Department for Business, Energy & Industrial Strategy

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Expansion of hydrogen production pathways analysis – import chains

Report

E4tech (UK) Ltd for the UK's Department for Business, Energy & Industrial Strategy (BEIS)

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1 Executive Summary

The UK's Low Carbon Hydrogen Standard[1] ('the standard') defines 'low carbon' hydrogen, to assess which pathways will be eligible for government support such as through the Net Zero Hydrogen Fund and/or the Hydrogen Business Model, as well as forming the basis of a future hydrogen certification scheme to support international trade in hydrogen and market development. Previous work[2] in 2021 by E4tech and Ludwig-Bölkow-Systemtechnik GmbH (LBST) to support the development of the standard included modelling of the GHG emissions of 10 hydrogen production pathways and 7 downstream distribution chains (and their combinations), focusing on UK production and UK use of low carbon hydrogen.

Since this original work was published along with the UK's Hydrogen Strategy, the UK Department for Business, Energy and Industrial Strategy (BEIS) has had further engagement with industry and identified additional potential routes. Further domestic production routes, not covered in the original study, were identified but are not included in this publication as they are not within the current scope of the standard and will require further consideration.

This report focuses on potential routes for imported hydrogen. It covers five theoretical supply chains for import of hydrogen into the UK, including: piping of compressed hydrogen; or shipping of ammonia; liquid organic hydrogen carriers (LOHCs); and liquid hydrogen (LH2).

Hydrogen may be imported to the UK, particularly from global regions with high resource availability of renewable electricity or natural gas. This project has not carried out any analysis comparing regions, production pathways or hydrogen carriers to determine which are most likely to be used for the import of hydrogen into the UK.

Table 1: Five theoretical case studies for imported hydrogen

Carrier and transport	Production location	Production type
Compressed H_2 pipeline	Norway	SMR+CCS
Compressed H_2 pipeline	Spain	Solar PV + electrolysis
Ammonia ship	Australia (Western)	Solar PV + electrolysis
LOHC (Methylcyclohexane) ship	UAE	SMR+CCS
Liquid H_2 ship	USA (Texas)	SMR+CCS

The same GHG methodology as the original work was followed to expand on the modelling, with the main details outlined in this report and appendices. The key results from this study are shown in Figure 1. The import chain results from this study can be compared with the UK production results in our original study and to the UK production threshold of 20 gCO_2e/MJ_{LHV} set in the standard.

[1] https://www.gov.uk/government/publications/uk-low-carbon-hydrogen-standard-emissions-reporting-and-sustainability-criteria
[2] E4tech and LBST (2021) 'Options for a UK low carbon hydrogen standard'. Available at: Options for a UK low carbon hydrogen standard: report - GOV.UK (www.gov.uk)

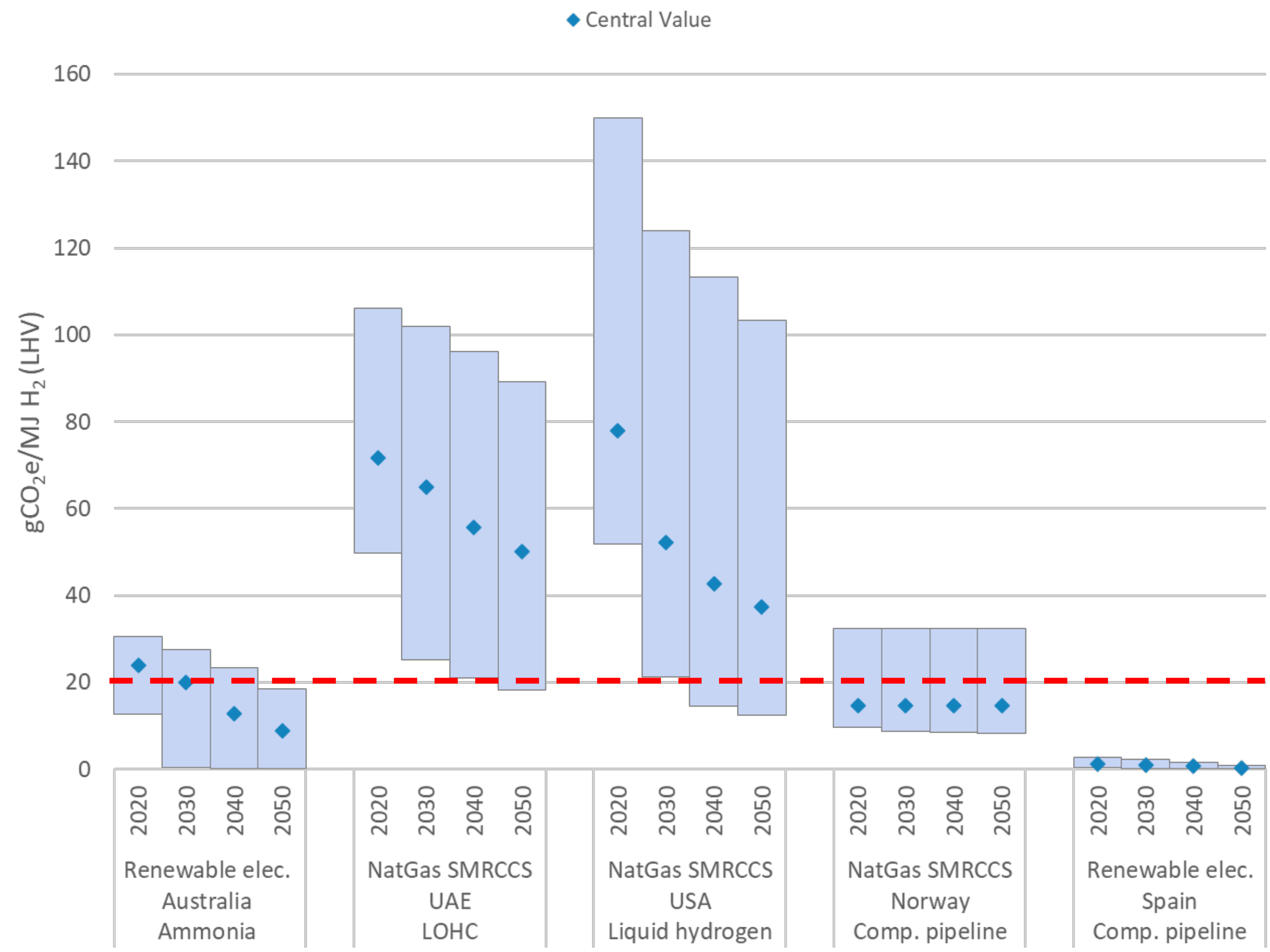

Figure 1: Overseas hydrogen production and import emissions (scenario ranges, 2020 to 2050, red dotted line as UK production threshold)

Figure 1 shows the GHG emissions for five theoretical case studies with overseas hydrogen production combined with various methods of importing this hydrogen into the UK. Key messages from the imported hydrogen results and sensitivity analysis are:

- Conversion/reconversion and long-distance shipping transport emissions can represent a significant contribution to overall imported hydrogen lifecycle emissions. This is particularly apparent for ammonia, LOHC and liquid hydrogen imports in earlier years when the emissions intensity of input transport fuels, grid electricity and heating fuels are highest.
- The added emissions of importing hydrogen via compressed pipeline are very low, given electricity for compression is the main input and this is still modest compared with inputs for other import chains. Even lower emissions could be achieved if renewable electricity were used for compression.
- Import of green hydrogen as ammonia appears advantaged amongst the non-piped import pathways considered, even when transported from as far as Australia. However, imports of green hydrogen via LOHC or liquified hydrogen from Australia were not

selected as case studies, so a direct comparison of which carrier is best for green hydrogen over a set distance cannot be determined directly from this study's results. Further follow-on analysis would be required, building on the import segment emissions in Section 3.

- Import options that involve shipping of blue hydrogen (SMR+CCS or ATR+CCS) are very unlikely to have emissions below the UK production threshold in the near-term, for locations with similar characteristics and assumptions to those we investigated (USA and UAE). Blue hydrogen imports will likely need to rely on decarbonisation of ships and extensive use of renewable heat and/or power along the import chains to have emissions below 20 gCO_2e/MJ_{LHV}. Blue ammonia imports were not one of the selected case studies, but could also be investigated further in follow-on work.
- However, compressed pipeline import of ATR+CCS blue hydrogen from a nearby country that has low emissions grid electricity and low upstream gas emissions (similar to Norway) is likely to have emissions below the UK production threshold.
- LOHC has higher residual import segment emissions in 2050 than other import chains because of the toluene make-up required plus reconversion heating (supplied from the UK gas grid, which only partially decarbonises). However, there is considerable uncertainty around the level of toluene replacement required (studies vary by an order of magnitude), and further research is needed. Different LOHCs to the methylcyclohexane/toluene system analysed in this study are being developed, and could also be investigated further.

2 Methodology

This extension project uses the same methodological principles of the previous study. More detail on the GHG methodology can be found in our report ‘Options for a UK Low Carbon Hydrogen Standard’.[3] This section outlines the methodology for only import chains.

Five theoretical case studies for imported hydrogen were identified and agreed with BEIS, as set out in Table 2. The imported hydrogen chains can be split into two components: the production of low-carbon hydrogen outside of the UK; and the import segment itself (involving compression/liquefaction/conversion, port storage, transportation to the UK and any reconversion back to gaseous hydrogen). The import chains stop at a common functional unit for gaseous hydrogen of 99.9% purity by volume and 3MPa within the UK (the same functional unit as for the UK production pathways), before any further distribution or use occurs within the UK. This is to ensure comparability with the result of the previous study.

We do not consider the direct use of imported ammonia or liquified hydrogen within the UK in this study, but this could be considered in follow-on work. The conversion, storage, transport and reconversion steps are explained in more detail in Appendix A.

Table 2: Five theoretical case studies for imported hydrogen

Import chain #	Carrier	Production location	Production type	Transport type	One-way distance (km)
1	Compressed H_2	Norway	SMR+CCS	Pipeline	1,000
2	Compressed H_2	Spain	Solar PV + electrolysis	Pipeline	1,500
3	Ammonia	Australia (Western)	Solar PV + electrolysis	Shipping	17,300 (Geraldton to Isle of Grain via Suez)
4	LOHC (Methyl-cyclohexane)	UAE	SMR+CCS	Shipping	11,300 (Dubai to Isle of Grain via Suez)
5	Liquid H_2	USA (Texas)	SMR+CCS	Shipping	9,100 (Texas City to Isle of Grain)

All trucking steps include the GHG impact of return journeys (either empty, or with toluene for the LOHC chain). A ‘switch’ has been added to the internal LCA modelling tool to toggle between including or excluding the return LH2 & ammonia tanker ship journeys in the GHG calculations, depending if the user wishes to assume that these tankers return empty (and so these GHG emissions belong to the hydrogen import chain being examined) or that they carry other cargo or go on to carry hydrogen produced elsewhere (and so any ship GHG emissions after delivery of hydrogen into the UK do not belong to the hydrogen import chain being examined). To be conservative, the return shipping emissions are included in all the ammonia

[3] E4tech and LBST (2021) ‘Options for a UK low carbon hydrogen standard’. Available at: https://www.gov.uk/government/publications/options-for-a-uk-low-carbon-hydrogen-standard-report

and LH2 analysis presented in this report. Toluene is always assumed to be shipped back to the country of LOHC production for conversion back into methylcyclohexane, and so always incurs these return shipping GHG emissions, regardless of the toggle choice.

The production of hydrogen outside the UK uses a similar model structure as for the UK production routes, but we have added new location-specific background data (e.g. upstream natural gas emission factors for Norway, UAE, USA), and replicated UK foreground data assumptions before replacing UK vectors with new location-specific vectors (e.g. USA grid electricity) to match the import chain descriptions in Table 2 above.

A manual sensitivity analysis was run to determine the effect of certain factors, such as shipping distance, power grid decarbonisation, heat decarbonisation or using ATR+CCS as an overseas production technology instead of SMR+CCS. A full discussion of the sensitivities run in this study is found in Section 3.

3 Results

The following sections present the main results from the expanded modelling, including a comparison of results from this study to the existing pathway results from previous work. So that these results can also be read independently of the original study, a summary of important information regarding the results is included below.

