Guidehouse

GIIGNL

Internal only, not to be circulated

New Gases Value Chains Study

Summary for CSG meeting

03 July 2024

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Project Objectives

Built an objective assessment on new gases

WP1: New gases value chains compared to the LNG ones

Technical descriptions & efficiencies estimate on every step of the value chain (LNG, BioLNG, e.methane, blue/green H2, LH2)

Analysis of various CO_2 sourcing routes (biogenic and non-biogenic) and hydrogen production options

WP2: Develop new gases analytical modelling tool, for 2030, 2040 and 2050:

Construction of an adjustable and configurable tool to calculate LCOx and delivered costs and other KPIs.

Based on recognized data sources
Transparent cost model, re-usable with transparent asssumptions

Work Package 3 - Perform regional analysis for Australia, Europe, the US and North Africa

Value chains intercomparison, production capacity by region or key countries and assessment of inter-regional flows, including transportation costs for 8 various corridors.

Export regions: Middle East, North Africa, Australia, US Gulf Coast
Import regions: Europe, Japan

This study is...

- **Objective assessment**
- **Initial asesssment,**
- **Based on recognized sources**

It is not...

As for now…

- It won't be published
- We are not creating a common view within GIIGNL
- It's not an advocacy

Could be part of next steps

Project timeline

3 work packages on 12 weeks project for a completion first week of July, 2024

April		May				June				July		
W1 Apr. 22	W2 Apr. 29	W3 May. 6	W4 May. 13	W5 May. 20	W6 May. 27	W7 Jun. 3	W8 Jun. 10	W9 Jun. 17	W10 Jun. 24	W11 Jul. 01	W12 Jul. 08	…

1. WP1. New gases value chains compared to the LNG ones

- Value chains technical descriptions for new gases (hydrogen, e-methane, ammonia, and bio-LNG)
- Analysis of various sources of H_2 & options for CO_2 sources to produce e-methane
- Intercomparison of new gas value chains
- GHG footprint estimation and round-trip efficiency

Interview 1, Tokyo Gas

Interview 2, Shell

2. WP2. New gases analytical modelling tool for 2030, 2040 and 2050

- Definition of key parameters and input criteria for the tool, as well as key hypothesis
- Construction of adjustable tool to calculate LCOx as well as cost of avoided CO_2
- Production and forecast volumes & capacity by region or key countries

3. WP3. Regional analysis for selected regions in Australia, Europe, the US and North Africa

- Country / region analysis based on forecasting exercise
- Description and assessment of 8 inter-regional flows, analysing of transportation costs for various couples

4. WP4. Final report, presentation and transfer

- Creation of user guide for the Model
- Transfer & handover of user guide to Central GIIGNL team
- Executive summary with recommendations & next steps

Next Steps

5. Project and Stakeholders management, inc. Project set-up

PMO set up with project governance Steering and Operational committee setup

Weekly Meetings:

Kick-off meeting, 23/04

WSP 1, 02/05
Data Gathering

Steerco 1, 03/06
Intermediate Report

WSP 2, 17/06
Modelling Tool

Final SteerCo, 28/06
Final report

GIIGNL CSG 03/07

Final submission

In scope activities | Optional activities

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Overall methodology approach

Data based on authoritative sources, transparent model

1. Review of the existing publications, clean fuel databases and assumptions

- To ensure the quality results, Guidehouse has analysed various external and internal resources on the subject, collecting information for the future benchmarking.
- Review of existing and upcoming technologies and their TRL across the new gas value chain, using sources such as IEA and IRENA, combing with internal view of the experts.
- Available databases and publications have been carefully reviewed with assumptions made where applicable.

2. Build-up of the model to represent results

- Configuration of the modelling tool for new gases with the view on 2030, 2040 and 2050.
- Feeding the model with collected input information coming from the literature review and performing analyses for:
  - Efficiency losses across the value chain for each gas
  - CO_2 emissions and CO_2 emissions abated
  - Calculation of LCOx and delivered quantities across the geographies
- Making necessary assumptions to deliver the results*

3. Exchange with experts

- Internal GH experts have been involved to share knowledge and best practices to perform the necessary calculations.
- List of interview questions sent to the GIIGNL members to help closing the data gap.
- Regular exchange with core GIIGNL team, reviewing the progress and setting next steps.

* See the next slides for assumptions made during the study

Deliverables summary

The project have ensured 3 main deliverables.

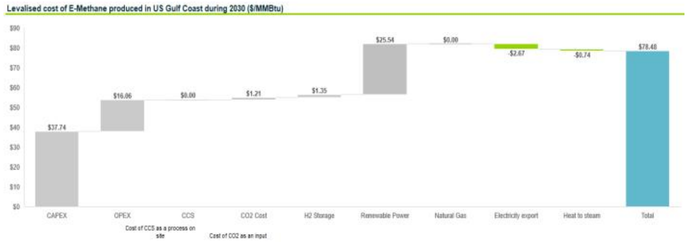
WP 1	→	WP 2	→	WP 3

Assess new gases technical value chains compared to the LNG one: technical descriptions & efficiencies estimate, analysis of various CO_2 sourcing routes (biogenic and non-biogenic) and hydrogen production options.

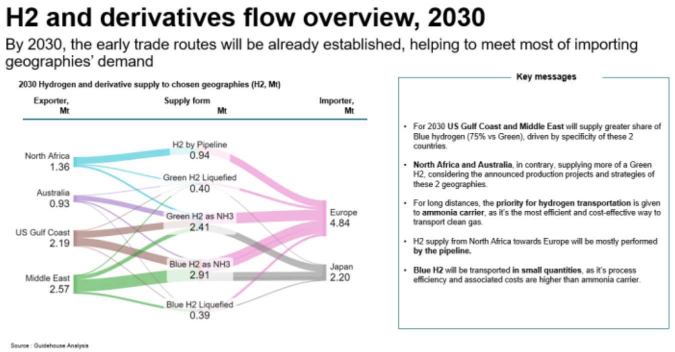
Pipeline distance: 1,000km				
10,000km, 2030	Synthesis	Total Losses (%)	Total efficiency of the gas value chain (%)	MMBTu content of delivered fuel from 1 MMBTu spent
	Blue H2 as NH3 reconverted	47.94%	52%	0.69
	Blue H2 liquefied	55.75%	44%	0.73
	Green H2 as NH3 reconverted	53.64%	46%	0.61
	Green H2 Liquefied	60.30%	40%	0.65
	Blue H2 by Pipeline	32.38%	68%	0.72
	LNG	13.81%	86%	0.95
	Green H2 by Pipeline	39.34%	61%	0.65
	e-Methane	53.57%	46%	0.51
	Bio-LNG	40.04%	60%	0.67
Pipeline distance: 1,000km				
10,000km, 2040	Synthesis	Total Losses (%)	Total efficiency of the gas value chain (%)	MMBTu content of delivered fuel from 1 MMBTu spent
	Blue H2 liquefied	49.18%	51%	0.73
	Blue H2 as NH3 reconverted	39.44%	61%	0.76
	Green H2 Liquefied	52.29%	48%	0.68
	Green H2 as NH3 reconverted	48.49%	52%	0.65
	Blue H2 by Pipeline	32.38%	68%	0.72
	Green H2 by Pipeline	39.34%	61%	0.65
	e-Methane	48.62%	51%	0.57
	Bio-LNG	35.76%	64%	0.72
	LNG	13.81%	86%	0.95
Pipeline distance: 1,000km				
10,000km, 2050	Synthesis	Total Losses (%)	Total efficiency of the gas value chain (%)	MMBTu content of delivered fuel from 1 MMBTu spent
	LNG	13.81%	86%	0.95
	Blue H2 as NH3 reconverted	36.55%	63%	0.76
	Blue H2 liquefied	44.79%	55%	0.73
	Blue H2 by Pipeline	32.38%	68%	0.72
	Green H2 Liquefied	44.79%	55%	0.73
	Bio-LNG	31.47%	69%	0.76
	Green H2 by Pipeline	39.34%	61%	0.65
	Green H2 as NH3 reconverted	41.85%	58%	0.70
	e-Methane	41.39%	59%	0.65

Develop new gases analytical modelling tool, including forecasting for 2030, 2040 and 2050: construction of an adjustable and configurable tool to calculate LCOx and delivered costs

With data workbook



Assess new gases technical value chains compared to the LNG one: technical descriptions & efficiencies estimate, analysis of various CO_2 sourcing routes (biogenic and non-biogenic) and hydrogen production options.



Overall Report

Value Chain Configuration Assumptions

A base case of assumptions were aligned on to produce a base set of results, which can be modified by the user to fit their understanding of technology efficiency, carbon intensity or cost.

FEEDSTOCK

- Renewables are co-located with production facility therefore no electricity losses to transmission are accounted for in the green hydrogen or e-methane production step, and CO_2 intensity is based on renewable power.
- All required feedstocks for molecule production are readily available and incur no energy losses to obtain, for example CO_2 is readily available for the production of e-methane.

PROCESS ELECTRICITY

- The proceeding processes that require electricity such as hydrogen compression, liquefaction, ammonia cracking and more draw from grid electricity in the exporting and importing country before and after transport. The carbon intensity of the respective grids is therefore used to calculate the total CO_2 emissions, which is forecasted to get cleaner over time in all geographies corresponding to the IRENA "Energy Transformation" scenario of fossil fuel reduction and renewables uptake.
- For bio-LNG and e-methane, we assume that pipeline compressors are powered with the clean fuel and as a result do not incur emissions at those steps, but final energy product is derated. Multiple value chain configurations can exist for e-methane, in which you power compressors with e-methane itself like is traditionally done with natural gas, or with outside electric power. Here we are prioritizing carbon intensity, so e-methane is used to power compressors resulting in 0 emissions at compression steps, but derating of the methane content moving through the value chain. You could instead prioritize final delivered product using electricity to power processes, but the emission intensity of your final product will be higher.

TECHNICAL ASSUMPTIONS

- Assuming average inlet pressure of H_2 liquefaction of 20 bar, so decompression energy requirement is covered in the H_2 storage step, and is considered to be negligibly different between decompression to transmission, distribution, and liquefaction pressure inlets (+/- 50 bar).
- At H_2 grid distribution level no energy requirement for compression is assumed, only leakage energy losses are accounted for at the modal change, assuming that the right pressure for distribution (~30 bar) will be obtained after ammonia cracking, H2 regassification, and H_2 pipeline transport.
- Variable losses include either boil off related losses from shipping or leakage over distance for pipeline transport.
- Time of storage and resulting boil off is not accounted for, considered to be a non-factor between gas value chains.
- We are still accounting for the warming via methane leakage effect of bio-CH_4 and e-methane because we are considering the final fuel product neutral at combustion in relation to the CO_2 that is required to make the fuel. Difference between GWP of CH_4 and CO_2 subtracted in the formula (30-1).

