the UK electricity market, primarily from wind- and solar-powered generation, the issues of balancing supply and demand for grid management and avoiding generation constraints are becoming increasingly important. Hydrogen production through electrolysis could absorb the surplus renewable electricity generated during periods of high output and low demand, such as strong wind during off-peak hours, and would allow further integration of renewable generation into the electricity grid. However, with strong competition for energy storage using batteries, large-scale deployment of energy storage by hydrogen production will require significant cost reductions and improved engineering.

A number of small pilot projects have been developed in the UK, for example, the Levenmouth Community Energy Project (LCEP) in the Fife area of Scotland[91]. However, the E4Tech/Element Energy roadmap envisages that only several projects will be operational by 2020 with further deployment dependent on cost reductions achieved by 2025.

C.4 Centralised heat and power generation

The UK has focused its renewable energy policy on electricity production primarily from offshore wind farms and there are currently no large-scale industrial hydrogen gas or steam turbines, or large-scale stationary fuels cells in the UK. Further, there is no government policy or ongoing work/projects to support such development. However, such facility(ies) could be envisaged in the future if large-scale hydrogen production facilities and hydrogen pipelines are deployed.

C.5 Industrial applications

Hydrogen is already a large global industrial business with the main uses being for the production of ammonia for for agricultural fertilizer purposes, methanol, and removal of sulphur compounds to purify/improve yields of petrol in refineries. Hydrogen has substantial potential to replace coking coal as a reducing agent in the steel-making industry. UK production of hydrogen is about 26.9 TWh/year over 15 sites. About half is a by-product, mainly from the chemical industry, which is either used on site or sold as chemical feedstock. Increases in capacity could lead to a surplus of up to 3.5 TWh/year, which could be used to supply early energy markets[92]. There is potential for use of hydrogen combustion in high temperature heat applications for industrial decarbonisation, which is likely to be commercially viable subject to large-scale gas network conversion combined with hydrogen production facilities and transport infrastructure.

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[91] Scottish Hydrogen and Fuel Cell Association, http://www.shfca.org.uk/news/2017/6/25/levenmouth-project-hydrogen-local-energy-system-goes-live, accessed 13 April 2018

[92] Energy Research Partnership, Potential Role of Hydrogen in the UK Energy System, op. cit.