Hydrogen after production or import is in gaseous form at 3 MPa (30 bar) and has a purity of at least 99.9% by volume. The Excel model allows for up to three scenarios to be modelled at the same time. Table 3 defines the parameter selection for the three scenarios which are represented in the following results sections. The Foreground data and Background data assumptions are discussed further in Appendix A.

Table 3: Parameter selection for three scenarios modelled

	Foreground data	Background data	CH_4 & N_2O GWPs	Hydrogen GWP
Scenario 1	Central (e.g. likely efficiency, capture rate, feedstock impact, leakage and distances)	Baseline impact	AR5 without feedback	Baseline H_2
Scenario 2	Best case (e.g. highest efficiency, highest capture rates, lowest impact feedstocks, lowest leakages, lowest distances)	Low impact	AR5 without feedback	Low H_2
Scenario 3	Worst case (e.g. lowest efficiency, lowest capture rates, highest impact feedstocks, highest leakages, highest distances)	High impact	AR5 without feedback	High H_2

For the foreground production data, the scenarios are defined based on the choice of feedstocks, process efficiencies and input/outputs, plus CO_2 capture rates of the pathways where applicable. Best represents a scenario with the highest process efficiency and capture rates and lowest impact feedstocks; worst represents a scenario with the lowest process efficiency, lowest capture rates and highest impact feedstocks; and central represents a likely set of values. In some cases, no technological differences were modelled between the different scenarios.

For the foreground data for the import segments, the scenarios are defined based on the step efficiencies and energy/material inputs for compression, liquification and ammonia or LOHC (re)conversion, and leakage/boil-off rates in the chains. Best represents a scenario with the highest efficiencies, lowest energy/material inputs and lowest leakage/boil-off rates; worst represents the opposite; and central represents a likely set of values. In some import steps, no differences were modelled between the different scenarios. Hydrogen shipping transport distances are user inputs based on the specific case study countries selected, and are not varied between the scenarios.

For the background data, the scenarios are defined based on the data availability for each parameter. The central impact represents the most likely impact factor for the parameter, whereas the low impact and high impact reflect the range seen in the literature for some parameters. For other parameters, the baseline impact, low impact and high impact are the same.

Imported hydrogen chain results

The impact of importing hydrogen to the UK is presented first, focusing only on the emissions associated with conversion, storage, transport and any reconversion steps. We subsequently combine these import segment results with the emissions from overseas hydrogen production to derive the total emissions impact of producing and importing hydrogen from overseas for five theoretical case studies.

Figure 2 shows the emissions associated with the five theoretical imported case studies, excluding the GHG emissions from overseas hydrogen production (i.e. only counting GHG emissions from compression/liquefaction/conversion in the country of origin up to the point of achieving 99.9% purity by volume and 3MPa gaseous hydrogen within the UK).

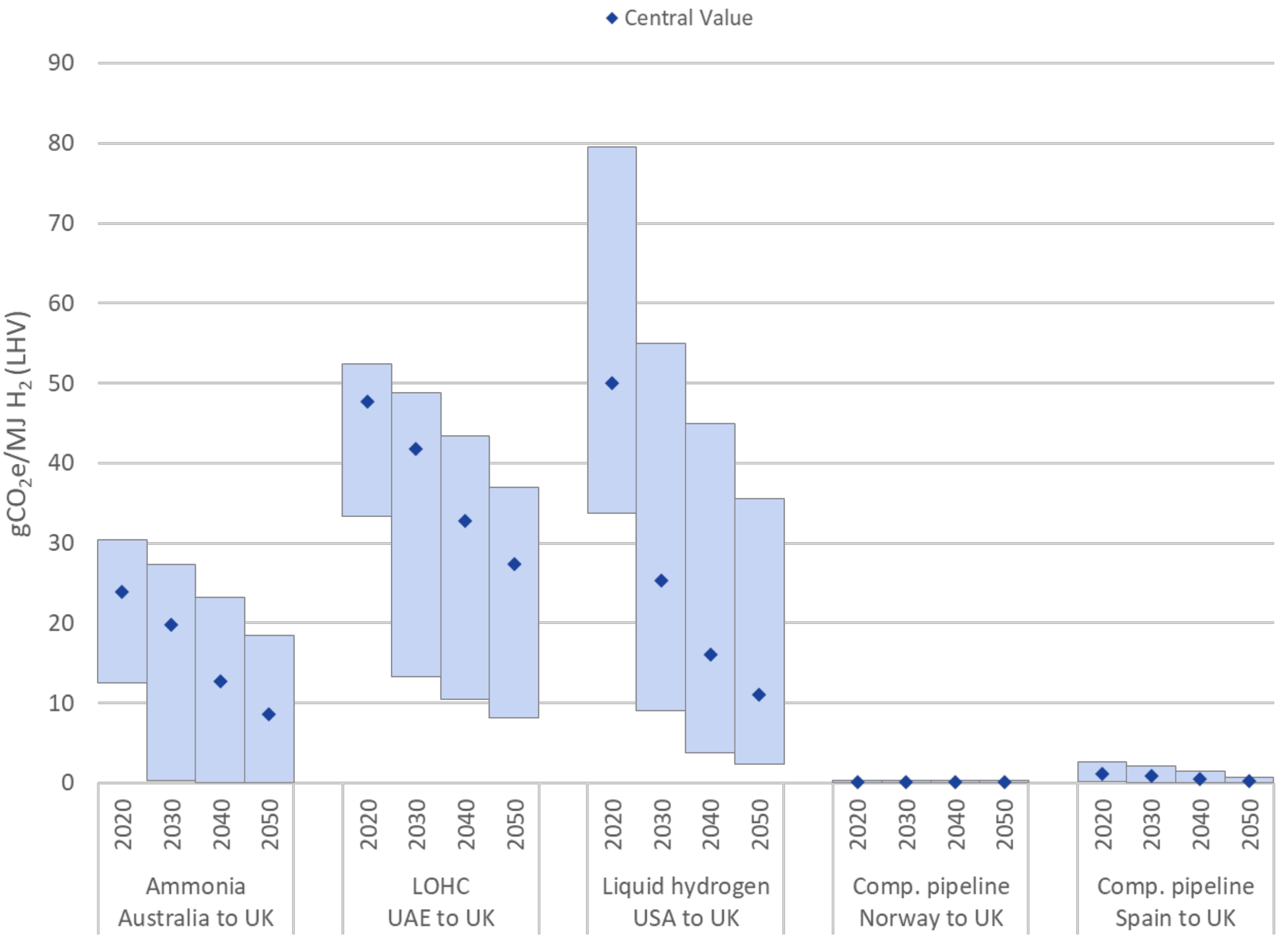

Figure 2: Hydrogen import segment emissions, excluding overseas hydrogen production and UK distribution (scenario ranges, 2020 to 2050)

The highest emissions in the early decades are observed for the liquid hydrogen and LOHC import segments, with a wide range across the scenarios, while the pipeline routes display very low emissions with small range across the scenarios.

For the liquid hydrogen import segment from the USA, the liquefaction conversion step is responsible for ~70% of the emissions for the central scenario in 2020 (Figure 3), due to the large use of electricity in liquefaction combined with the grid electricity intensity in Texas, USA. Emissions do fall significantly over time, due to improved liquefaction efficiency and USA grid decarbonisation, along with shipping and trucking decarbonisation assumptions. To achieve the Best case results, low carbon power and transport fuels are required.

For LOHC from UAE in the Middle East, there are three large contributors to the overall emissions for the LOHC import segment. There is the LOHC conversion step (due to power and toluene make-up requirements), the dehydrogenation plant in UK (due to gas grid input for heating) and the emissions associated with LOHC transport (trucking and shipping of hydrogenated methylcyclohexane and dehydrogenated toluene). The Best case has a much lower assumed toluene make-up in the LOHC cycle (0.2% replacement rate compared to 2.2% in the Central and Worst cases), lower natural gas use in dehydrogenation, and the Best case in future years also benefits from zero-emissions shipping and trucking, and faster grid decarbonisation in UAE. To achieve the Best case results, low carbon power and transport fuels are required, along with low make-up rates for toluene and efficient heat recycling.

For ammonia produced in Australia from green hydrogen, it is also assumed the ammonia conversion step is powered with renewable electricity. The transport emissions due to shipping of ammonia from Australia to the UK are therefore the most significant contributor for the ammonia chain given, followed closely by gas grid use for ammonia cracking. Decarbonisation in shipping and trucking over time results in a steady decline in overall GHG emissions for the ammonia chain as shown in Figure 2. Remaining emissions in 2050 in the Central and Worst cases are mostly related to gas grid inputs for ammonia cracking in the UK.

The emissions from the compression step for the Spanish pipeline segment are greater than those for the Norway pipeline chain, due to the grid emissions factor for Spain being higher in 2020 than Norway’s almost fully hydroelectric grid. However, as the Spanish grid decarbonises over time, the GHG impact of the Spanish import pipeline segment decreases (Figure 2).

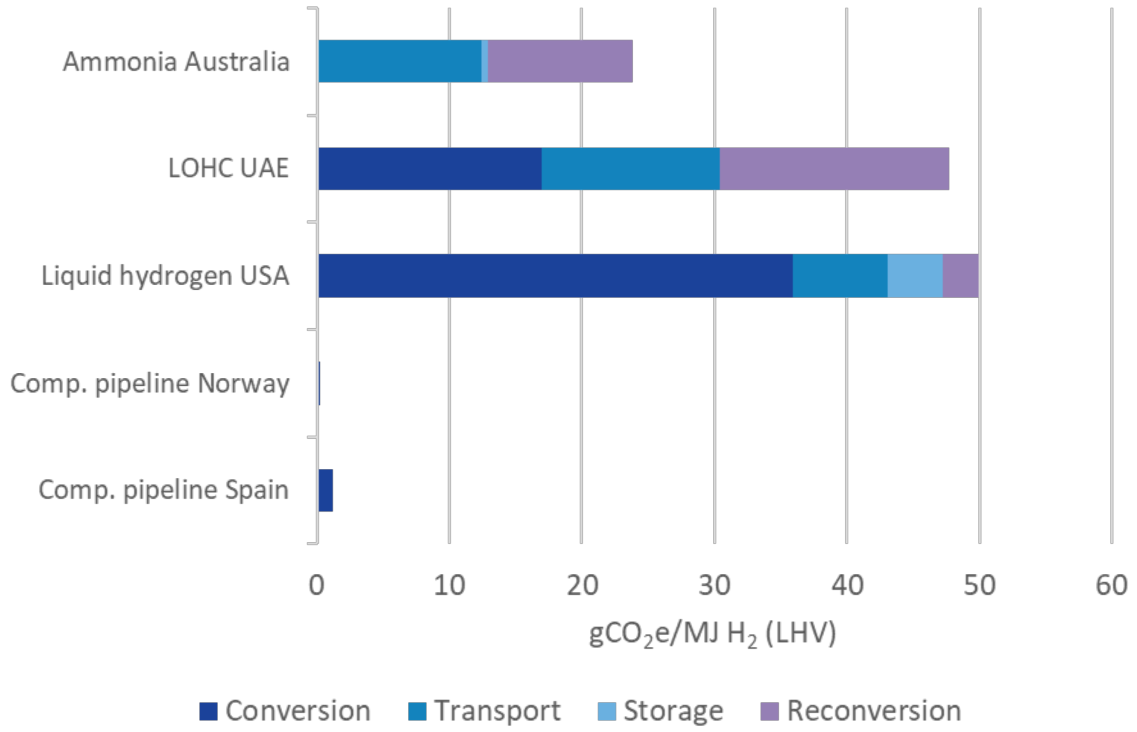

Figure 3: Hydrogen import segment emissions by step, excluding overseas hydrogen production and UK distribution (Scenario 1, 2020)

Combined overseas hydrogen production and import results

Figure 4 combines the emissions from the overseas hydrogen production pathways with the corresponding import segment emissions. We include the standard's UK production threshold of 20 gCO_2e/MJ_{LHV} as a red dotted line for comparison purposes only.