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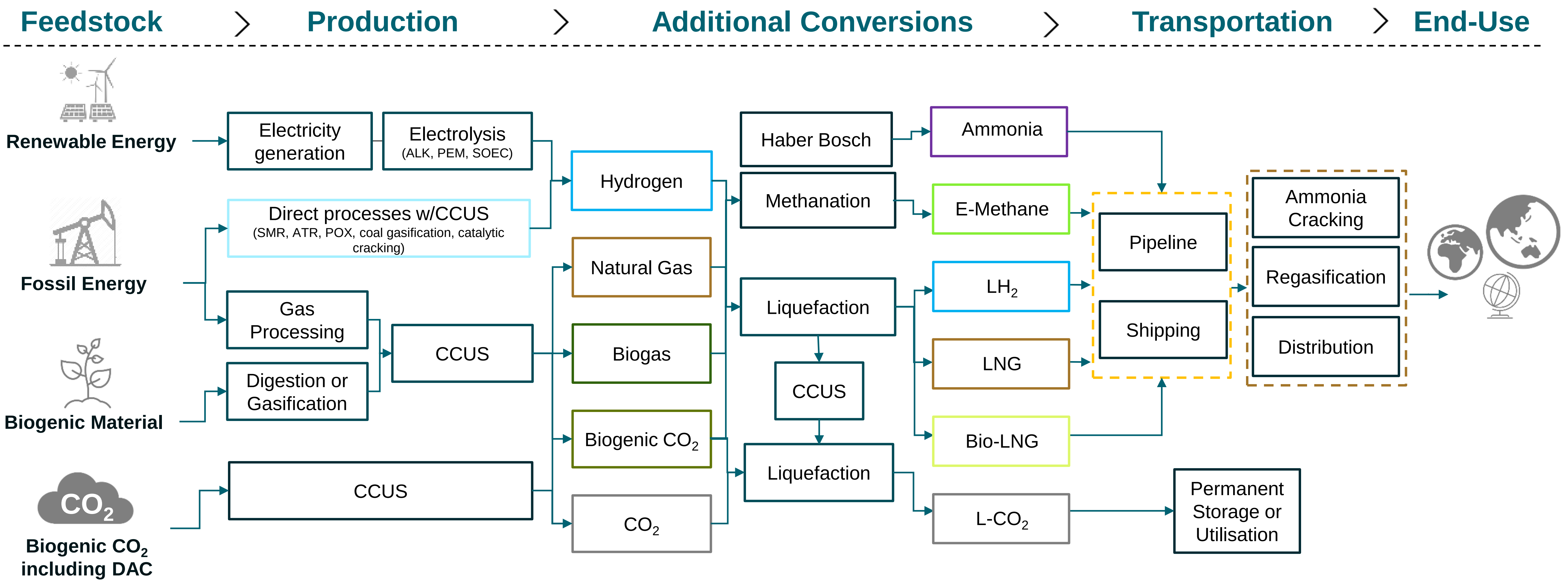
New gases value chain efficiency and emissions intensity

-Work package 1-

LNG E-methane Hydrogen e-Ammonia

Methodology: Analysis of the clean fuels value chains

The efficiency and the carbon intensity have been estimated based on the following steps



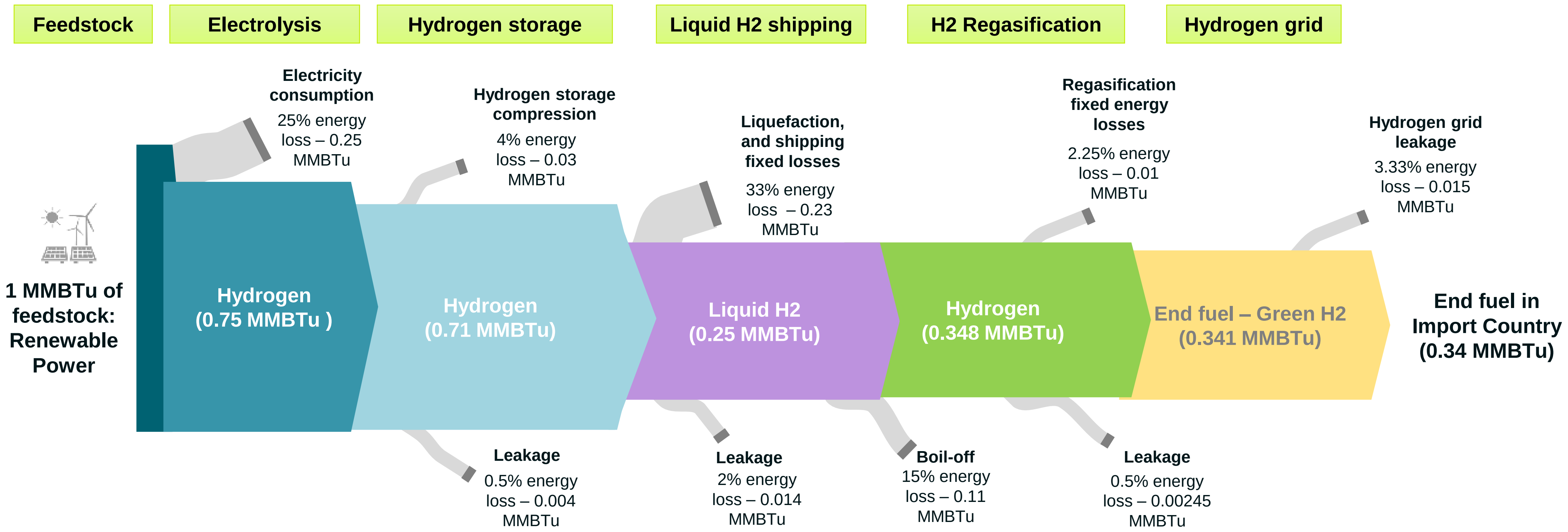
*Simplified view of the clean fuels value chains in focus, Guidehouse will detail efficiency losses, final delivered energy content, embedded emissions, and LCOE between selected regions

Extract of analysis

Zoom: Efficiency losses of Green H2 used as NH3

e-Ammonia

Value Chain of Green H2 Liquefied (35,000km representative of Gulf Coast to Japan)



CO_2e emissions: + 10.16 kgCO_2/Mmbtu | +3.17 kgCO_2/Mmbtu | +47.21 kgCO_2/Mmbtu | + 3.4 kgCO_2/Mmbtu | + 2 kgCO_2/Mmbtu | **Total 66 kgCO_2/Mmbtu**

Values presented on a per MMBtu of feedstock energy, not final delivered fuel. Since the fuel is not delivered until the last step, the total CO2 must be divided by the total value chain efficiency to achieve the kgCO_2e/MMBtu.

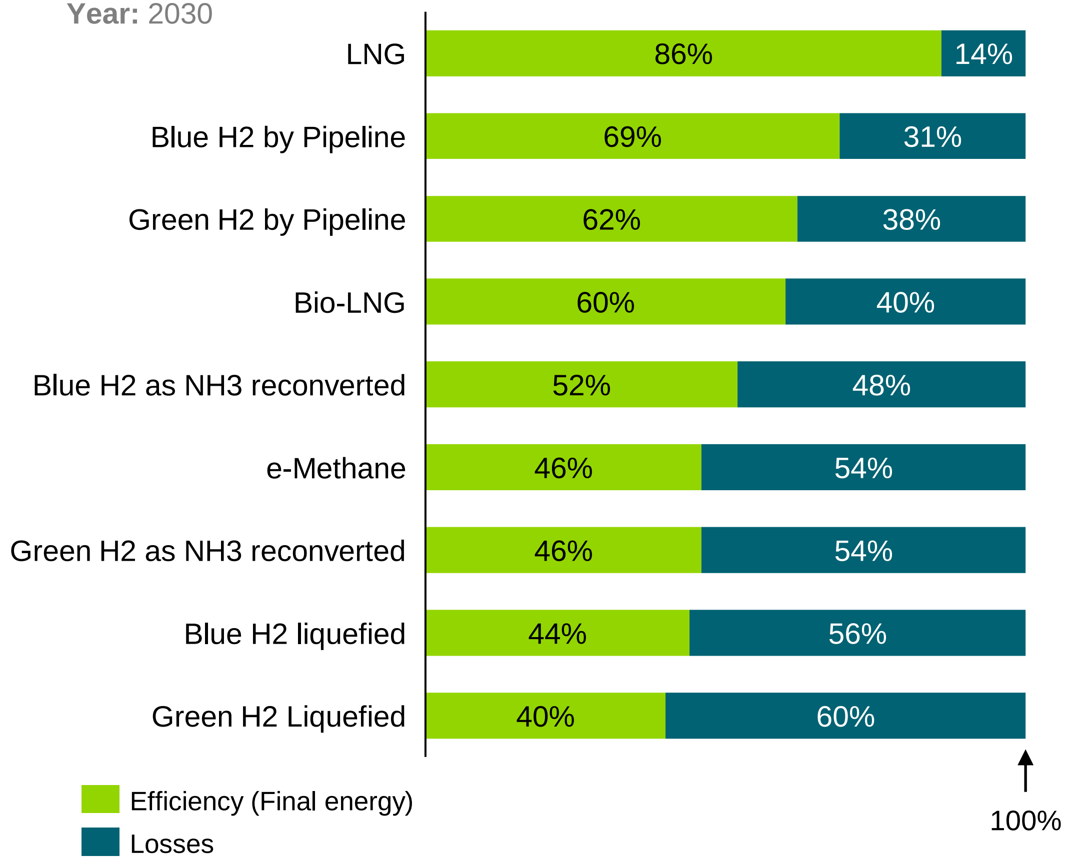
Guidehouse outwit complexity

Gas value chain round trip efficiency overview

E-methane and liquefied hydrogen suffer the most energy losses across the value chain in 2030

Round trip efficiency throughout the gas value chains studied (%)

Shipping distance: 10,000km
Pipeline distance: 1,000km
Distribution distance: 200km
Year: 2030



Source : Guidehouse Analysis, see detailed losses in Sankey Diagram slides

Key messages

- LNG and piped hydrogen are the gases displaying **the highest efficiency levels.**
- E-methane less efficient that the other methane-based value chains because of its current technology development status and corresponding production efficiency for methanation in 2030. **Technology improvements and economies of scale are expected to make e-methane more efficient over time**, which is presented in later slides.
- Green and blue liquified hydrogen incur total **losses of over 55%** in this example, largely due to energy intensive compression and liquefaction steps. Losses in the hydrogen value chain are largest at the liquefaction step due to the energy required to cool hydrogen to its boiling point of −253°C.
- Large losses are also incurred from the boil-off of liquid hydrogen, which are particularly minimal at a distance of **10,000 km (4.7%)** but much higher at **35,000 km (15.4%)** at a boil off rate of 0.326% per day.[3]
- Hydrogen transported as ammonia is more efficient than liquefied hydrogen **at all ranges in 2030.** The most energy intensive part of the liquid ammonia value chain is cracking (~25% losses).
- Hydrogen delivered by pipeline is more efficient than shipping as ammonia **up to around 3,500km**, around the distance between the UAE and Greece over land.

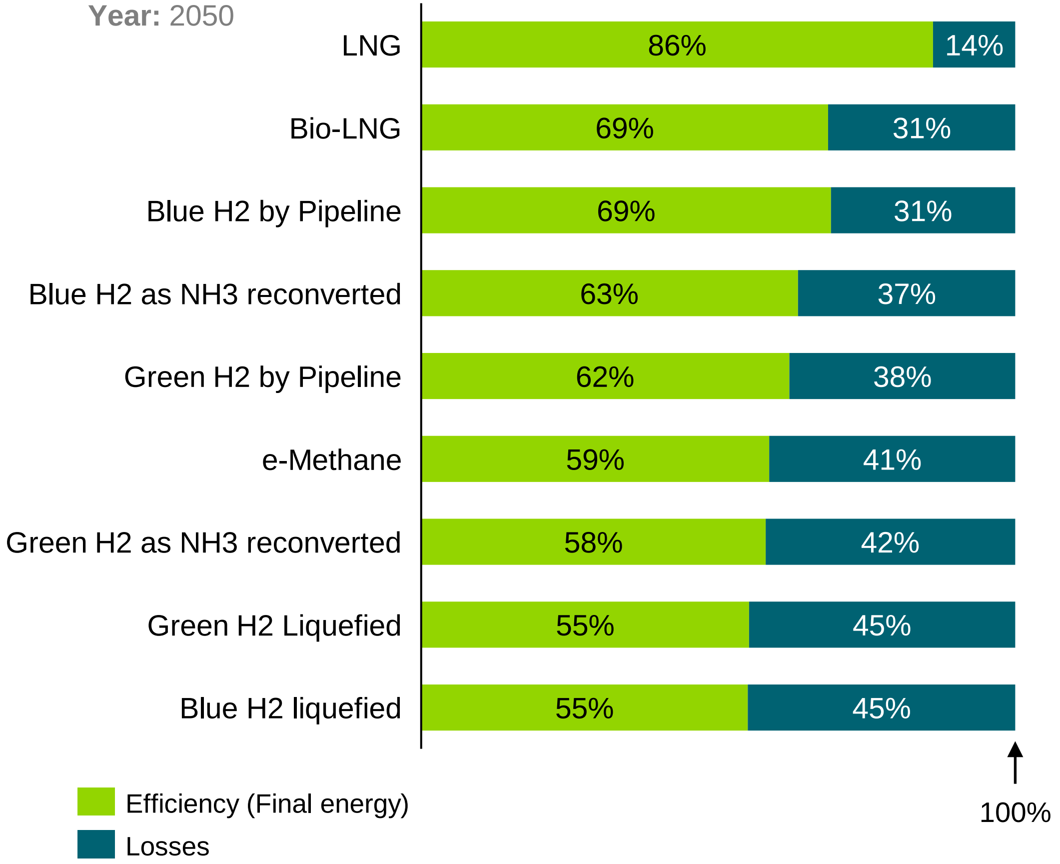
[1]A wide range of efficiency assumptions can be used for different technologies making up these gas value chains, the ones selected are 2030 oriented. Certain technologies are expected to improve over time.
[2]Efficiency of e-methane and clean ammonia
[3]Hydrogen boil-off rate

Gas value chain round trip efficiency overview

E-methane and liquefied hydrogen value chains suffer the most energy losses across the value chain

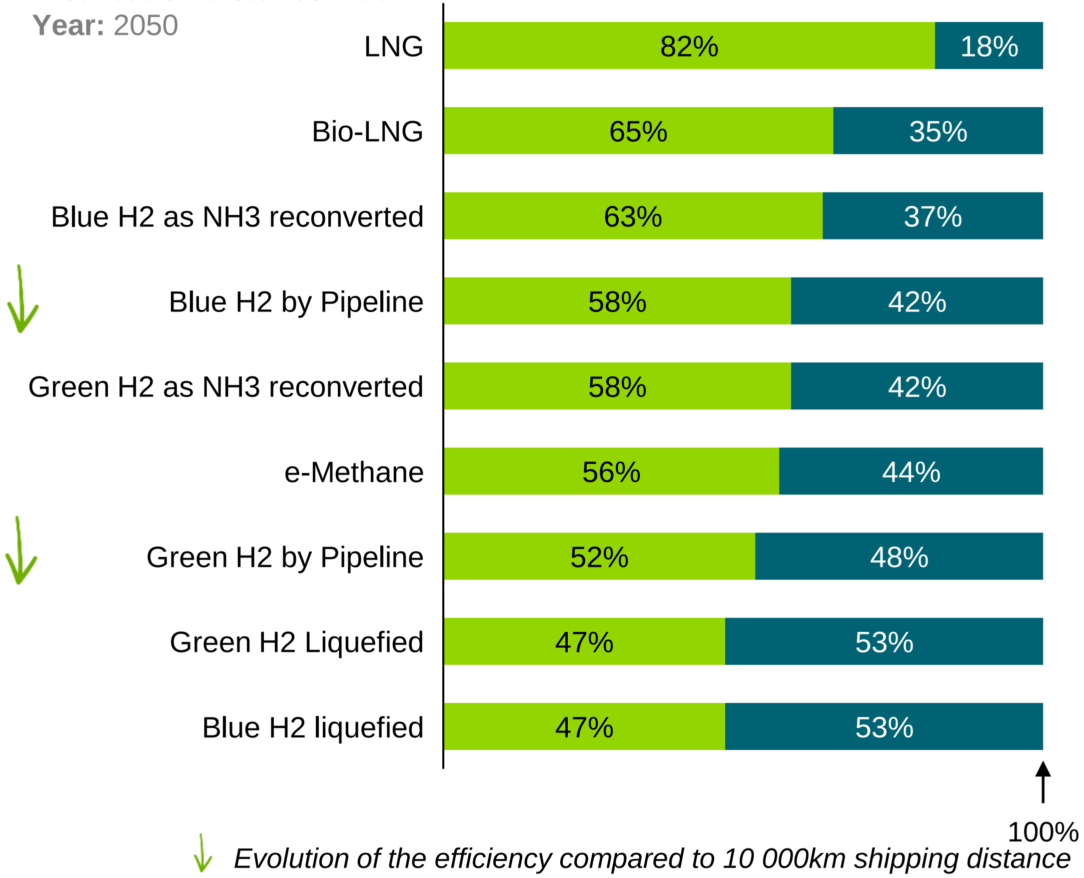
Gas value chain round trip efficiency at short distance in 2050 (%)

Shipping distance: 10,000km
Pipeline distance: 1,000km
Distribution distance: 200km
Year: 2050



Gas value chain round trip efficiency at long distance in 2050 (%)

Shipping distance: 35,000km distance between US Gulf Coast and Japan
Pipeline distance: 3,000km
Distribution distance: 200km
Year: 2050



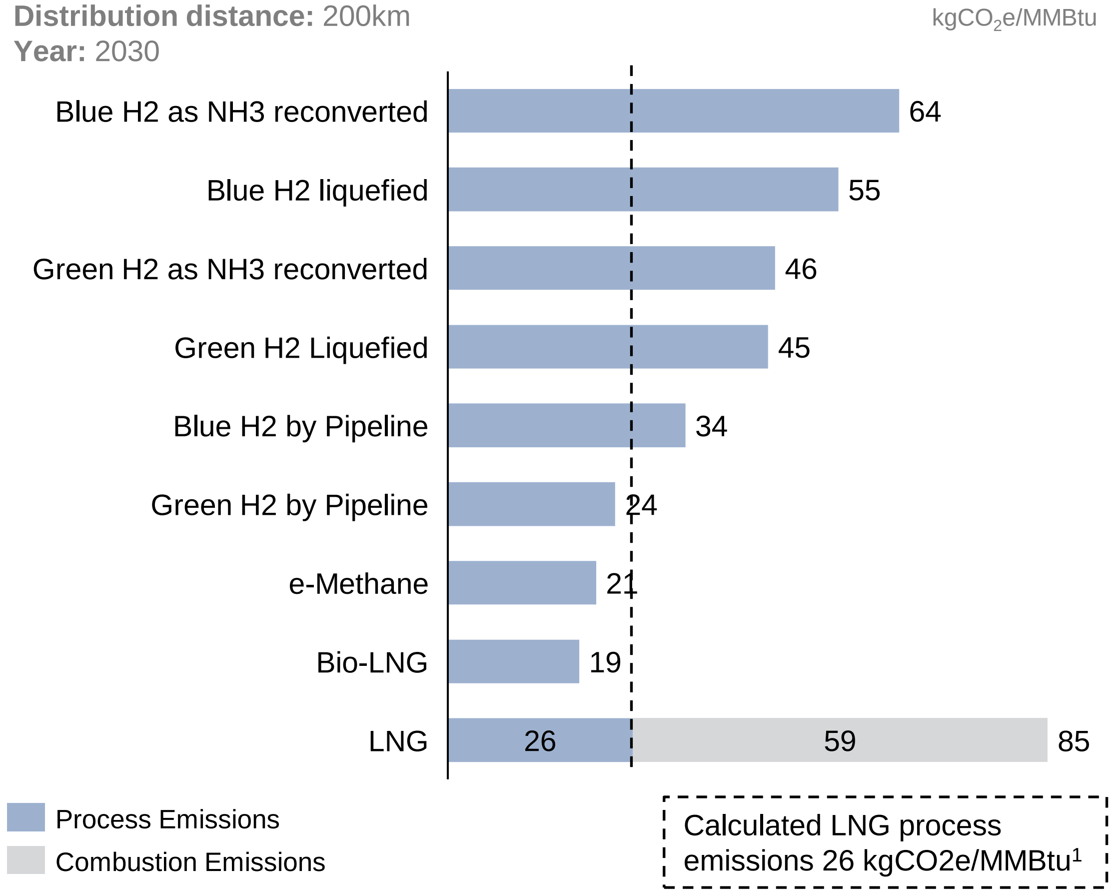
Notes: Guidehouse Analysis, Technology efficiencies are assumed to be low relative to possible improvements. Liquid hydrogen incurs much larger losses to boil-off during shipping than methane and ammonia-based fuels, making longer distances much more inefficient.

Gas value chain CO_2e emissions overview

Most new gas value chains have higher process emissions than a state-of-the-art LNG value chain

Emissions intensity of the gas value chains studied (kgCO_2e/MMBtu)

Shipping distance: 10,000km
Pipeline distance: 1,000km
Distribution distance: 200km
Year: 2030



Source : Guidehouse Analysis, stepwise emissions shown in Sankey Diagram slides.