The trends observed in Figure 2 (import emissions only) are similar to those displayed in Figure 4 and show that with the combined production and import segments, some imported hydrogen could have very significant GHG emissions compared to domestic UK production under the Low Carbon Hydrogen Standard, particularly in the near-term (before global shipping, overseas electricity grids and conversion/reconversion facilities decarbonise). If the standard were to be expanded to include imports and were to set the same emissions threshold for imports as for UK production (20 gCO_2e/MJ_{LHV}), it is highly likely some imported hydrogen chains would not be able to meet this indicative threshold, even in future decades.

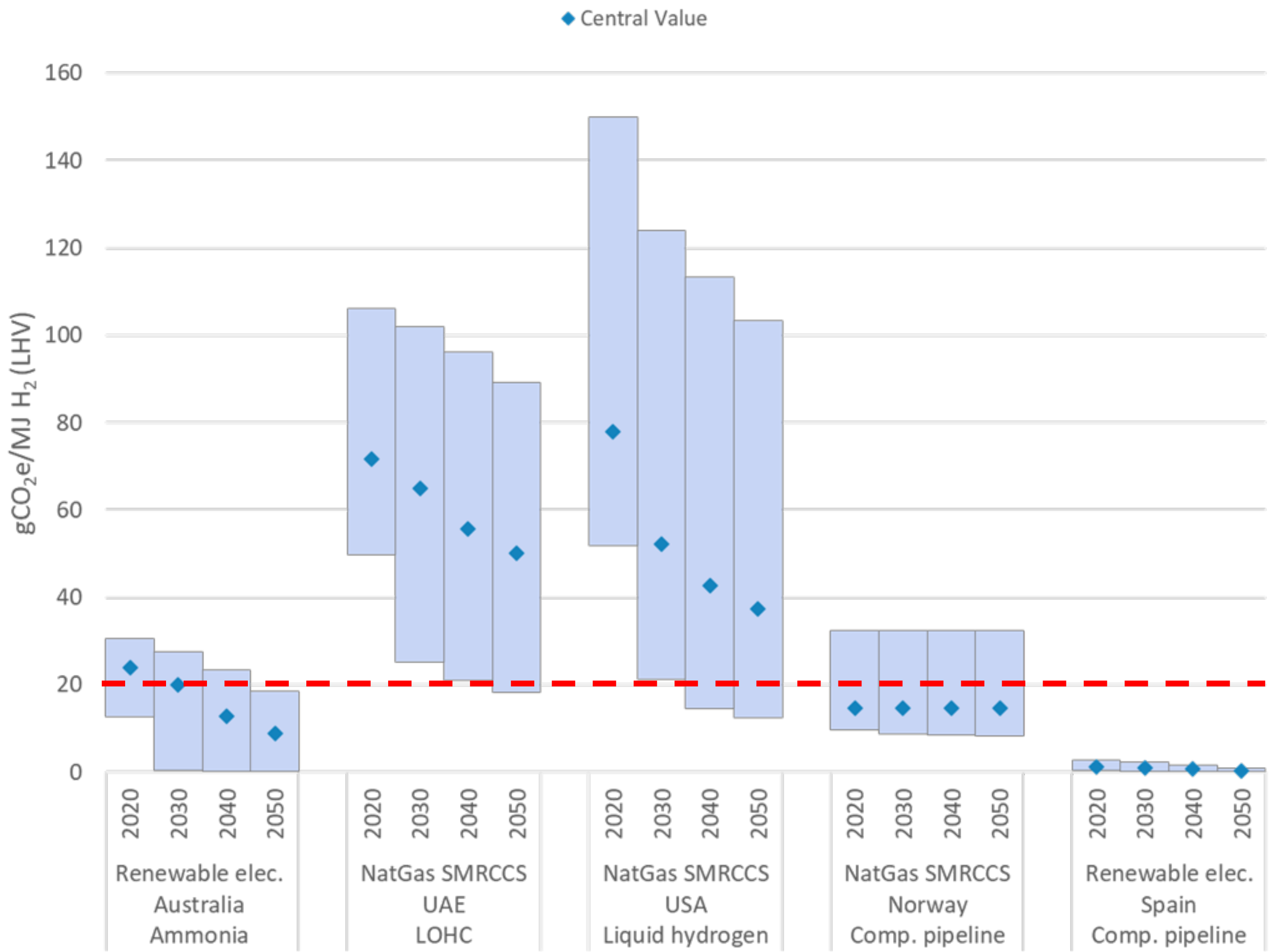

Figure 4: Combined overseas hydrogen production plus import segment emissions (scenario ranges, 2020 to 2050, red dotted line as UK production threshold)

The imported hydrogen with the lowest GHG impact of the five case studies considered is the Spanish green hydrogen delivered by compressed pipeline, which only has emissions associated with the grid electricity needed for compression, plus minor pipeline leakages. This case study would be likely to meet the indicative threshold. Spanish electricity grid factors were assumed to operate compressors along the pipeline, rather than dividing sections of the pipeline between Spain, France and the UK.

The Norwegian blue pipeline emissions are significantly above the Spanish green pipeline emissions, due to the differences in hydrogen production emissions, and do not change significantly over time. However, the better end of the Norwegian blue pipeline chains could potentially meet the indicative threshold. Norwegian upstream gas emissions are also small (due to low fugitive methane emissions and some platform electrification), helping to minimise Norwegian blue hydrogen production emissions.

The Central values for the Australian green ammonia chain are higher than the Norway blue pipeline chain until around 2040, despite the former starting with green hydrogen compared to the latter starting with blue hydrogen. This is because the shipping and cracking emissions for the ammonia chain are currently relatively significant, given the much longer transport distance and shipping fuel use required from Australia compared to piping compressed hydrogen across the North Sea, plus the added thermal input of natural gas for cracking ammonia. However, as global shipping and the UK gas grid decarbonise, the emissions from the Australian green ammonia chain decrease over time. The Australian green ammonia chain could meet the indicative threshold during the 2020s depending on the cracking plant heat integration, ship type and return journey assumptions, and this case study appears likely to meet the indicative threshold from around 2030 onwards.

The LOHC and LH2 import segments are also combined with overseas blue hydrogen production and hence their emissions are higher than just their respective import segment emissions. In the Worst cases in the earlier years, the GHG emissions from these import chains could be significantly higher than unabated SMR hydrogen production in the UK, despite these import routes being assumed to use CO_2 capture in the generation of blue hydrogen. Even by 2050 with efficiency improvements and emissions intensity reductions, these two case study routes are still likely to have GHG emissions of around 40-50gCO_2e/MJ_{LHV} in their Central cases. These two import case studies appear unlikely to meet the indicative threshold.

Combined well-to-point-of-use chain results

Figure 5 represents the GHG emission results of combining overseas hydrogen production, import segment and downstream distribution to UK consumers via pipeline in the year 2030. In the previous study, seven downstream distribution chains were modelled. In this extension study, only UK pipeline distribution (with low added emissions) is matched up with the overseas hydrogen production and import segments to give a brief view of potential well-to-point-of-use emissions for the five case studies.

Two UK production pathways (renewable electrolysis and fossil gas SMR+CCS) paired with pipeline distribution have also been included on the right-hand side of Figure 5 for comparison. The GHG impact from producing hydrogen via renewable electrolysis in Spain is not much greater than production via the same technology in the UK due to only electricity for compression and pipeline leakages contributing to the import emissions. The emissions of SMR+CCS piped from Norway are slightly lower than SMR+CCS in the UK, due to Norway having lower upstream fossil gas emission factors (stringent regulations) and a lower electricity grid intensity than the UK, which more than compensate for the minor additional pipeline emissions.

The import chains that include shipping (ammonia, LOHC and liquid hydrogen) have much greater GHG impacts compared to the corresponding UK hydrogen production chains. However, over time these additional emissions are expected to decrease as shipping and conversion/reconversion facilities decarbonise.

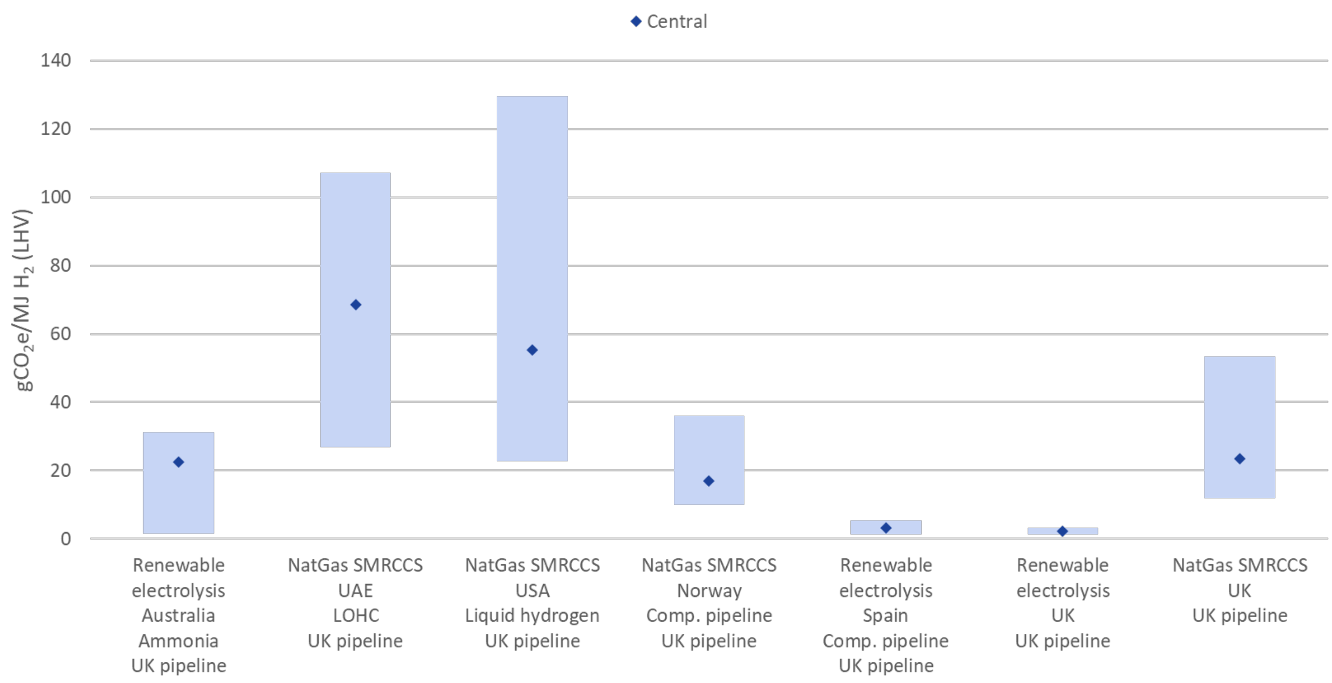

Figure 5: Well-to-point-of-use emissions of UK pipeline distribution paired with imported hydrogen or UK hydrogen production (scenario ranges, 2030)

Sensitivity analysis

Sensitivities were run on the Central foreground data and Baseline background data (i.e. starting from Scenario 1 results) for the chains added to this study. This was done to understand the impact of changing to zero carbon power, changing to zero carbon heat, using different shipping distances, or using ATR+CCS instead of SMR+CCS in the relevant blue hydrogen import chains. The sensitivities performed are described in Table 4 below.

Table 4: List of the sensitivities carried out

Sensitivity	Description
Renewable power	Changed the grid electricity emissions factor for all upstream production and import chains to 0 gCO_{2e}/MJ electricity: **Base case**: Grid electricity emissions factors (country specific) **Sensitivity**: Renewable electricity emissions factor (0 gCO_2e/MJ elec)
Renewable heat	**Base case:** Various step specific heating fuel inputs **Sensitivity**: Set any heating fuel or steam inputs for the import chains to zero**,** which is the equivalent of setting these input intensities to zero. We chose not to set the heating fuel and steam emissions intensities to zero, so as to maintain upstream feedstock fossil gas emissions factors.