Key messages

- Many new gas value chains such as liquefied hydrogen, clean ammonia cracked into hydrogen, and e-methane emit more process CO_2 / MMBtu of input due to having **more energy intensive value chains.**
- The total carbon intensity of the value chain depends largely on the carbon intensity of **power used** for compression, liquefaction, cracking etc. this example is using the average grid intensity of ERCOT in Texas for 2023 (0.380 kgCO_2/kWh).[2]
- For the methane-based value chains, it is assumed gas flowing through distribution and storage pipelines are used to power compressors. For the case of bio-LNG and e-methane, consumption of this gas for compression energy **does not lead to CO_2 emissions** as the combustion of the fuel is considered carbon neutral.[3] Hydrogen and ammonia compressors are assumed to be powered by **external electrical power** from the grid due to pour energy efficiency of hydrogen used for gas compression.
- Electrolysers used for green hydrogen, green ammonia, and e-methane production are assumed to be **powered by co-located renewables**, which are on average 10x less carbon intensive than the Texas grid for example (0.026 kgCO_2/kWh).
- Leakage of hydrogen through the value chain is **much higher than methane,** making up 10% of total CO_2e emissions **over a distance of 10,000km.**[4]

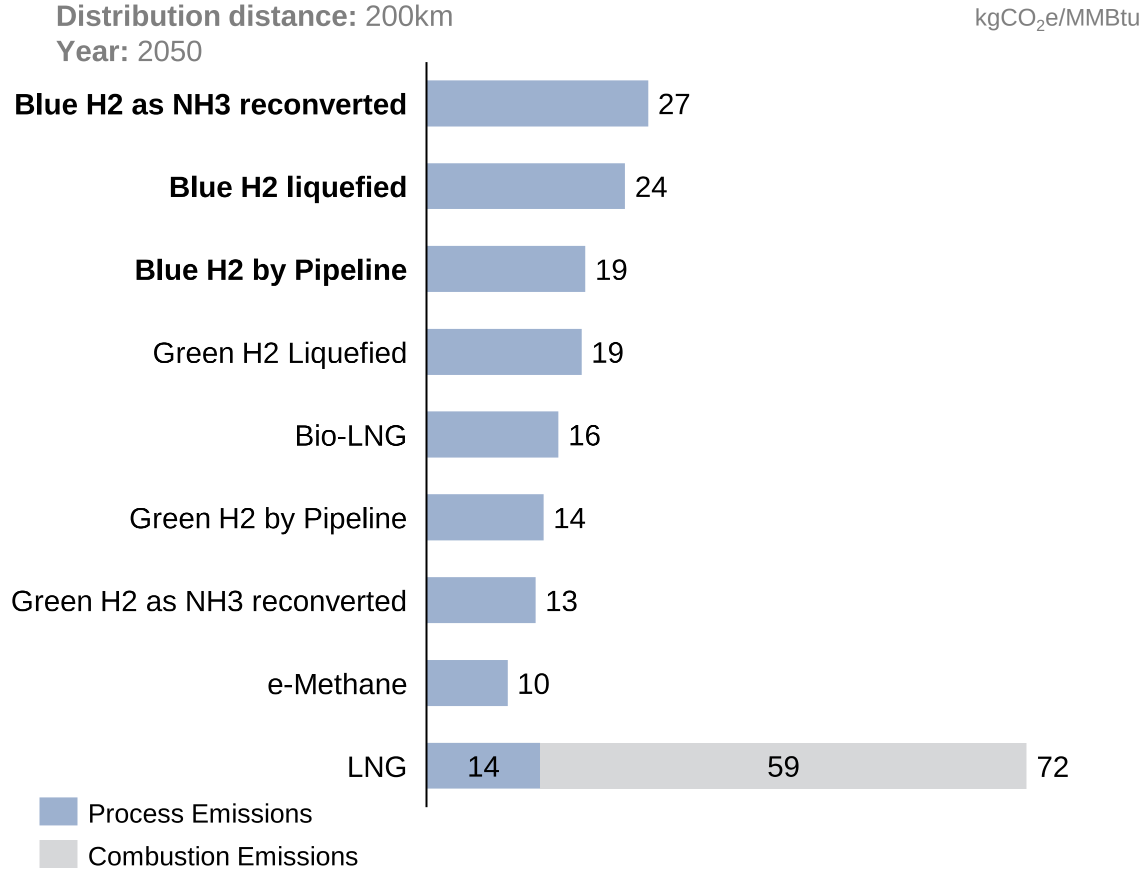
[1]Upstream methane emissions of natural gas assumed to be 1% - general US average. GWP of 30 used for CH4 as per IPCC 6. State of the art liquefaction efficiency of 91% assumed.
[2]2023 carbon intensity of ERCOT
[3]Combustion of new gases in scope is considered to be carbon neutral. For e-methane and bio-LNG, it is assumed that an equivalent amount of CO_2 that is released during combustion is required as an input into the process, which requires removing or preventing CO_2 from entering the atmosphere, making the combustion carbon neutral.
[4]Hydrogen GWP of 11.6 assumed. Nature

Gas value chain CO_2e emissions overview

Most new gas value chains have higher process emissions than a state-of-the-art LNG value chain

Emissions intensity of the gas value chains studied ($kgCO_2e/MMBtu$)

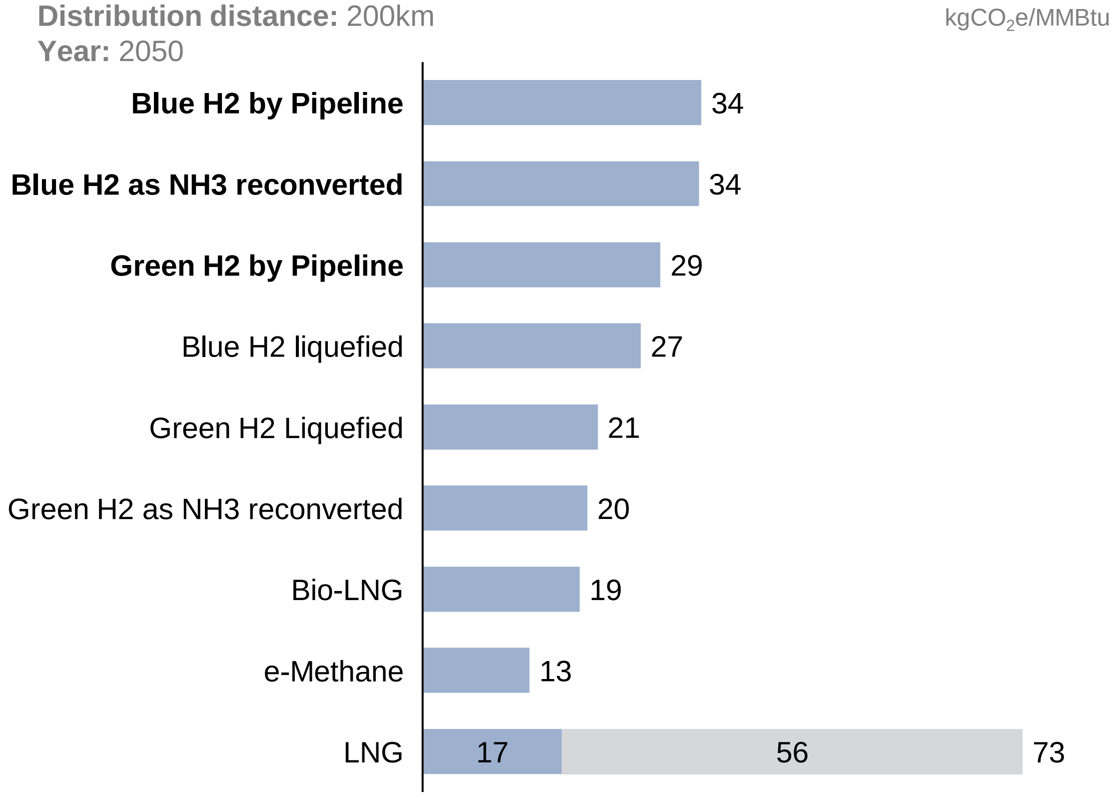
Shipping distance: 10,000km
Pipeline distance: 1,000km
Distribution distance: 200km
Year: 2050



Source : Guidehouse Analysis, stepwise emissions shown in Sankey Diagram slides.

Emissions intensity of equivalent delivered fuel energy ($kgCO_2e/MMBtu$)[1]

Shipping distance: 35,000km
Pipeline distance: 3,000km
Distribution distance: 200km
Year: 2050



↑ *Evolution of the efficiency comparted to 10 000km shipping distance*

New gases – delivered costs

-Work package 2-

LNG

E-methane

Hydrogen (LH2, Green & Blue converted to NH3)

e-Ammonia

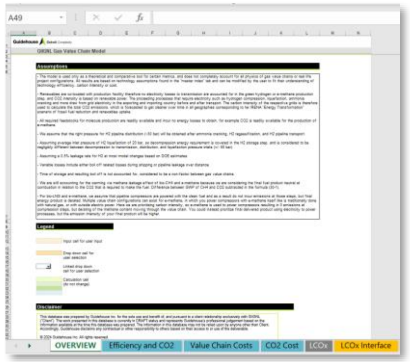
Methodology: LCOx & delivered cost model

The model is built for users to run their own LCOx scenarios and interpret differences between regions and gases, **detailed assumptions are to be shared along with the model via Excel**

Data workbook → **LCOx** → **Delivered cost per value chain steps** → **Interactive LCOx Tool**

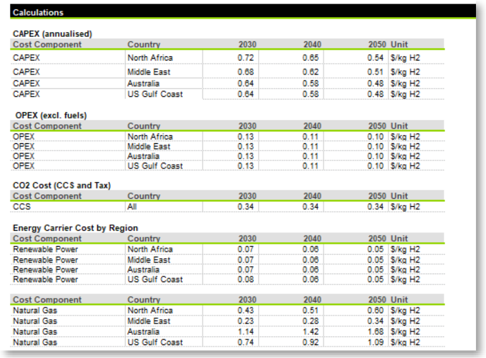
Data workbook

- A suite of assumptions are made on **cost of each value chain technology included**. A general evolution is assumed across 2030, 2040, and 2050.
- **Values are presented as $/MMBtu average levalised costs** typically in the middle of a range of reported costs. Guidehouse chose the most realistic assumptions for the presented base case.



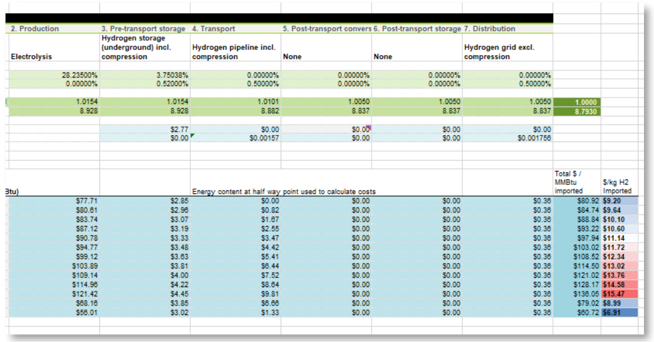
LCOx

- Financial assumptions are made across technologies and regions including capacity factors, CAPEX, OPEX, WACC, storage, oversizing needs and more to calculate detailed LCOx. **Multiple scenarios are built in, related primarily to energy cost and oversizing.**



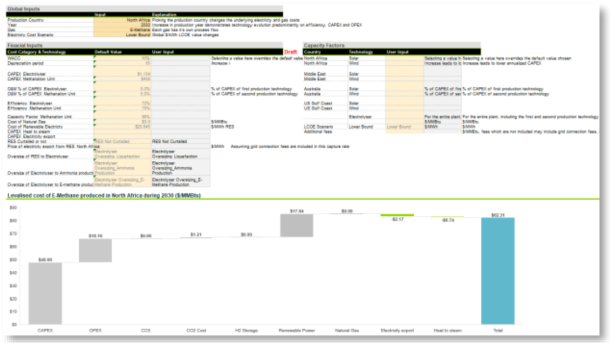
Delivered cost per value chain steps

- Complete value chain costs including LCOx are calculated for each exporting and importing region in scope on a **2024 USD per MMBtu received in the importing country, after one step of distribution** (hydrogen or methane grid).



Interactive LCOx Tool

- A highly customizable LCOx tool will be transferred to GIIGNL members in the coming weeks, **which will allow for comparisons of production costs in various regions and impact on delivered cost of new gases**. The tool can be useful in the optimisation of project parameters or quick hypothetical comparisons.



Sample of Assumptions

Methodology: Key Cost Assumptions - LCOx

Detailed scaling and calculations behind cost assumptions presented in the Excel Model

LCOx Financial parameters

- All $ are presented in USD 2024 $
- CAPEX are inflated using the average 2023 CEPCI index (797.9)

Natural Gas Cost	Unit	2030	2040	2050
North Africa	USD/MMBtu	$3.0	$3.6	$4.2
Middle East	USD/MMBtu	$1.6	$2.0	$2.4
Australia	USD/MMBtu	$8.0	$10.0	$11.8
US Gulf Coast	USD/MMBtu	$5.2	$6.5	$7.7
Europe	USD/MMBtu	$8.5	$10.6	$12.5

LCOE (USD/MWh)	Technology	Scenario	2030	2040	2050
North Africa	Solar PV	Lower Bound	$20.64	$16.58	$13.88
Middle East	Solar PV	Lower Bound	$19.48	$15.65	$13.09
Australia	Solar PV & Onshore Wind	Lower Bound	$24.87	$20.82	$17.63
US Gulf Coast	Solar PV & Onshore Wind	Lower Bound	$25.51	$21.28	$18.01
North Africa	Solar PV	Upper Bound	$36.09	$20.90	$17.51
Middle East	Solar PV	Upper Bound	$34.05	$19.72	$16.53
Australia	Solar PV & Onshore Wind	Upper Bound	$40.09	$25.19	$21.57
US Gulf Coast	Solar PV & Onshore Wind	Upper Bound	$41.41	$25.83	$22.08

Country	Technology	Capacity factor
North Africa	Solar	24%
North Africa	Wind	32%
Middle East	Solar	24%
Middle East	Wind	31%
Australia	Solar	22%
Australia	Wind	37%
US Gulf Coast	Solar	20%
US Gulf Coast	Wind	39%

WACC (%)	Country	%
	North Africa	10%
	Middle East	9%
	Australia	8%
	US Gulf Coast	8%

Depreciation factor		Years
	All locations	15

CAPEX	Unit	2030	2040	2050
Blue Hydrogen	$/kW H2	1,376	1,238	1,032
Blue Ammonia	$/kW H2	471	424	318
Green Ammonia	$/kW H2	855	855	855
Green Hydrogen	$/kW H2	1,134	785	558
E-Methane	$/kW CH4	439	319	279

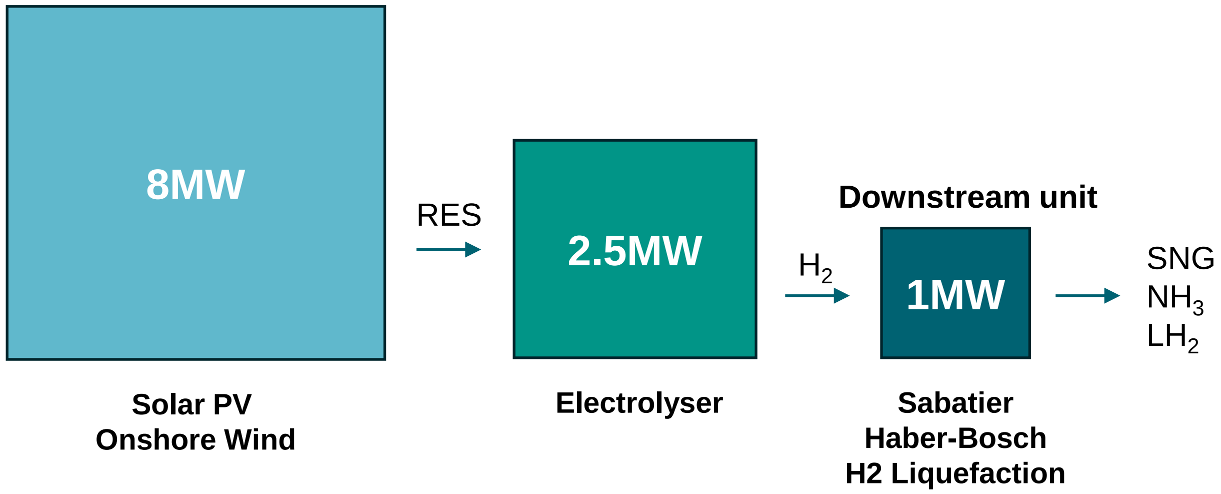
OPEX as a % of CAPEX	Unit	2030	2040	2050
Blue Hydrogen	% of CAPEX	2.3%	2.3%	2.3%
Blue Ammonia	% of CAPEX	4.7%	4.7%	4.7%
Green Ammonia	% of CAPEX	4.7%	4.7%	4.7%
Green Hydrogen	% of CAPEX	5.0%	5.0%	5.0%
E-Methane	% of CAPEX	5.0%	5.0%	5.0%

Efficiency of process	Unit	2030	2040	2050
Blue Hydrogen	%	80%	80%	80%
Blue Ammonia	%	70%	78%	78%
Green Ammonia	%	62%	66%	71%
Green Hydrogen	%	72%	75%	80%
E-Methane	%	75%	79%	85%

Oversizing for green molecule production

Oversizing of RES and electrolysers is assumed to maintain near full time gas production

Optimal ratio of value chain capacities determined by 8760 analysis:



Average Capacity Factors (%) - Dedicated Solar PV oversizing Example

Solar PV	Electrolyser	Downstream unit
24%	37%	95%

Solar PV with an average CF of 24% oversized by 3.2 compared to the electrolyser gives an electrolyser CF of 37%, which is oversized by 2.5 compared to the downstream unit achieving a final capacity factor of ~95%.

These oversizing ratios are working into the final LCOx calculations presented.

Key messages

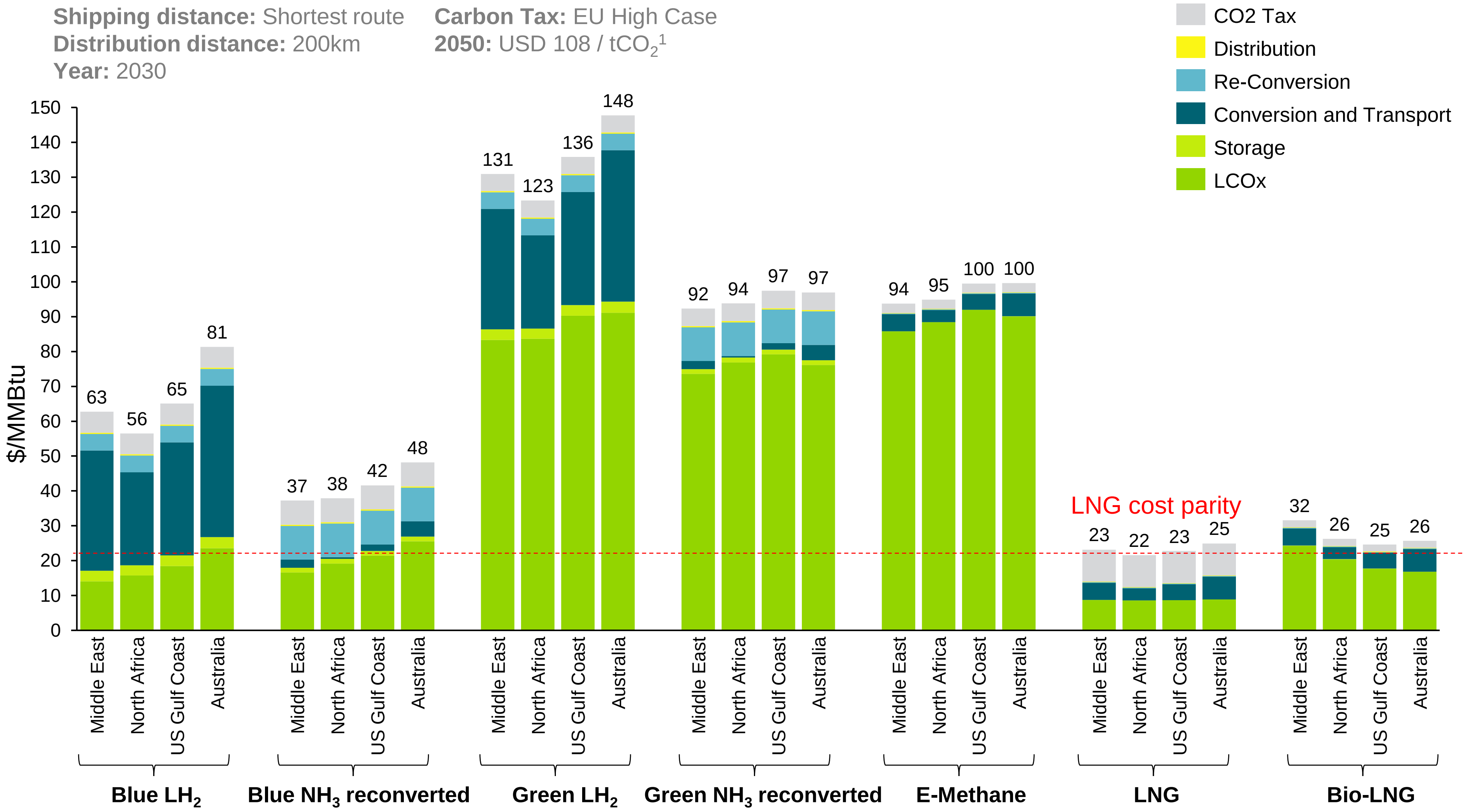
- E-methanation, ammonia production, and H2 liquefaction technology cannot typically ramp up and down in operation and temperature at risk of damaging technology such as catalysts.
- For all clean gas value chains involving electrolysis, we have studied various levels of oversizing of electrolyser and RES **to achieve a near complete (95%) capacity factor on the downstream process**.
- In order to achieve a consistent capacity factor on the downstream process, a typical 8760 solar PV production profile in North Africa was used to determine the average requirement of oversizing in each production region, which are on similar latitudes.[1]
- The **optimal ratio of oversizing was found to be 1 : 2.5 : 8 downstream unit to electrolyser to RES capacity.** A similar result was also in a report on clean ammonia[2]
- We have also studied cases of no oversizing, which often calculate a slightly less expensive LCOx, **but we do not present them in final results due to feasibility concerns**. Additional operational strategies such as hot-standby can be implemented at a cost to maintain catalyst integrity and future developments are expected in this domain.[3]

[1]**CAVEAT:** We are assuming that all hydrogen is produced by solar PV in all regions for simplicity's sake, dedicated hybrid production profiles including wind should be considered.
[2]Techno-economic assessment of blue and green ammonia
[3]Cost benefits of optimizing hydrogen storage and methanation capacities

Delivered cost of new gas molecules to Europe in 2030

In 2030, most green hydrogen-based gases are non-competitive with natural gas-based molecules

Delivered cost of new gasses to Europe 2030 ($/MMBtu delivered)



Key messages

- The cheapest imports are expected to come from Middle East and North Africa for most new gases, due to low-cost solar resource and shorter transport distances compared to US Gulf Coast and Australia.
- Liquefaction and high boil off make liquid hydrogen more expensive than ammonia-based value chains.[2]
- In 2030, blue ammonia and liquid blue hydrogen value chains are more cost competitive than green hydrogen-based value chains due to massive oversizing needs and high electrolyser CAPEX.
- LNG LCOx is based on an average spot price forecast in Europe to compare against the alternative to clean gas imports.