Shipping distance (one-way)	Changed the shipping distances for the relevant import chains: **Base case:** Shipping distances correspond to shipping from the country of hydrogen production to the UK **Sensitivity:** All shipping distances changed to match a single common distance to the UK from: (1) Morocco = 2,775 km (Agadir to Isle of Grain) (2) USA = 9,100 km (Texas City to Isle of Grain) (3) UAE = 11,300 (Dubai to Isle of Grain via Suez) (4) Chile = 13,600 km (Punta Arenas to Isle of Grain) (5) Australia = 17,300 (Geraldton to Isle of Grain via Suez)
ATR+CCS in blue hydrogen pathways	**Base case**: SMR+CCS used in Norway, USA, UAE **Sensitivity**: ATR+CCS used in Norway, USA, UAE

Results from each sensitivity are provided in tables in the following sections. For the import chains, the sensitivities have been applied to the combined overseas hydrogen production and import segment results. No further distribution or use of hydrogen within the UK is considered.

Sensitivity: Renewable power used throughout the chain

The grid electricity inputs for each import chain have been changed to renewable electricity (0 gCO_{2e}/MJ elec). These inputs include both the grid electricity intensity specific to the country of hydrogen production and any UK grid electricity used in the import segment.

Table 5: Renewable power sensitivity results

All units are in gCO_{2e}/MJ_{LHV} H_2 Sensitivity: Renewable power					
		2020	**2030**	**2040**	**2050**
Renewable Electrolysis – Ammonia production (Australia)	Base case	24.0	20.0	12.8	8.8
	After sensitivity	21.2	19.0	12.4	8.6
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	60.6	58.2	50.3	45.8
SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	35.2	33.6	30.9	30.8
SMR CCS – Compressed pipeline (Norway)	Base case	14.7	14.6	14.6	14.6
	After sensitivity	14.6	14.6	14.6	14.6
Renewable Electrolysis – Compressed pipeline (Spain)	Base case	1.3	1.0	0.7	0.3
	After sensitivity	0.2	0.2	0.2	0.2

The impact of changing the grid emissions factor to a renewable source for all steps of the import chains varies across the cases. The grid emissions factors for the base case are country-specific, so a greater reduction is observed for those countries with high grid intensities (USA and UAE) and those case study chains with higher use of electricity (e.g. liquefaction).

Sensitivity: Renewable heat used throughout the chain

For import chains that utilise heat, the heat inputs have been removed to represent the use of renewable heat (assumed to be zero emissions from renewable electricity or green hydrogen).

Table 6: Renewable heat sensitivity results

All units are in gCO_{2e}/MJ_{LHV} H_2 Sensitivity: Renewable heat					
		2020	**2030**	**2040**	**2050**
Renewable Electrolysis -Ammonia production (Australia)	Base case	24.0	20.0	12.8	8.8
	After sensitivity	15.5	11.6	5.2	2.1
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	56.3	50.0	42.1	38.0
SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	77.8	52.1	42.6	37.3

The heating emissions factor has a significant impact on the ammonia and LOHC import chains, due to their use of fuel in conversion and/or reconversion, whereas the liquid hydrogen import route shows negligible change in these Central scenario results because the heating fuel input to regasification is minimal.

Sensitivity: Shipping distance

For the three import chains that include shipping to the UK (ammonia, LOHC and liquid hydrogen), we have updated the different shipping distances that currently apply to the different countries to be the same value in each of these three import chains, but without changing any other aspects of the hydrogen production pathways or import segments (i.e. no change to background national emissions factors). The labelling on the left-hand column of Table 7 therefore retains the country of origin assumed.

Five common indicative distances have been applied based on shipping routes from five different countries (Morocco, USA, UAE, Chile, and Australia) to the UK (Isle of Grain in South East England). Shipping distances have been calculated using the Sea Distances online tool. In all these results, the emissions of the return shipping journey are included.

Table 7: Shipping distance sensitivity results

All units are in gCO_{2e}/MJ_{LHV} H_2 Sensitivity: Shipping distance set to 2,775 km (indicatively based on Morocco to UK)					
		2020	**2030**	**2040**	**2050**
Renewable Electrolysis - Ammonia production (Australia)	Base case	24.0	20.0	12.8	8.8
	After sensitivity	15.8	13.3	9.2	7.5
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	64.2	59.0	52.5	49.0

SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	73.6	49.3	41.0	35.8
Sensitivity: Shipping distance set to 9,100 km (indicatively based on USA to UK)					
		2020	**2030**	**2040**	**2050**
Renewable Electrolysis - Ammonia production (Australia)	Base case	24.0	20.0	12.8	8.8
	After sensitivity	19.4	16.2	10.8	8.1
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	69.7	63.5	54.9	49.9
SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	77.9	52.2	42.7	37.4
Sensitivity: Shipping distance set to 11,300 km (indicatively based on UAE to UK)					
		2020	**2030**	**2040**	**2050**
Renewable Electrolysis - Ammonia production (Australia)	Base case	24.0	20.0	12.8	8.8
	After sensitivity	20.6	17.2	11.3	8.3
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	71.6	65.0	55.8	50.2
SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	79.4	53.2	43.3	38.0
Sensitivity: Shipping distance set to 13,600 km (indicatively based on Chile to UK)					
		2020	**2030**	**2040**	**2050**
Renewable Electrolysis - Ammonia production (Australia)	Base case	24.0	20.0	12.8	8.8
	After sensitivity	21.9	18.3	11.9	8.5
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	73.6	66.7	56.6	50.5
SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	80.9	54.2	43.9	38.5
Sensitivity: Shipping distance set to 17,300 km (indicatively based on Australia to UK)					
		2020	**2030**	**2040**	**2050**
Renewable Electrolysis - Ammonia production (Australia)	Base case	24.0	20.0	12.8	8.8
	After sensitivity	24.0	20.0	12.8	8.8
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	76.9	69.3	58.1	51.1
SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	83.5	55.9	44.9	39.5

The shipping distance has a noticeable impact on the import segment emissions due to transport emissions contributing a significant portion to the final GHG impact, particularly in the earlier years when shipping is yet to start to decarbonise. Comparing the results in 2020, the ammonia, LOHC and liquid hydrogen GHG emissions are 8.2, 12.7 and 9.9 gCO_2e/MJ_{LHV} higher when shipping distances are 17,300 km compared to only 2,775 km. By 2050, the differences are much smaller.

Sensitivity: ATR+CCS used in blue hydrogen import pathways

In the analysis above, all blue hydrogen import case studies used SMR+CCS. This sensitivity investigates how these import chain results would change if ATR+CCS were used instead.

Table 8: Blue hydrogen production technology sensitivity results

All units are in gCO_{2e}/MJ_{LHV} H_2 Sensitivity: Blue hydrogen produced via ATR CCS					
		2020	**2030**	**2040**	**2050**
SMR CCS – LOHC production (UAE)	Base case	71.6	65.0	55.8	50.2
	After sensitivity	71.2	61.7	51.5	45.0
SMR CCS – Liquid hydrogen production (USA)	Base case	77.9	52.2	42.7	37.4
	After sensitivity	76.2	46.3	35.8	29.5
SMR CCS – Compressed pipeline (Norway)	Base case	14.7	14.6	14.6	14.6
	After sensitivity	6.3	6.1	6.0	6.0

For the LOHC UAE and liquid hydrogen USA import chains, there is only a small decrease in emissions observed for 2020 when blue hydrogen is produced via ATR+CCS as opposed to SMR+CCS. This is because the higher efficiency and higher CO_2 capture rate of ATR+CCS is mostly offset by the enhanced requirements for input electricity, and the USA and UAE currently have high grid intensities. However, the benefit of switching to ATR+CCS grows over time due to electricity grid decarbonisation.

A more significant drop in near-term emissions is observed for Norwegian blue hydrogen production when switching to ATR+CCS, as Norwegian grid power already has almost zero emissions, hence the full benefit of higher CO_2 capture rates and higher process efficiency from ATR+CCS can be immediately seen. There is then little further improvement over time.

4 Conclusions and recommendations

This section discusses the implications of the results of import chains. This study's results have been compared with those in the original report and with the UK production threshold of 20 gCO_2e/MJ_{LHV} within the published standard.

- Conversion/reconversion and long-distance shipping transport emissions can represent a significant contribution to overall imported hydrogen lifecycle emissions. This is particularly apparent for ammonia, LOHC and liquid hydrogen imports in earlier years when the emissions intensity of input transport fuels, grid electricity and heating fuels are highest.
- The added emissions of importing hydrogen via compressed pipeline are low, given electricity for compression is the main input and this is still modest compared with inputs for other import chains. Even lower emissions can be achieved if renewable electricity is used for compression, e.g. for the Spanish renewable electrolysis via pipeline chain.
- Import of green hydrogen as ammonia appears advantaged amongst the non-piped import pathways considered, even when transported from as far as Australia. However, imports of green hydrogen via LOHC or liquified hydrogen were not selected as case studies, so a direct comparison of which carrier is best for green hydrogen over a set distance cannot be determined from this study's results. Further follow-on analysis would be required.
- Import options that involve shipping of blue hydrogen (SMR+CCS or ATR+CCS) are very unlikely to have emissions below the UK production threshold in the near-term, for locations with similar characteristics and assumptions to those we investigated (USA and UAE). Blue hydrogen imports will likely need to rely on decarbonisation of ships and extensive use of renewable heat and/or power along the import chains to have emissions below 20 gCO_2e/MJ_{LHV}. Blue ammonia imports were not one of the selected case studies, but could also be investigated further.
- However, compressed pipeline import of ATR+CCS blue hydrogen from a nearby country that has low emission grid electricity and low upstream gas emissions (e.g. similar to Norway) is likely to have emissions below the UK production threshold.
- LOHC has higher residual import segment emissions in 2050 than other import chains because of the toluene make-up required plus reconversion heating (supplied from the UK gas grid, which only partially decarbonises). However, there is considerable uncertainty around the level of toluene replacement required (studies vary by an order of magnitude), and further research is needed. Different LOHCs to the methylcyclohexane/toluene system analysed in this study are being developed, and could also be investigated further.

Appendix A – Data collection

Data collection for pathways considered in the original study can be found in Appendix B of the original report 'Options for a UK Low Carbon Hydrogen Standard'.[4] These are not repeated here as they have not been changed.

Foreground data for import chains

When building the foreground data set, three scenarios were defined for each import chain: Central, Best and Worst. The scenarios are defined based on the choice of step efficiencies and energy/material inputs for compression, liquification and ammonia or LOHC (re)conversion, and leakage/boil-off rates in the chains. Best represents a scenario with the highest efficiencies, lowest energy/material inputs and lowest leakage/boil-off rates; worst represents the opposite; and central represents a likely set of values. In some import chain steps, no differences were modelled between the different scenarios. Hydrogen shipping transport distances are user inputs based on the specific case study countries selected and are not varied between the scenarios.

Ammonia imports

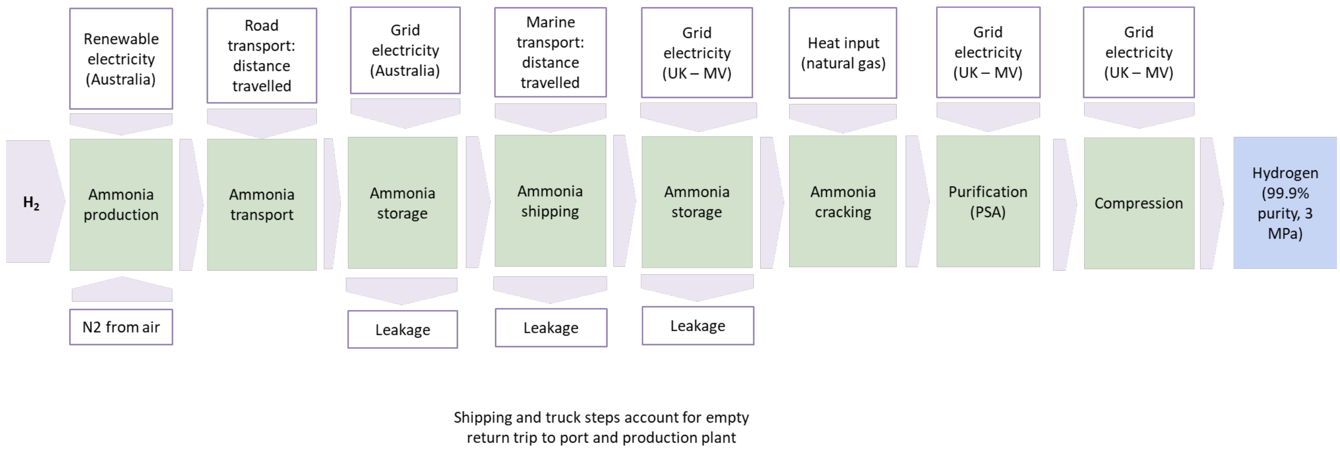

Figure 6: Ammonia import segment

Figure 6 outlines the ammonia import pathway modelled in this study, for the Australian green hydrogen case study. The foreground data assumptions used for each step are explained in the following sections.