Guidehouse analysis 2024. [1]S&P Carbon Tax Energy prices and capacity factors vary by region. Oversizing dimensions are the same for liquified green hydrogen, green ammonia, and e-methane.[2]liquefaction of hydrogen is included in the Conversion and Transport bar, re-conversion incudes regassification and ammonia cracking.

Guidehouse outwit complexity

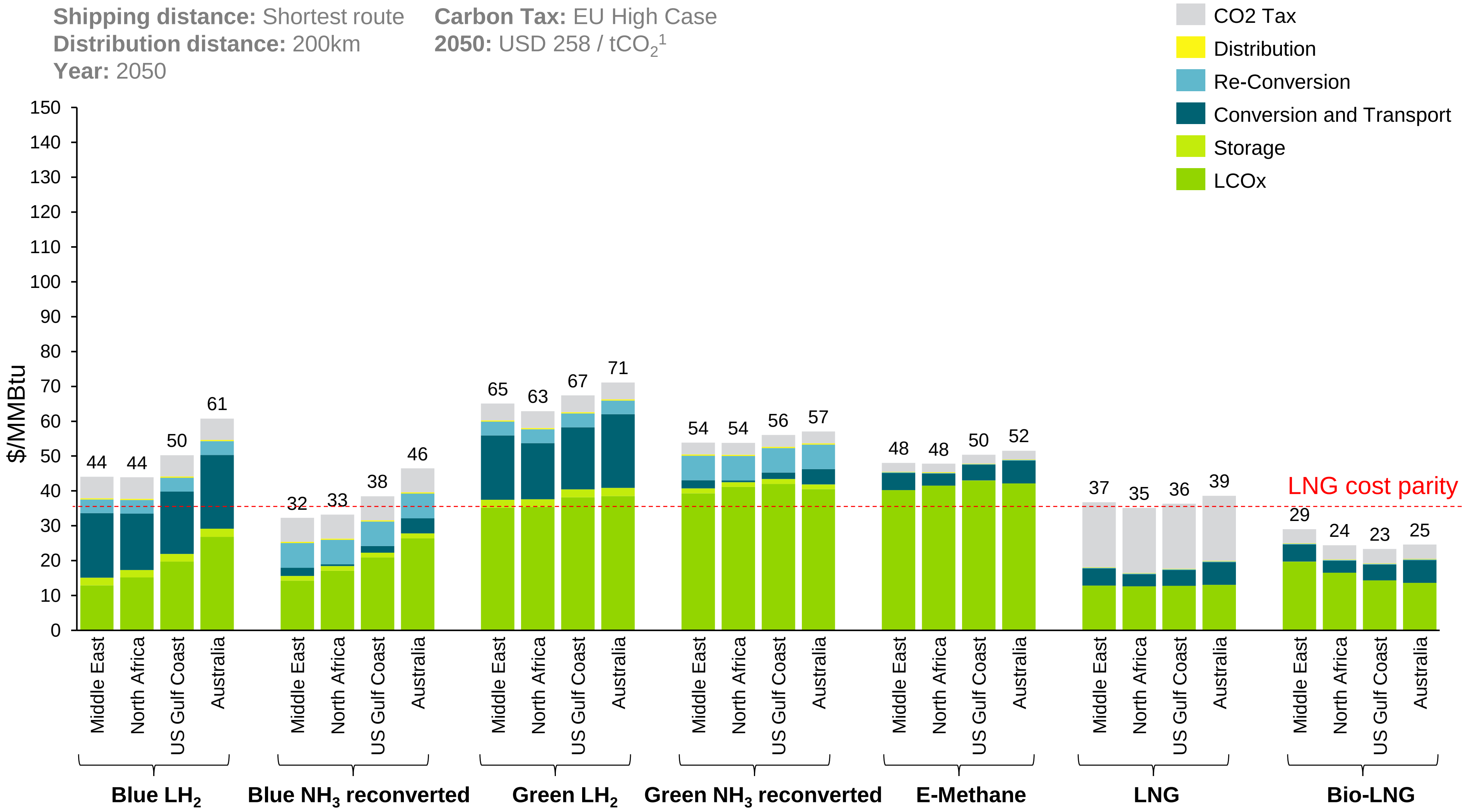
Delivered cost of new gas molecules to Europe in 2050

With a high carbon tax, blue ammonia re-converted and bio-LNG become competitive with LNG

Delivered cost of new gasses to Europe 2050 ($/MMBtu delivered)

Shipping distance: Shortest route
Distribution distance: 200km
Year: 2050

Carbon Tax: EU High Case
2050: USD 258 / tCO_2[1]



Key messages

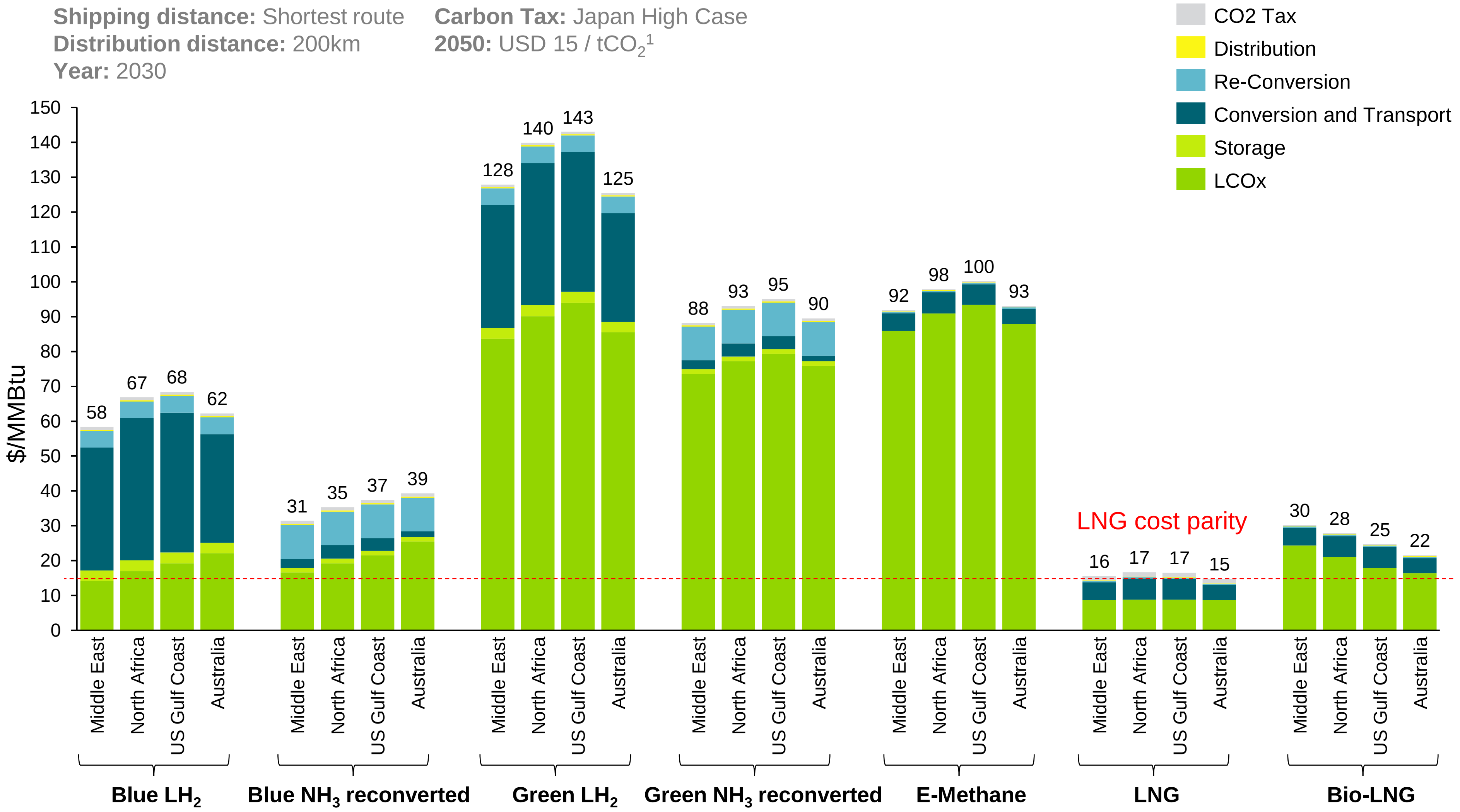
- The cheapest imports are expected to come from Middle East and North Africa for most new gases, due to low-cost solar resource and shorter transport distances compared to US Gulf Coast and Australia.
- Liquefaction and high boil off make liquid hydrogen more expensive than ammonia-based value chains.[2]
- In 2050, e-methane import to Europe is more cost-effective than other green hydrogen-based value chains and long-distance liquid hydrogen transport (LH_2).
- LNG LCOx is based on an average spot price forecast in Europe to compare against the alternative to clean gas imports.

Guidehouse analysis 2024. [1]S&P Carbon Tax
Energy prices and capacity factors vary by region. Oversizing dimensions are the same for liquified green hydrogen, green ammonia, and e-methane.[2]liquefaction of hydrogen is included in the Conversion and Transport bar, re-conversion incudes regassification and ammonia cracking.

Delivered cost of new gas molecules to Japan in 2030

In 2030, the gap between LNG cost and green hydrogen-based molecules and LH_2 is large

Delivered cost of new gasses to Japan 2030 ($/MMBtu delivered)



Key messages

- With a lower carbon tax expected than Europe, LNG remains more cost competitive in 2030 compared to all new gases.
- Bio-LNG, blue LH_2 and ammonia are the most cost competitive new gases.
- Australia is the most competitive supplier of green hydrogen-based value chains including e-methane due to proximity and high solar irradiance. Australia also has a lower assumed WACC which contributes to a lower LCOx.
- Technology improvements are needed to make green hydrogen value chains more competitive with LNG.

Guidehouse analysis 2024. [1]Extrapolation from $12/tCO2 target in 2030 out to 2050 using the same growth rate as EU high case. S&P Carbon Tax
Energy prices and capacity factors vary by region. Oversizing dimensions are the same for liquified green hydrogen, green ammonia, and e-methane.