[4] E4tech and LBST (2021) 'Options for a UK low carbon hydrogen standard'. Available at: https://www.gov.uk/government/publications/options-for-a-uk-low-carbon-hydrogen-standard-report

Ammonia production

Data for the ammonia production step is provided from the IEA with some calculations from DNV[5]. For the electricity use in the central scenario, data is from the IEA Future of Hydrogen Assumptions Annex[6]. The range and trend in PEM electrolyser efficiency modelled for the low temperature electrolysis chains in the previous study is assumed to apply to the electricity used for ammonia production to give a range and trend for hydrogen to ammonia step efficiencies over time.

For the central scenario, 5% of the current electrolysis to ammonia plant power use is for ASU + Haber-Bosch synthesis units (from IEA, 2021)[7] so this is accounted for in the central value. The LHV of ammonia is used to convert the units to MJ elec/MJ ammonia (IEA, 2021).

- **Central**: 0.102 MJ elec/MJ ammonia in 2020 decreasing to 0.089 MJ elec/MJ ammonia

For the best and worst cases, data was obtained from the IEA Future of Hydrogen report which is calculated by DNV.

- **Best**: 0.079 MJ elec/MJ ammonia in 2020 decreasing to 0.069 MJ elec/MJ ammonia
- **Worst**: 0.204 MJ elec/MJ ammonia in 2020 decreasing to 0.0179 MJ elec/MJ ammonia

Ammonia transport

The distance from production plant to port is assumed to be same as the distance from production plant to a retail site used in JEC (2020)[8]. The distance ammonia would be trucked is assumed to be the same for liquid hydrogen, ammonia and LOHC. An adjustment factor from the JEC (2020) trucking intensity is applied for trucking ammonia based on the IEA Future of Hydrogen Annex[9], given IEA assume an ammonia truck can only carry 2.6 tonnes of hydrogen (14.7 tonnes of ammonia). Units are converted to a per MJ ammonia basis using the LHV of ammonia (IEA, 2021)[10].

The value used for road transport is the same across all three scenarios (0.031 t.km/MJ ammonia).

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[5] DNV (2020) Database with techno-economic data for the import of liquid renewable energy carriers. Available at: https://www.gie.eu/wp-content/uploads/filr/2599/2020-09-09%20-%20DNV%20GL%20-%20GIE%20database%20Liquid%20Renewable%20Energy%20(draft%20final).xlsx
[6] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[7] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf
[8] JEC (2020) JEC Well-to-Tank report v5. Available at: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-tank-report-v5
[9] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[10] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

Ammonia storage

The electricity use for storage is from the IEA Future of Hydrogen Annex[11] and is assumed to be kWh/kg of stored product (not kWh/kg H_2 given the three different columns in the source). The electricity use is converted to MJ elec/MJ ammonia to give 0.0010 MJ elec/MJ ammonia across all three scenarios for storage in Australia and 0.0039 MJ elec/MJ ammonia for storage in the UK.

Ammonia emissions are calculated from the boil-off rate and the storage time which is assumed to be 20 days across all scenarios (IEA, 2020). The boil-off rate for the central and best scenarios is 0% (IEA, 2020) leading to no ammonia emissions. A boil-off rate of 0.03% is assumed for the worst case based on data from the DNV, 2020[12] leading to 0.32 gNH_3/MJ ammonia emissions.

Ammonia shipping

Data for the travel distance one-way is based on the Geraldton, Australia to Isle of Grain via the Suez canal (Sea-Distances, 2021)[13] and converted to a per MJ ammonia basis using the LHV of ammonia. This results in the value of 1.86 t.km/MJ ammonia for all three scenarios, across all timeframes.

Whether the return journey of the vessel is empty or loaded with other cargo needs to be accounted for within the hydrogen lifecycle emissions. If the return leg is loaded it is not accounted for within the hydrogen lifecycle emissions. This is a user choice in the Summary Results tab. The default assumption is the return leg is empty/needs accounting for.

The travel distance, ship speed, boil-off rate and flash rate are used to calculate the ammonia emissions. There are no ammonia emissions calculated for the central and best cases due to the boil-off rate being 0% (IEA, 2020)[14]. A boil-off rate of 0.08% is assumed for the worst case based on data from the DNV, 2020[15] leading to 1.03 gNH_3/MJ ammonia emissions.

Ammonia cracking

IEA Future of Hydrogen Assumptions Annex[16] gives a 99% recovery rate of impure hydrogen from ammonia cracking, applied in the Central and Worst scenarios. H21's assumption of 99.5% recovery is applied in the Best scenario. In all scenarios, it is assumed that the other

[11] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[12] DNV (2020) Database with techno-economic data for the import of liquid renewable energy carriers. Available at: https://www.gie.eu/wp-content/uploads/filr/2599/2020-09-09%20-%20DNV%20GL%20-%20GIE%20database%20Liquid%20Renewable%20Energy%20(draft%20final).xlsx
[13] Sea-Distances (2021) Sea Distances/Port Distances Available at: https://sea-distances.org/
[14] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[15] DNV (2020) Database with techno-economic data for the import of liquid renewable energy carriers. Available at: https://www.gie.eu/wp-content/uploads/filr/2599/2020-09-09%20-%20DNV%20GL%20-%20GIE%20database%20Liquid%20Renewable%20Energy%20(draft%20final).xlsx
[16] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf

minor gases generated are recycled and consumed in the process heating and are therefore not an exported co-product.

The natural gas input is calculated using the cracker heating requirement and the gas boiler heating efficiency. The heating requirement of 9.7 kWh heat/kg pure hydrogen is taken from IEA, 2020[17], and assumed to all be met by input natural gas in the Worst case scenario with a heating efficiency of 90% based on the industrial gas boiler efficiency in the heat and power workbook from JEC[18]. In the Best scenario, all the heating for cracking is assumed to come from cracker and PSA off-gases, as per the fully heat integration concepts in H21, 2018[19]. In the Central scenario, the IEA heating requirement is assumed to be reduced (but not fully met) by recycling of the IEA quantified off-gases from the cracker and PSA. This results in UK gas grid input values of 0, 0.11 and 0.27 MJ gas grid (process input)/MJ impure hydrogen across the Best, Central and Worst scenarios respectively. Fuel switching to other heating sources, such as low carbon hydrogen, may also be possible, but was not investigated in this study.

PSA

IEA Future of Hydrogen Assumptions Annex[20] gives a 85% recovery rate of pure H2 from impure hydrogen via PSA after ammonia cracking, which is applied in the Central and Worst scenarios. H21 NoE[21] gives a 91% PSA efficiency, which is applied in the Best scenario. In the Central and Best cases, it is assumed the residue off-gases from PSA would be internally recycled for ammonia cracking heating, which would remove them as a co-product stream and increase the PSA hydrogen allocation factor to 100%. However, in the Worst scenario, it is assumed that these PSA off-gases would be sold without further compression, i.e. it is valid to consider these as an exported co-product stream (to which a proportion of the higher upstream emissions are allocated, due to the higher natural gas use in cracking).

The electricity use of 1.5 kWh/kg H_2 in the Central and Worst cases for the PSA step is based on the IEA Future of Hydrogen Assumptions annex[22]. These values are converted to a per MJ H_2 basis to give 0.05 MJ elec/MJ H_2 across the Central and Worst scenarios. For the Best case, H21 NoE[23] gives an electricity use of 0.0014 MJ elec/MJ H_2.

Compression

The PSA output pressure is not reported in the IEA (2020) study, so 17 bar is assumed for the output in line with the H21 NoE study[24]. Therefore, further compression from 17 bar to 30 bar is required to ensure comparability with other routes. Following the theoretical compression

[17] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[18] JEC (2020) JEC Well-to-Tank report v5. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC119036
[19] H21 North of England Report, 2018, Section 3.6.3 https://www.h21.green/app/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf
[20] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[21] H21 North of England Report, 2018, Section 3.6.3 https://www.h21.green/app/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf
[22] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[23] H21 North of England Report, 2018, Section 3.6.3 https://www.h21.green/app/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf
[24] H21 North of England Report, 2018, Section 3.6.3 https://www.h21.green/app/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf

formula given in the Low Carbon Hydrogen Standard Data Annex[25], the electricity required is 0.34 kWh/kg H_2. This is converted to a per MJ H_2 basis to give 0.010 MJ elec/MJ H_2 across all scenarios.

LOHC imports

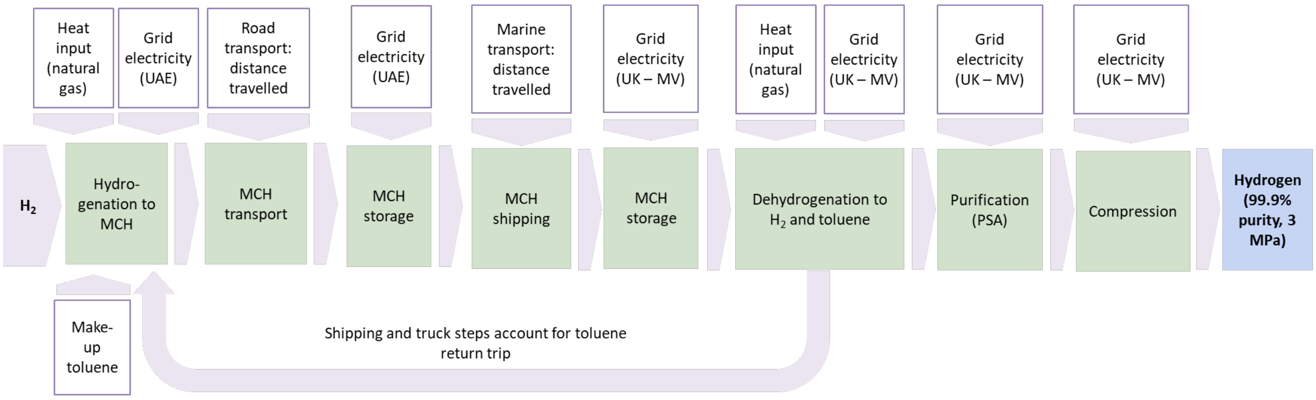

Figure 7: LOHC import segment

Figure 7 outlines the LOHC import pathway modelled in this study. The foreground data assumptions used for each step are explained in the following sections.

LOHC production

The electricity and natural gas inputs used for LOHC production are based on the IEA Future of Hydrogen Assumptions annex[26]. Across all scenarios, the electricity use is 1.5 kWh/kg H_2 and natural gas use is 0.2 kWh gas/kg H_2 stored in methylcyclohexane (MCH). These values are converted to a per MJ H_2 basis to give 0.05 MJ elec/MJ H_2 stored in MCH and 0.006 MJ gas grid (process input)/MJ H_2 stored in MCH.

The toluene inputs are calculated from the toluene make-up and the hydrogen carrying capacity of MCH. The toluene make-up is compared to the annual plant capacity, toluene and MCH molar weights (IEA, 2020) to give 0.022 kg toluene/kg MCH for the Central and Worst cases. The toluene make-up of 0.002 kg toluene/kg MCH for the Best case is sourced from Argonne, 2020[27]. The hydrogen carrying capacity (0.06 kg H_2 stored in MCH/kg MCH) is calculated from molar weights (Juangsa, 2018)[28]. The LHV of hydrogen is used to 0.003 kg

[25] BEIS, 2022, Low Carbon Hydrogen Standard Data Annex, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1082379/low-carbon-hydrogen-standard-guidance-data-tables-v2.0.pdf
[26] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[27] Argonne (2020) Toluene-MCH as a Two-Way Carrier for Hydrogen Transmission and Storage Available at: https://www.hydrogen.energy.gov/pdfs/review20/h2058_ahluwalia_2020_p.pdf
[28] Juangsa et al (2018) Highly Energy-Efficient Combination of Dehydrogenation of Methylcyclohexane and Hydrogen-Based Power Generation. Available at: https://www.aidic.it/cet/18/70/349.pdf

toluene/MJ H_2 stored in MCH for the central and worst cases and 0.0003 kg toluene/MJ H_2 stored in MCH for the best case.

LOHC transport

The distance from the production plant to port is the same as the distance from the production plant to retail site (JEC, 2020)[29]. The distance the LOHC would be transported is assumed to be the same for liquid hydrogen, ammonia and LOHC. An adjustment factor is applied for trucking an MCH tanker based on the dataset from the synfuels workbook (JEC, 2020). Units are converted to a 'per MJ H_2 stored in MCH' basis using the LHV of hydrogen (IEA, 2021)[30].

The value for road transport used is the same across all the three scenarios (0.044 t.km/MJ H_2 stored in MCH).

After delivery of MCH to the port, toluene has to be returned to the LOHC production plant. The road transport MJ/t.km value already factors in this return trip.

LOHC storage

The electricity use for storage is from the IEA Future of Hydrogen Annex[31] and is assumed to be in the units of kWh/kg H_2. The electricity use is converted to MJ elec/MJ H_2 stored in MCH to give 0.0003 MJ elec/MJ H_2 across all three scenarios for storage in the UAE and for storage in the UK.

MCH emissions are calculated from the boil-off rate and the storage time. The boil-off rate for all scenarios is 0% (IEA, 2020) leading to no MCH emissions. The storage days are assumed to be the same as the import terminal after shipping.

LOHC shipping

Data for the one-way travel distance is based on Dubai to Isle of Grain via the Suez canal (Sea-Distances, 2021)[32] and converted to a 'per MJ H_2 stored in MCH' basis using the LHV of hydrogen (IEA, 2021)[33]. The one-way distance is always doubled due to needing to return the toluene back to the UAE, regardless of the user's choice in the Summary Results tab.

This results in a value of 3.0766 t.km/MJ H_2 stored in MCH for all scenarios, across all timeframes.

[29] JEC (2020) JEC Well-to-Tank report v5. Available at: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-tank-report-v5
[30] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf
[31] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[32] Sea-Distances (2021) Sea Distances/Port Distances Available at: https://sea-distances.org/
[33] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

There are no fugitive MCH, toluene or hydrogen emissions calculated, due to the boil-off rate being 0% (IEA, 2020)[34].

LOHC dehydrogenation

IEA Future of Hydrogen Assumptions Annex[35] gives a 90% recovery rate of impure hydrogen from dehydrogenation.

The electricity use for the dehydrogenation step is from the IEA Future of Hydrogen Assumptions Annex[36], and converting the units using the LHV of hydrogen to give 0.011 MJ elec/MJ impure hydrogen for all scenarios.

The natural gas input is calculated using the heating requirement and the heating efficiency. The heating requirements for the central and best cases are from the DNV database[37] while the heating requirement for the worst case is from the IEA Future of Hydrogen Assumptions Annex. This results in the following values for the heating requirement:

- **Central:** 12.0 kWh heat/kg pure H_2
- **Best:** 9.4 kWh heat/kg pure H_2
- **Worst:** 13.6 kWh heat/kg pure H_2

A heating efficiency of 90% is assumed across all scenarios based on the industrial gas boiler efficiency in the heat and power workbook from the JEC[38]. In the Central and Best cases, the off-gases arising from PSA and dehydrogenation are assumed to be recycled to reduce the input of natural gas required, and these off-gases are therefore not exported as co-products. In the Worst case, these off-gases are assume to be exported as co-products, and there is no reduction in natural gas use. The resulting natural gas use factors are therefore:

- **Central:** 0.23 MJ gas grid (process input)/MJ impure H_2
- **Best:** 0.15 MJ gas grid (process input)/MJ impure H_2
- **Worst:** 0.41 MJ gas grid (process input)/MJ impure H_2

Future fuel switching to other heating sources, such as low carbon hydrogen, may also be possible, but was not investigated in this study.

[34] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[35] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[36] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[37] DNV (2020) Database with techno-economic data for the import of liquid renewable energy carriers. Available at: https://www.gie.eu/wp-content/uploads/filr/2599/2020-09-09%20-%20DNV%20GL%20-%20GIE%20database%20Liquid%20Renewable%20Energy%20(draft%20final).xlsx
[38] JEC (2020) JEC Well-to-Tank report v5. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC119036

PSA

IEA Future of Hydrogen Assumptions Annex[39] gives a 98% recovery rate of pure H2 from impure hydrogen via PSA after dehydrogenation. In the Worst case, it is assumed this small volume of residue off-gases from PSA do not need further compression and would be sold, i.e. it is valid to consider these as an exported co-product stream. In the Best and Worst cases, they are assumed to be internally reused for dehydrogenation heating, which removes them as a co-product stream and increases the PSA hydrogen allocation factor to 100%.

The electricity use for the PSA step in the LOHC chain is 1.1 kWhe/kg H2, from IEA 2020[40]. This is converted into 0.03 MJe/MJ H2, and used across all scenarios.

Compression

The PSA output pressure is not reported in the IEA study above, so we assume a 17bar output as for the ammonia cracker in the H21, 2018 report[41]. Therefore, further compression from 17 bar to 30 bar is required to ensure comparability with other routes. Following the theoretical compression formula given in the Low Carbon Hydrogen Standard Data Annex[42], the electricity required is 0.34 kWh/kg H_2. This is converted to a per MJ H_2 basis to give 0.010 MJ elec/MJ H_2 across all scenarios.

Liquified hydrogen imports

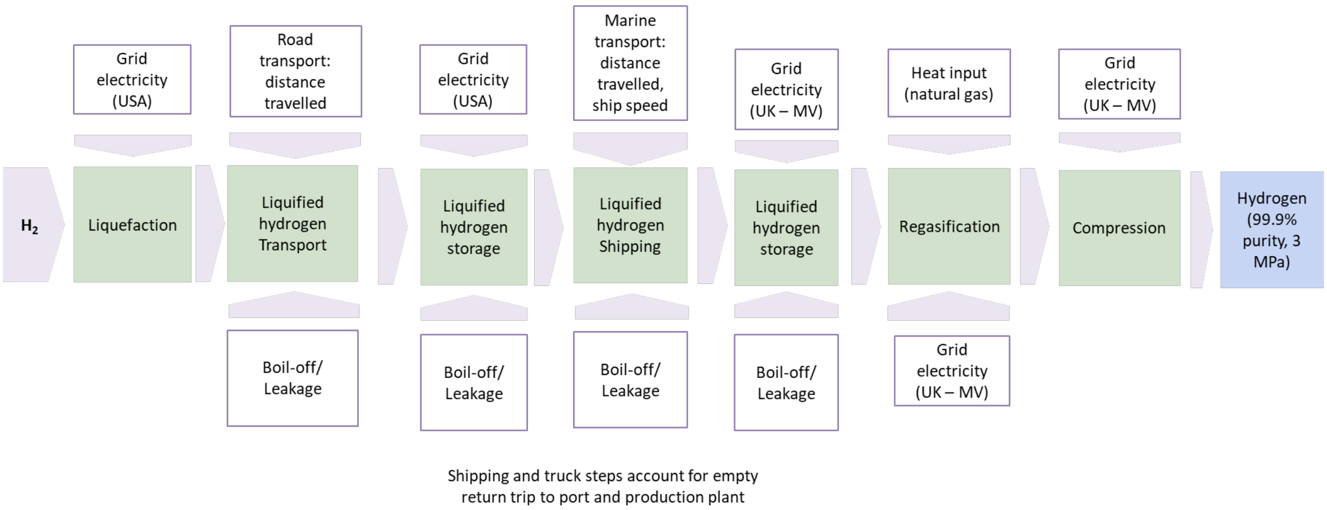

Figure 8: Liquified hydrogen import segment

[39] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[40] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[41] H21 North of England Report, 2018, Section 3.6.3 https://www.h21.green/app/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf
[42] BEIS, 2022, Low Carbon Hydrogen Standard Data Annex, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1082379/low-carbon-hydrogen-standard-guidance-data-tables-v2.0.pdf

Figure 8 outlines the liquified hydrogen import pathway modelled in this study. The foreground data assumptions used for each step are explained in the following sections.

Liquefaction

Electricity requirements are reported in kWh elec/tonne LH2 and converted to a per MJ LH2 basis using the LHV of hydrogen (IEA, 2021)[43]. For the best case, the electricity use is based on data from the DNV[44] and decreases to the IEA Future of Hydrogen Assumptions Annex value by 2030[45]. For the central case, the IEA value is assumed to be reached by 2050 with a steady reduction between the DNV (2020) and the IEA (2050) values. This results in the following values:

- **Central:** 0.30 MJ elec/MJ LH2 in 2020 decreasing to 0.183 MJ elec/MJ LH2 by 2050
- **Best:** 0.24 MJ elec/MJ LH2 in 2020 decreasing to 0.183 MJ elec/MJ LH2 by 2030 and remaining constant to 2050

The 2020 value for electricity used for the worst case is from the DNV which is assumed to decrease across the 2020-2050 time period at the same rate as the central case.

- **Worst**: 0.39 MJ elec/MJ LH2 in 2020 decreasing to 0.238 MJ elec/MJ LH2 by 2050

Liquid hydrogen transport

The distance for transport of liquid hydrogen from the production plant to port is assumed to be the same as the distance from the production plant to a retail site (JEC, 2020)[46]. An adjustment factor is applied for trucking LH2 tanker based on the dataset from the hydrogen workbook (JEC, 2020), as liquid hydrogen trucks are assumed to carry only 3.5 tonnes of cargo compared to 26 tonnes of room-temperature liquids like diesel or vegetable oils. Units are converted to 0.02 t.km/MJ LH2 basis using the LHV of hydrogen (IEA, 2021), and is the same value used across all three scenarios.

Hydrogen emissions are calculated from the boil-off rate and the trucking time. The boil-off rate varies across the scenarios from 0.3% best case to 0.6% worst case (0.45% central case) (Aziz, 2021)[47]. The trucking time is 0.25 days across all scenarios, assuming the average truck speed to be 50 km/hr. Converting to a per MJ hydrogen basis using the LHV of hydrogen (IEA, 2021[48]) results in:

[43] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

[44] DNV (2020) Database with techno-economic data for the import of liquid renewable energy carriers. Available at: https://www.gie.eu/wp-content/uploads/filr/2599/2020-09-09%20-%20DNV%20GL%20-%20GIE%20database%20Liquid%20Renewable%20Energy%20(draft%20final).xlsx

[45] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf

[46] JEC (2020) JEC Well-to-Tank report v5. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC119036

[47] Aziz (2021) Liquid Hydrogen A Review on Liquefaction, Storage, Transportation, and Safety, page 19 Available at: https://www.mdpi.com/1996-1073/14/18/5917/pdf

[48] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

- **Central:** 0.009 gH_2/MJ LH2
- **Best:** 0.006 gH_2/MJ LH2
- **Worst:** 0.013 gH_2/MJ LH2

Liquid hydrogen storage

The electricity use for storage is from the IEA Future of Hydrogen Annex[49] and is assumed to be in the units of kWhe/kg H_2. The electricity use is converted to MJ elec/MJ LH_2 to give 0.0183 MJ elec/MJ LH_2 for storage in the USA and 0.0006 MJ elec/MJ LH_2 for storage in the UK, across all three scenarios.