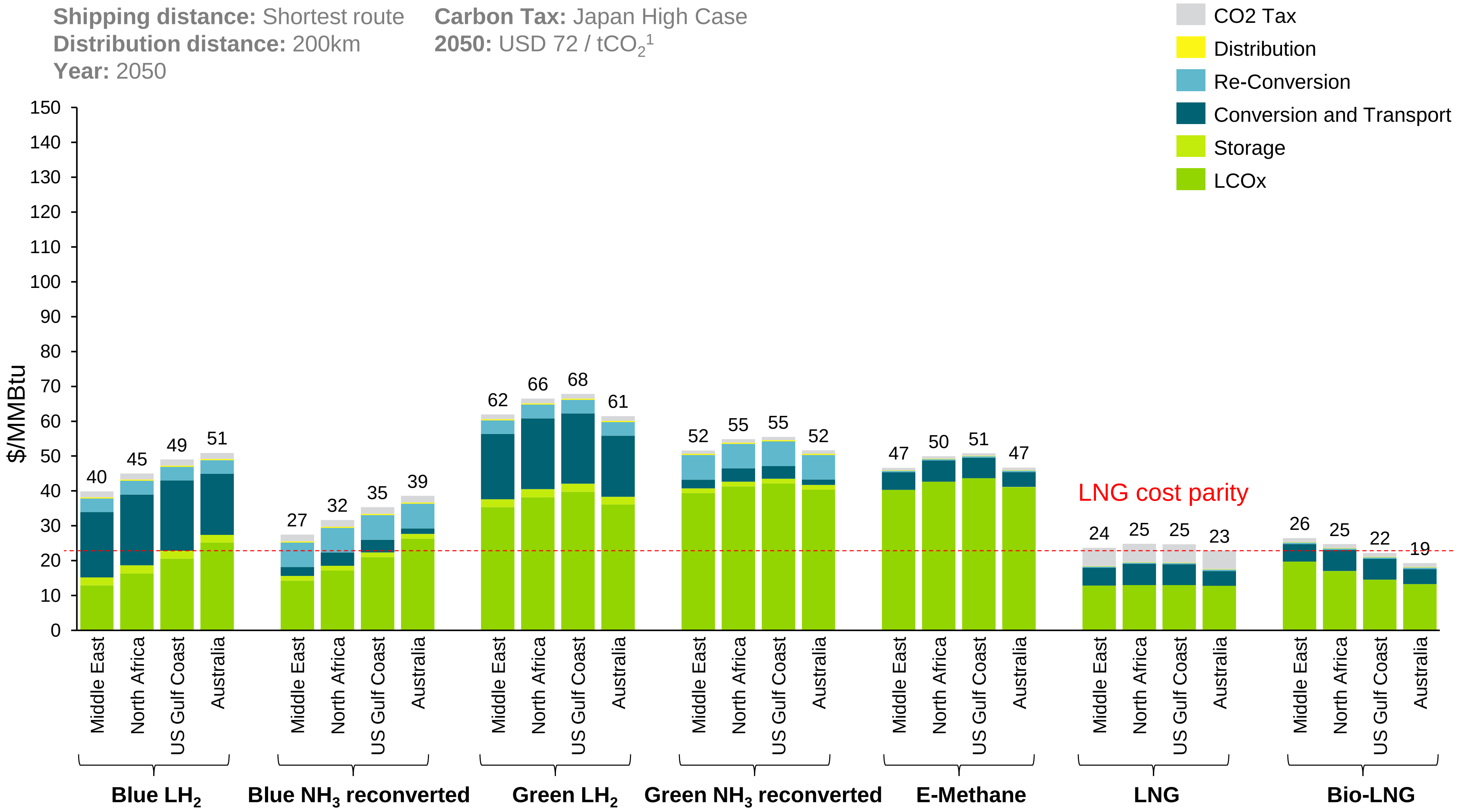
Delivered cost of new gas molecules to Japan in 2050

Blue ammonia, liquid blue hydrogen, bio-LNG and e-methane are the most cost competitive

Delivered cost of new gasses to Japan 2050 ($/MMBtu delivered)

Shipping distance: Shortest route
Distribution distance: 200km
Year: 2050

Carbon Tax: Japan High Case
2050: USD 72 / tCO_2[1]



Key messages

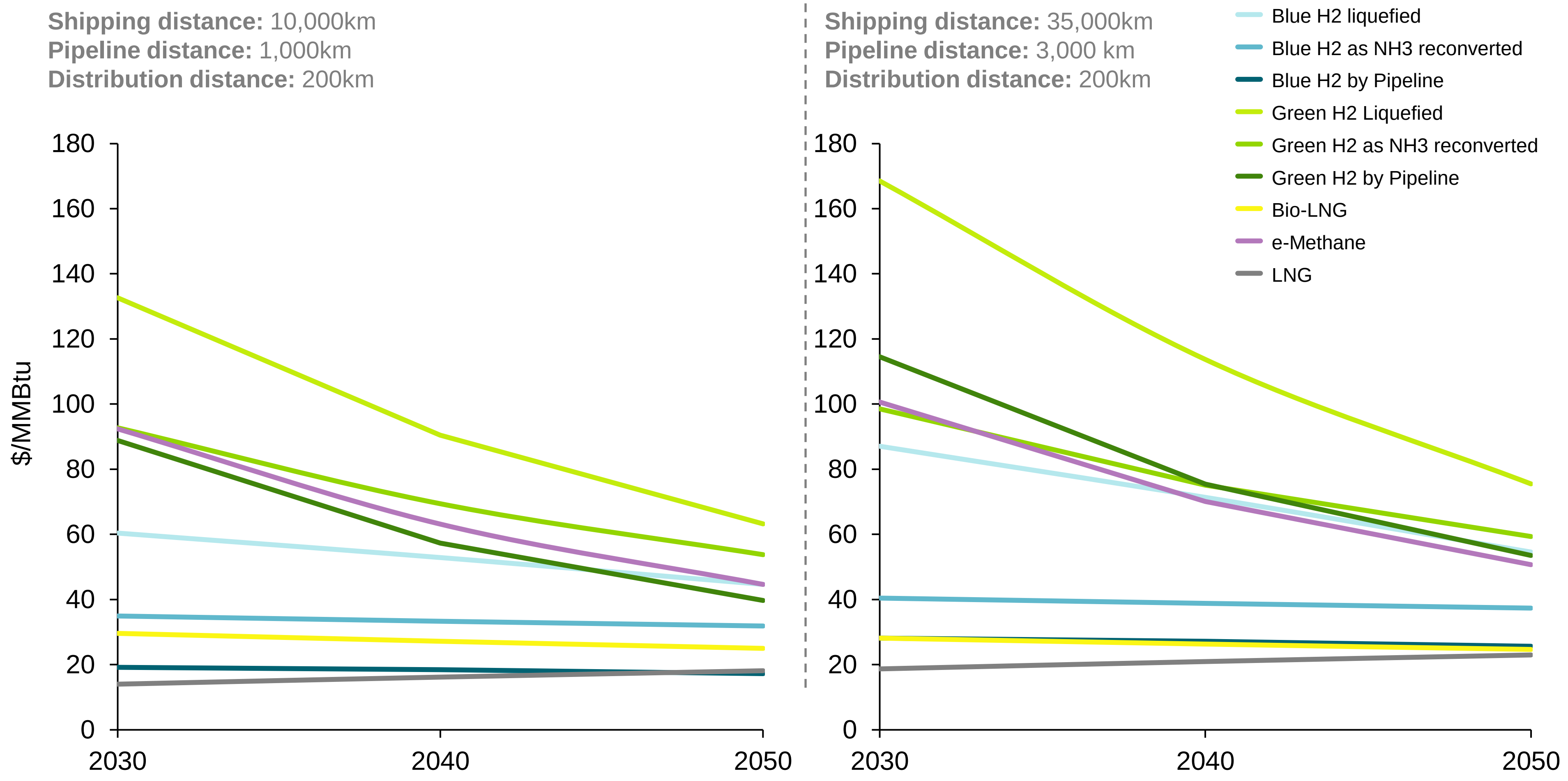
- With a lower carbon tax expected than Europe, LNG remains more cost competitive in 2050 compared to most new gases.
- Australia is the most competitive supplier of green hydrogen-based value chains including e-methane due to proximity and high solar irradiance. Australia also has a lower assumed WACC which contributes to a lower LCOx.
- Other factors are likely to drive the preference for import of new gasses to Japan, such as large existing infrastructure base for regassification, pipelines, and gas fired power production.

Guidehouse analysis 2024. [1]Extrapolation from $12/tCO2 target in 2030 out to 2050 using the same growth rate as EU high case. S&P Carbon Tax
Energy prices and capacity factors vary by region. Oversizing dimensions are the same for liquified green hydrogen, green ammonia, and e-methane.

Delivered cost of new gas molecules per year

Costs mostly reduce over time due to technology improvements, particularly hydrogen and e-methane gas value chains since they are currently the lowest TRL

Delivered cost of new gasses over time at two different distances ($/MMBtu delivered)