Hydrogen emissions are calculated from the boil-off rate, flash rate and the storage time. The values are assumed to be the same for both storage in the USA and storage in the UK. The flash rate for all scenarios is 0.1% (IEA, 2020) and the storage time is 20 days. The boil-off rate is from the DNV dataset[50] for the best (0.03%) and worst (0.3%) cases. The boil-off rate for the central case is based on data from the IEA Future of Hydrogen Assumptions Annex (0.1%). Using the LHV of hydrogen (IEA, 2021), the units are converted to a per MJ LH_2 basis:

- **Central**: 0.18 gH_2/MJ LH2
- **Best**: 0.06 gH_2/MJ LH2
- **Worst**: 0.51 gH_2/MJ LH2

Liquid hydrogen shipping

Data for the one-way travel distance is based on Texas City to Isle of Grain (Sea-Distances, 2021)[51] and converted into 0.152 t.km/MJ LH2 using the LHV of hydrogen (IEA, 2021)[52]. This applies for all scenarios, across all timeframes.

Whether the return journey of the vessel is empty or loaded with other cargo needs to be accounted for within the hydrogen lifecycle emissions. If the return leg is loaded with other hydrogen, the return leg is not accounted for within the hydrogen lifecycle emissions. This is a user choice in the Summary Results tab. The default assumption is the return leg is empty/needs accounting for.

The travel distance, ship speed, boil-off hydrogen for propulsion, boil-off rate and flash rate are used to calculate the hydrogen fugitive emissions. Data for the flash rate (1.3%), the use of boil-off hydrogen for propulsion (0.08%/day) and the ship speed (30 km/hr) is from the IEA

[49] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[50] DNV (2020) Database with techno-economic data for the import of liquid renewable energy carriers. Available at: https://www.gie.eu/wp-content/uploads/filr/2599/2020-09-09%20-%20DNV%20GL%20-%20GIE%20database%20Liquid%20Renewable%20Energy%20(draft%20final).xlsx
[51] Sea-Distances (2021) Sea Distances/Port Distances Available at: https://sea-distances.org/
[52] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

Future of Hydrogen Assumptions Annex[53]. The boil-off rate is from the DNV dataset for the best (0.1%) and worst (0.4%) cases. The boil-off rate for the central case is based on data from the IEA Future of Hydrogen Assumptions Annex (0.2%). These are converted into a per MJ LH2 basis:

- **Central:** 0.32 gH_2/MJ LH2 in 2020 decreasing to 0.23 gH_2/MJ LH2 in 2050
- **Best:** 0.21 gH_2/MJ LH2 in 2020 decreasing to 0.17 gH_2/MJ LH2 in 2050
- **Worst:** 0.53 gH_2/MJ LH2 in 2020 decreasing to 0.44 gH_2/MJ LH2 in 2050

Decarbonisation in shipping is assumed to be correlated to the use of boil-off hydrogen in ship propulsion. Ship propulsion cannot use all the boil-off hydrogen, and some will be uncaptured.

Regasification

The electricity and natural gas energy input values used for the central and worst cases are from Øyvind (2020)[54]. For the best case, no energy use in regasification is assumed for this step because the process is assumed to be self-sufficient, e.g. with use of an onsite cold engine/Brayton cycle to generate necessary power (IEA, 2020; Hinkley, 2021)[55,56]. Using the LHV of hydrogen, the units are converted to a per MJ hydrogen basis to give the following across all scenarios:

Natural gas usage values:

- **Central:** 0.0012 MJ gas grid (process input)/MJ H_2
- **Best:** 0 MJ gas grid (process input)/MJ H_2
- **Worst:** 0.0043 MJ gas grid (process input)/MJ H_2

Future fuel switching to other heating sources, such as low carbon hydrogen, may also be possible, but was not investigated in this study.

Grid electricity usage values:

- **Central:** 0.0006 MJ elec/MJ LH_2
- **Best:** 0 MJ gas grid MJ elec/MJ LH_2
- **Worst:** 0.0009 MJ MJ elec/MJ LH_2

[53] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[54] Øyvind Sekkesæter (2020) Evaluation of Concepts and Systems for Marine Transportation of Hydrogen p.94. Available at: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2623195/no.ntnu%3Ainspera%3A2525165.pdf?sequence=1&isAllowed=y
[55] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[56] Hinkley (2021) A New Zealand Perspective on Hydrogen as an Export Commodity: Timing of Market Development and an Energy Assessment of Hydrogen Carriers. Available at: https://www.mdpi.com/1996-1073/14/16/4876/htm

Compression

For the central and worst cases, it is assumed that compression from 1 bar to 30 bar is required to ensure comparability with other routes, assuming isentropic compression with 92% driver efficiency. Converting to an energy basis (IEA, 2021)[57] leads to 0.06 MJ elec/MJ H_2 across all years for the central and worst cases.

It is possible that a cold engine/Brayton cycle at high efficiency (up to 72%) could generate the required electricity from the LH2 regasification step (Hinckley, 2021)[58]. This generation could be up to a theoretical maximum of 2.8 kWhe/kg H_2, hence in the best case we assume this is sufficient to fully meet the compression needs so there is no grid electricity input.

No PSA step is required, as liquid hydrogen is extremely pure.

Compressed hydrogen pipeline imports

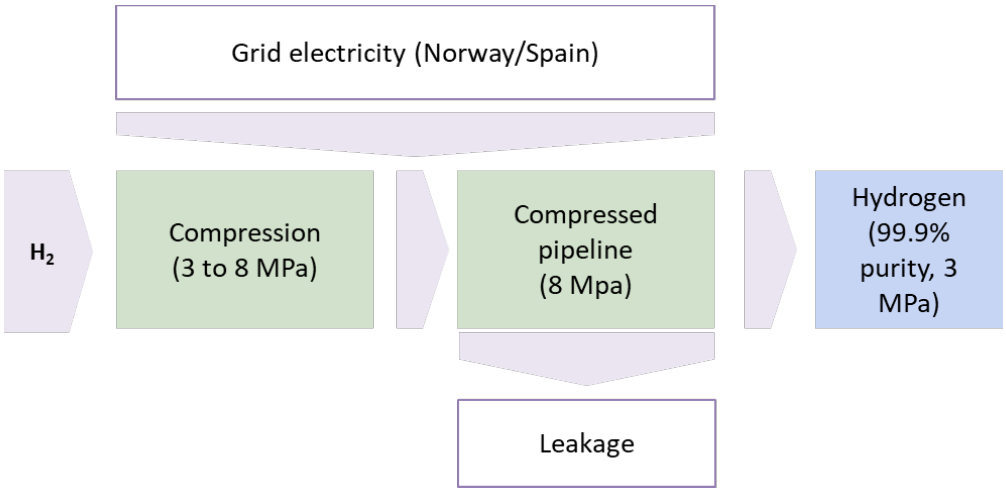

Figure 9: Compressed hydrogen pipeline import segment

Figure 9 outlines the compressed hydrogen import pathway modelled in this study from both Norway and Spain. The foreground data assumptions used for each step are explained in the following sections.

Compression

The electricity use for compression is based on the compression needed across three different diameters and pressures of hydrogen pipeline, modelled in the European Hydrogen Backbone study[59]. These three pipes are 48-inch at 80 bar, 36-inch at 50 bar and 20-inch at 50 bar.

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[57] IEA (2021) Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

[58] Hinkley (2021) A New Zealand Perspective on Hydrogen as an Export Commodity: Timing of Market Development and an Energy Assessment of Hydrogen Carriers. Available at: https://www.mdpi.com/1996-1073/14/16/4876/htm

[59] European Hydrogen Backbone (2021) 'Analysing future demand, supply, and transport of hydrogen'. Page 107, Table 35, Appendix C (compressor capacity / throughput) https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf

Values are given for each of these pipelines at 100%, 75% and 25% capacity respectively. The required capacity of compressors (MW/km) is divided by the pipeline throughput (GW) to get electricity input per hydrogen transported, per km of pipeline. The electricity inputs below include both the initial compression from 3MPa (30bar) up to the pipeline pressure, and subsequent compression stations along the pipeline to maintain pressures:

- **Central**: 36-inch pipe 75% capacity - 1.11*10^-5 MJe/MJ H_2.km
- **Best**: 20-inch pipe 25% capacity - 2.00*10^-6 MJe/MJ H_2.km
- **Worst**: 48-inch pipe 100% capacity - 25.7*10^-5 MJe/MJ H_2.km

Hydrogen piped from Norway is indicatively assumed to be transported 1,000km, and hydrogen piped from Spain is assumed to be transported 1,500km.

Pipeline transport losses

The hydrogen emissions for the best and worst cases are based on National Grid data (collected as part of the Element Energy - Zemo Well-to-Tank Pathways Study[60]), which reports transmission level leakage is 0.1-0.2%. For the central case, 0.15% losses are assumed. Converting to an energy basis leads to the following values:

- **Central:** 0.0125 gH_2/MJ H_2
- **Best:** 0.0083 gH_2/MJ H_2
- **Worst:** 0.0167 gH_2/MJ H_2

Background and feedstock data

When building the background datasets, similarly to the foreground datasets, three scenarios were defined: Baseline impact, Low impact and High impact.

Table 9 outlines the data sources for each process input/output impact factor used for the pathways modelled in this extension study. Background data that only applies to the pathways modelled in the previous study can be found in in Appendix B of 'Options for a UK Low Carbon Hydrogen Standard: report'. Note that some background factors were calculated in the LCA modelling tool or were provided by BEIS and will be explained in greater detail below.

Table 9: Background data sources for the global warming impacts of inputs and outputs

Parameter	Baseline impact	Low Impact	High Impact
Emission of Hydrogen	BEIS (2018)[61] – central	BEIS (2018) – low	BEIS (2018) – high
Emission of Oxygen	No GHG impacts associated with oxygen emission to air		

[60] Element Energy (2021) Low Carbon Hydrogen Well-to-Tank Pathways Study - Full Report. p.101 Available at: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2021/08/Zemo-Low-Carbon-Hydrogen-WTT-Pathways-full-report.pdf
[61] BEIS (2018) Hydrogen for heating: atmospheric impacts – a literature review. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760538/Hydrogen_atmospheric_impact_report.pdf

Emission of Ammonia	UNEP (2016)[62]
Emission of MCH	Amelio (2014)[63]
Emission of Toluene	Dietz (2019)[64]

Grid electricity emissions intensities

Overseas electricity grids (USA, UAE, Norway, Australia and Spain)

For the Baseline case of the USA chain, the Texas grid factor is used from the EPA, 2019[65] assuming a 75% reduction is reached by 2050. For the High impact case, a slower pace of change is assumed, reaching a 50% reduction by 2050.

For the UAE, data from Carbon Footprint (2020)[66] is used for the 2020 Baseline case which only covers generation, so grid losses determined for Grid Electricity (MV) are assumed. By 2030, the UAE plans to achieve 30% renewables penetration on the grid, which is projected to increase to 50% by 2050[67].

The 2020 Baseline values for Norway, Australia and Spain are also taken from Carbon Footprint (2020). A 50% reduction is assumed every decade for the Norway grid factor while a slower pace of change is assumed for the High impact case for this grid. These grid emissions are already extremely low in 2020, given the dominance of hydro-electric generation in Norway.

The Baseline value for the Australia grid is assumed to be at 23% low carbon generation in 2020 and projected to reach 61% in 2030 and 85% in 2050[68]. For the High impact case, the 2030 grid emissions reduction target in the Finkel Review is used, assuming the 2020 levels are similar to 2005[69]. A 20% reduction is then assumed on the previous decade for 2040 and 2050.

The reduction in emissions for the Spain Baseline case is assumed to follow the change in percentage of renewables on the grid. Currently the grid is made up of 44% renewables with an aim to move to 74% by 2030[70]. A linear decrease is then predicted to reach a 90%

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[62] UNEP (2016) Global Warming Potential (GWP) of Refrigerants: Why are Particular Values Used?Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/28246/7789GWPRef_EN.pdf?sequence=2&isAllowed=y
[63] Amelio et al 2014 Guidelines based on life cycle assessment for solvent selection during the process design and evaluation of treatment alternatives, Annex. The Royal Society of Chemistry 2014. Available at: http://www.rsc.org/suppdata/gc/c3/c3gc42513d/c3gc42513d1.pdf
[64] Dietz et al (2019) Carbon Performance assessment of oil and gas producers: note on methodology. Available at: https://www.transitionpathwayinitiative.org/publications/39.pdf?type=Publication
[65] EPA (2019) Data Explorer Available at: https://www.epa.gov/egrid/data-explorer for Grid electricity
[66] Carbon Footprint (2020) Country specific electricity grid greenhouse gas emission factors. Available at: https://www.carbonfootprint.com/docs/2020_09_emissions_factors_sources_for_2020_electricity_v14.pdf
[67] UNFCC (2020) Second Nationally Determined Contribution of the United Arab Emirates. Page 3. Available at: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/United%20Arab%20Emirates%20Second/UAE%20Second%20NDC%20-%20UNFCCC%20Submission%20-%20English%20-%20FINAL.pdf
[68] Australian Government (2021) Australia's Long-Term Emissions Reduction Plan. Available at: https://www.industry.gov.au/sites/default/files/October%202021/document/australias-long-term-emissions-reduction-plan.pdf
[69] Hare et al (n.d.) The Finkel Review and scientific consistency with the Paris Agreement. Available at: Proposed Australian electricity sector target contradicts Paris Agreement / Climate Analytics
[70] RED Eléctrica de España (2021) Press release: This year Spain is poised to surpass the renewable generation record set in a historic 2020. Available at: https://www.ree.es/en/press-office/news/press-release/2021/06/this-year-spain-poised-surpass-renewable-generation-record-set-in-historic-2020#:~:text=The%20growth%20in%20installed%20power,than%20in%20the%20previous%20year%2C

reduction by 2050 compared to 2020[71]. A slower pace is assumed for the High impact case with a 20% reduction expected by 2030 and only 80% reduction reached by 2050 with a linear decline in-between.

For all countries, the Low impact case assumes the IEA Net Zero 2050 trajectory (similar to UK trajectory) is followed, i.e. effectively fully decarbonised grid electricity by 2040.

UK power grid

For this study, the UK's electricity grid decarbonisation trajectory to 2050 as set out in the Green Book[72] has been used, differentiating between industrial (high and medium voltages) and small commercial (low voltage) grid electricity consumption intensities. These values have been applied to High, Low and Baseline impact scenarios, given there was minimal variation between the UKTM grid intensity trajectories used in the previous study.

Gas grid process inputs

UK gas grid

The gas input for the UK hydrogen production pathways and the reconversion steps of the import chains (ammonia cracking, LOHC dehydration and LH2 regasification) relies on the UK gas grid emissions factors which were determined in the previous study. The UK gas grid is projected to decarbonise, in part due to increasing biomethane injection into the gas grid. Three scenarios are modelled for biomethane mixing into the gas grid:

- Baseline Impact based on UKTM "Core" run – CB6 965Mt – CCC trajectory, going from 2% biomethane mixed in 2020 up to 36% by 2050.
- Low Impact based on UKTM "High CCS" – CB6 965Mt – CCC trajectory, going from 2% biomethane mixed in 2020 up to 53% by 2050.
- High Impact based on UKTM "CCS Delay" – CB6 965 Mt – CCC trajectory, going from 2% biomethane mixed in 2020 up to 31% by 2050.

These blend scenarios are then coupled with GHG impact factors for natural gas and biomethane. The impacts from natural gas supply and combustion and biomethane combustion are based on the data in BEIS Conversation Factors 2020 Full Set[73]. The impacts from biomethane production are from BEIS' Impact Assessment on the Future Support for Low Carbon Heat[74]. Based on this data, fossil natural gas has current combined emission factor of 64.2 gCO_2e/MJ_{LHV} (includes supply and combustion), while biomethane has a combined emission factor of 25.1 gCO_2e/MJ_{LHV}. For simplicity, these component intensity values are not

[71] European Parliament (2021) Climate action in Spain. Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/690579/EPRS_BRI(2021)690579_EN.pdf
[72] Green Book Data Tables 1-19, Table 1, columns J, H and I, https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal
[73] BEIS (2020) Government conversion factors for company reporting of greenhouse gas emissions. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020
[74] BEIS (2020) Consultation Stage IA: Future Support for Low Carbon Heat. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/881623/future-support-for-low-carbon-heat-impact-assessment.pdf

assumed to change over time (although some improvement is likely), but are used to calculate a weighted average gas grid emissions factor based on the blended scenarios defined above (which does improve over time as more biomethane is introduced).

UAE gas grid

The production of LOHC in the UAE requires an input of natural gas from the UAE gas grid. In a similar way to the UK natural gas emissions factor, the combustion emissions factor is combined with the upstream UAE emissions under three scenarios in Foreground data tab. No deployment of biomethane is assumed in the UAE, given the IEA (2020)[75] Outlook for biogas and biomethane has effectively nil biomethane deployment potential in 2040 in the Middle East. IRENA (2015)[76] similarly concluded that final energy consumption from modern biogas (the precursor to biomethane upgrading) in UAE would be nil in 2030.

Feedstock fossil gas

UK upstream fossil gas emissions

Values for Best, Baseline and Worst cases have been updated from the original study to reflect the latest 2021 BEIS Energy Trends[77] and North Sea Transition Authority (previously OGA)[78] data on the supply and intensities of different natural gas sources. Piped imports from Europe are assumed for the Best case (3.91gCO2e/MJ_{LHV}), the weighted average intensity of LNG imports to the UK is assumed in the Worst case (15.94gCO2e/MJ_{LHV}) and then the weighted average of piped imports, LNG imports and UK produced gas (4.56gCO2e/MJ_{LHV}) is taken as the Baseline case (6.29gCO2e/MJ_{LHV}, as per the latest Low Carbon Hydrogen Standard Data Annex[79]). These intensity values take into account the National Transmission System (NTS)'s own use of gas (0.15%) and leaks (0.15%)[80], i.e. are reflective of the upstream emissions associated with industrial-scale consumption of fossil natural gas from the UK NTS. Intensities would be higher if consuming gas from the lower pressure gas distribution network, due to high leakage rates (0.45%)[81].

The original study assumed static upstream fossil gas emissions over time in all three cases (Baseline, Best and Worst). In this report within the Best case, an upstream emissions reduction has been applied to the fossil natural gas supply, based on the decarbonisation trajectory compliant with a 1.5°C global scenario within the IEA's Net Zero by 2050 report[82].

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[75] IEA (2020) Outlook for biogas and biomethane has effectively nil biomethane deployment potential in 2040 in the Middle East (slide 36) https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf
[76] IRENA (2015) REmap UAE https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_REmap_UAE_report_2015.pdf
[77] BEIS 2021 Energy Trends https://www.gov.uk/government/statistics/gas-section-4-energy-trends
[78] NSTA 2020 https://www.nstauthority.co.uk/the-move-to-net-zero/net-zero-benchmarking-and-analysis/natural-gas-carbon-footprint-analysis/
[79] BEIS, 2022, Low Carbon Hydrogen Standard Data Annex, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1082379/low-carbon-hydrogen-standard-guidance-data-tables-v2.0.pdf
[80] Element Energy 2021 Zemo Low Carbon Hydrogen WTT pathways, pages 95 & 97 http://www.element-energy.co.uk/wordpress/wp-content/uploads/2021/08/Zemo-Low-Carbon-Hydrogen-WTT-Pathways-full-report.pdf
[81] Element Energy 2021 Zemo Low Carbon Hydrogen WTT pathways, pages 95 & 97 http://www.element-energy.co.uk/wordpress/wp-content/uploads/2021/08/Zemo-Low-Carbon-Hydrogen-WTT-Pathways-full-report.pdf
[82] IEA (2021) Net Zero by 2050: A Roadmap for the Global Energy Sector. Available at: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

For the years 2030, 2040 and 2050, upstream fossil gas CO_2 emissions are reduced by 38%, 81%, and 100% respectively compared to 2020 values in the Best case, in line with the global total CO_2 trajectory (IEA Table A.4). This relies on full decarbonisation of energy, fuel and chemical inputs that flow into these upstream supply chains. Upstream CO_2 intensity values for oil and gas provision are not explicitly given by IEA, but assuming net zero CO_2 emissions by 2050 is a relatively conservative interpretation of the IEA's scenario, given that global fuel supply and industrial process emissions within the "other energy sector" category achieve net-negative emissions by 2040.

Upstream methane emissions from the supply of fossil gas are reduced by 68% in 2030, 69% in 2040, and 70% in 2050 compared to 2020 values in the Best case. This is based on IEA Figure 3.5 and IEA Table A.1 data to 2030 (effectively exhausting the technical potential for methane reductions by 2030), with only a further 2% improvement then achieved across all fossil fuels supplied by 2050.

Overseas upstream fossil gas emissions (UAE, USA and Norway)

For the pathways that produce hydrogen overseas, upstream natural gas emissions were found for UAE[83], USA[84] and Norway[85]. These values were used for the central values in 2020. In the absence of data ranges, the ratios of Central to Best and of Central to Worst from UK upstream fossil gas emissions were applied to each country to create a proxy range for best and worst values in these other countries (so Central and Worst cases do not change over time, but Best cases improve in line with the IEA's Net Zero by 2050 report). The methane split assumed for UK production was applied to calculate the fossil CO_2 and methane inputs in each case[86].

Ammonia and LOHC sea transport

Fuel use and ship capacity values are provided from IEA (2020)[87] to calculate the 2020 value for both LOHC and ammonia sea transport.

The Baseline trajectory for decarbonisation of shipping is based on the average shipping fuel GHG intensities to 2050 given in figure 03.25 from the IEA Net Zero 2050 report, which shows a 85% drop by 2050.[88] The Low impact scenario assumes that by 2030, all vessels involved in the global trade of hydrogen (in its various forms) are running on zero carbon H_2/ammonia.

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[83] Sphera (2021) Table G-2 Middle east East gas production, processing and pipeline transport. https://3gry456jeet9ifa41gtbwy7a-wpengine.netdna-ssl.com/wp-content/uploads/2021/04/Sphera-SEA-LNG-and-SGMF-2nd-GHG-Analysis-of-LNG_Full_Report_v1.0.pdf
[84] Sphera (2021) Table G-2 North America gas production, processing and pipeline transport.. https://3gry456jeet9ifa41gtbwy7a-wpengine.netdna-ssl.com/wp-content/uploads/2021/04/Sphera-SEA-LNG-and-SGMF-2nd-GHG-Analysis-of-LNG_Full_Report_v1.0.pdf
[85] Equinor (2021) 'Greenhouse gas and methane intensities along Equinor's Norwegian gas value chain' Figure 4; Page 5; Addition of Upstream and Midstream ghg intensities. https://www.equinor.com/content/dam/statoil/documents/sustainability-reports/greenhouse-gas-and-methane-intensities-along-equinors-norwegian-gas-value-chain-2021.pdf[86] Balcombe et al. (2017) The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions. Available at: https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.6b00144[87] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[86] Balcombe et al. (2017) The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions. Available at: https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.6b00144[87] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[87] IEA (2020) The Future of Hydrogen - Assumptions annex. Available at: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[88] IEA (2021) Net Zero by 2050. Available at: https://www.iea.org/reports/net-zero-by-2050

The High impact scenario assumes the IMO's current goal of a 70% reduction in global shipping emissions intensity by 2050 is met, and 40% by 2030, relative to 2008 baseline. The global shipping industry already has saved ~33% today compared to the 2008 baseline, due to slow steaming and other measures.[89]

Liquid hydrogen sea transport

Similar to the ammonia and LOHC sea transport, the fuel use and capacity of a liquid hydrogen ship are provided from IEA (2020) to calculate the 2020 values.

In the Low impact scenario, it is assumed by 2030, all vessels involved in the global trade of hydrogen (in its various forms) are running on zero carbon hydrogen/ammonia. Liquid hydrogen ship propulsion needs can be met entirely by the boil-off.

In the Baseline impact scenario, it is assumed by 2030, 50% of vessels involved in the global trade of hydrogen (in its various forms) are running on zero carbon hydrogen (boil-off), or otherwise using dual-fuel engines. Assumed from 2040 onwards, all liquid hydrogen vessels run on 100% zero carbon hydrogen (from the liquid hydrogen boil-off).

In the High impact scenario, it is assumed IMO goals are met.

[89] Rutherford et al (2020) Limiting engine power to reduce CO2 emissions from existing ships. Available at: https://theicct.org/sites/default/files/publications/Limiting_engine_power_02112020_0.pdf

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