Key messages

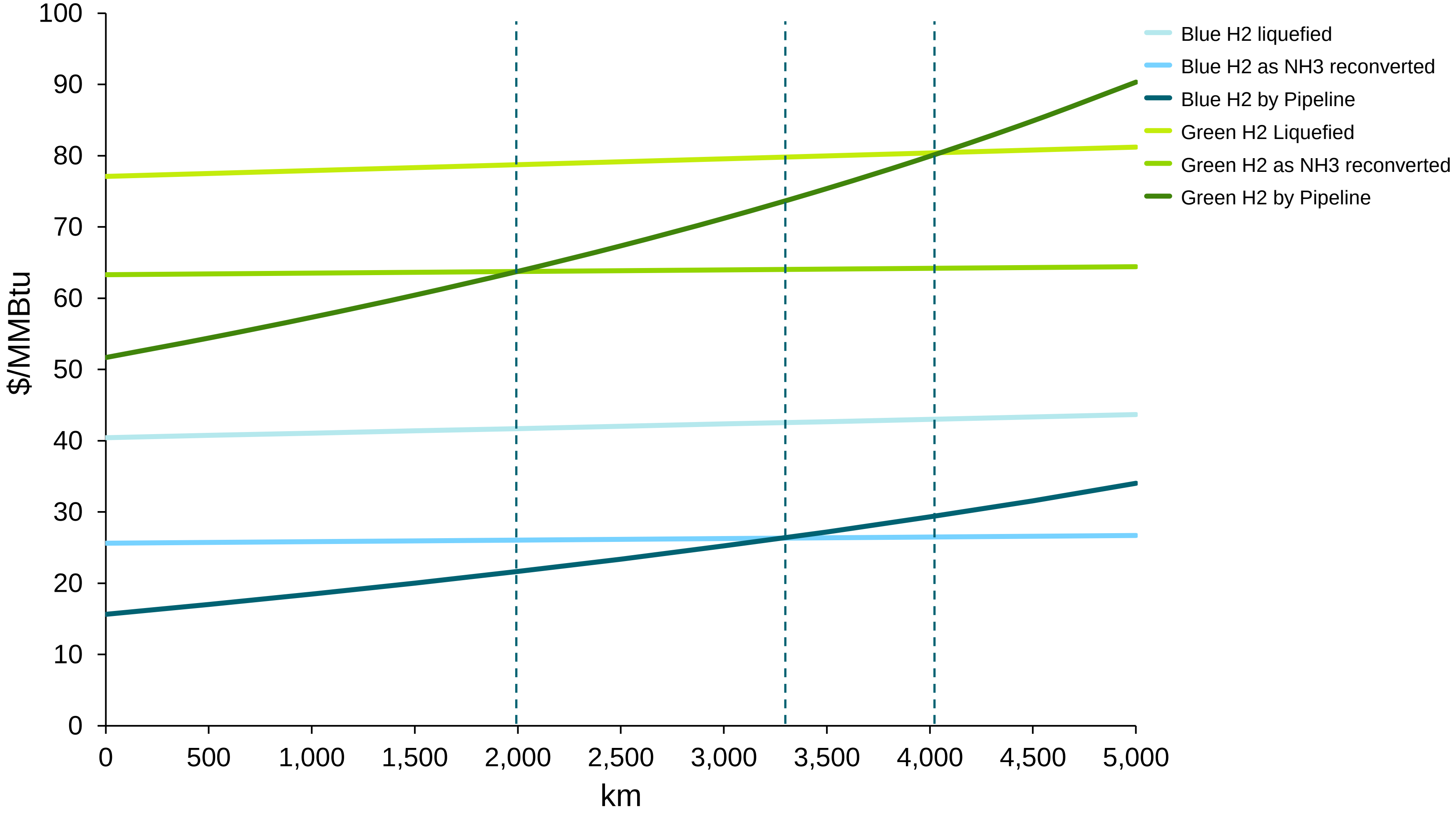
- Large cost reductions are expected for hydrogen-based value chains due to dramatic improvements in electrolyser CAPEX (from ~$1,150 in 2030 to ~$550 $/kW H_2 in 2050) and technology efficiency such as liquefaction.
- Liquid green hydrogen, green ammonia, and e-methane remain expensive relative to other gasses because of the need of oversized RES, electrolyser capacity, and on-site hydrogen storage to maintain a high gas production load factor.
- LNG is typically the cheapest gas even towards 2050[1], but blue hydrogen transported by pipe, bio-LNG, and to a lesser extend blue ammonia are quite competitive.

Guidehouse analysis 2024. [1]No carbon tax assumed. Energy prices and capacity factors vary by region. Oversizing dimensions are the same for liquified green hydrogen, green ammonia, and e-methane.

Cost of delivered gas based on distance

Hydrogen pipelines are the most cost effective for hydrogen delivery up to 3,000 km

Delivered cost of clean hydrogen by distance - 2040 $/MMBtu



Key messages

- Up to 2,000km, the most cost-effective way to transport green hydrogen via pipeline in 2040.
- After 2,000km it is more cost effective to transport green hydrogen as green ammonia an reconvert into hydrogen at the end destination than transport via pipe due to higher leakage rate of hydrogen pipelines compared to almost no leakage and higher efficiency of the ammonia value chain. After 4,000km it is even more cost effective to transport green hydrogen in liquid form due to high leakage.
- Oversizing dimensions are the same for liquified green hydrogen, green ammonia, and piped green hydrogen. Although, if no oversizing is assumed for piped green hydrogen due to having no downstream transformation unit, it remains more cost effective than all other transport methods up to 4,000km.
- Blue hydrogen is more cost effective than green hydrogen, and remains more cost effective than ammonia or liquified transport over longer distances because of a lower LCOx to losses ratio compared to green hydrogen.

Guidehouse analysis 2024. [1]No carbon tax assumed. Energy prices and capacity factors vary by region.

Regional import-export flows

-Work package 3- zoom on 8 corridors

LNG E-methane Hydrogen e-Ammonia

Methodology: Scope of flow study

Work package quantifying the potential export of new gases on 8 corridors from 4 exporting regions towards Europe and Japan

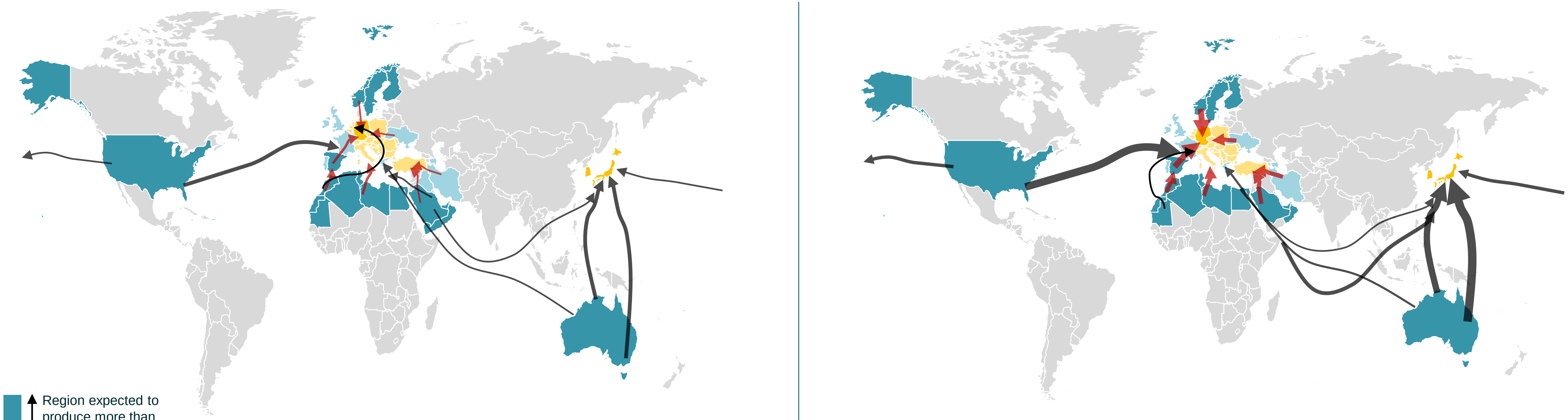
4 Exporting regions	New gases flow	2 Importing regions
US Gulf Coast: **North Africa** **Middle East** **Australia**	• Green H2 as NH3 • Green H2 Liquified • H2 by pipeline • Blue H2 as NH3 • Blue H2 Liquefied • LNG • Bio-LNG • E-methane	**European Union** **Japan**

Note: other flows are out of scope

Expected trade : H2 and its derivatives

Europe and Japan both has set ambitious targets for hydrogen supply, rapidly developing trade routes with exporting countries. By 2050, extensive trade links will allow efficient delivery of required quantities of clean gases.

2030 vs 2050 H_2 and its derivatives flow between considered geographies



Total flow 2030: 7 Mt

Total flow 2050: 52 Mt

Region expected to produce more than consumed

Balanced or non-actors

Region expected to consume more than produced

>10 Mt

5-10 Mt

2-5 Mt

0-2 Mt

Mostly Piped

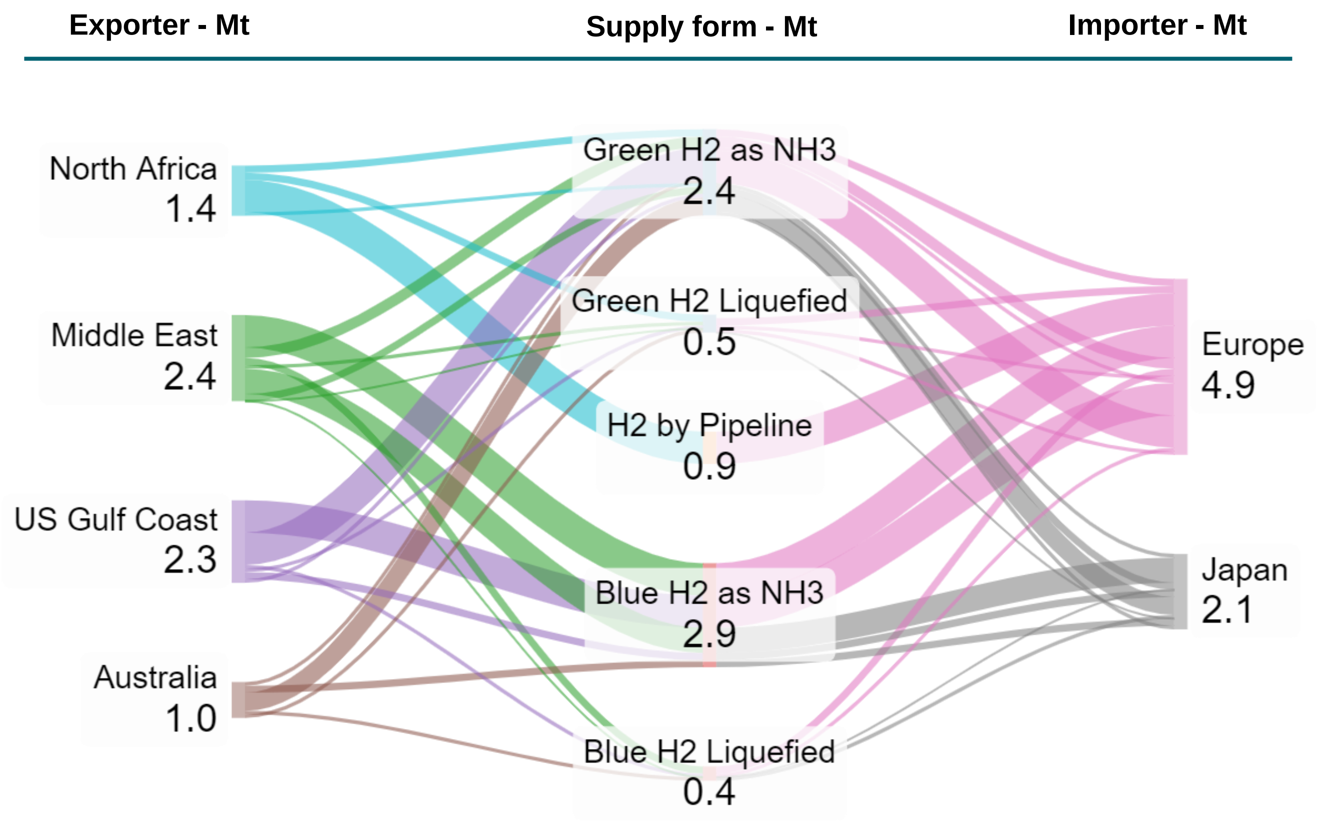
Mostly Shipped

Source : Guidehouse Analysis

Global H2 flow overview around 2030

Around 2030[2], early trade routes are being established, helping to meet emerging demand for hydrogen

2030 Hydrogen supply to chosen geographies (Hydrogen, Mt)



Source: Guidehouse Analysis, only showing the import and export potential between the listed countries, not including the rest of demand met by other exports. [1]Other hydrogen derivatives such as LOHC, methanol and MCH are not studied here, but could be part of the overall share of hydrogen assumed to be transported as ammonia. [2]projects such as the H2Med hydrogen pipeline from North Africa to Europe are planned for 2030, but could be pushed back towards 2035.

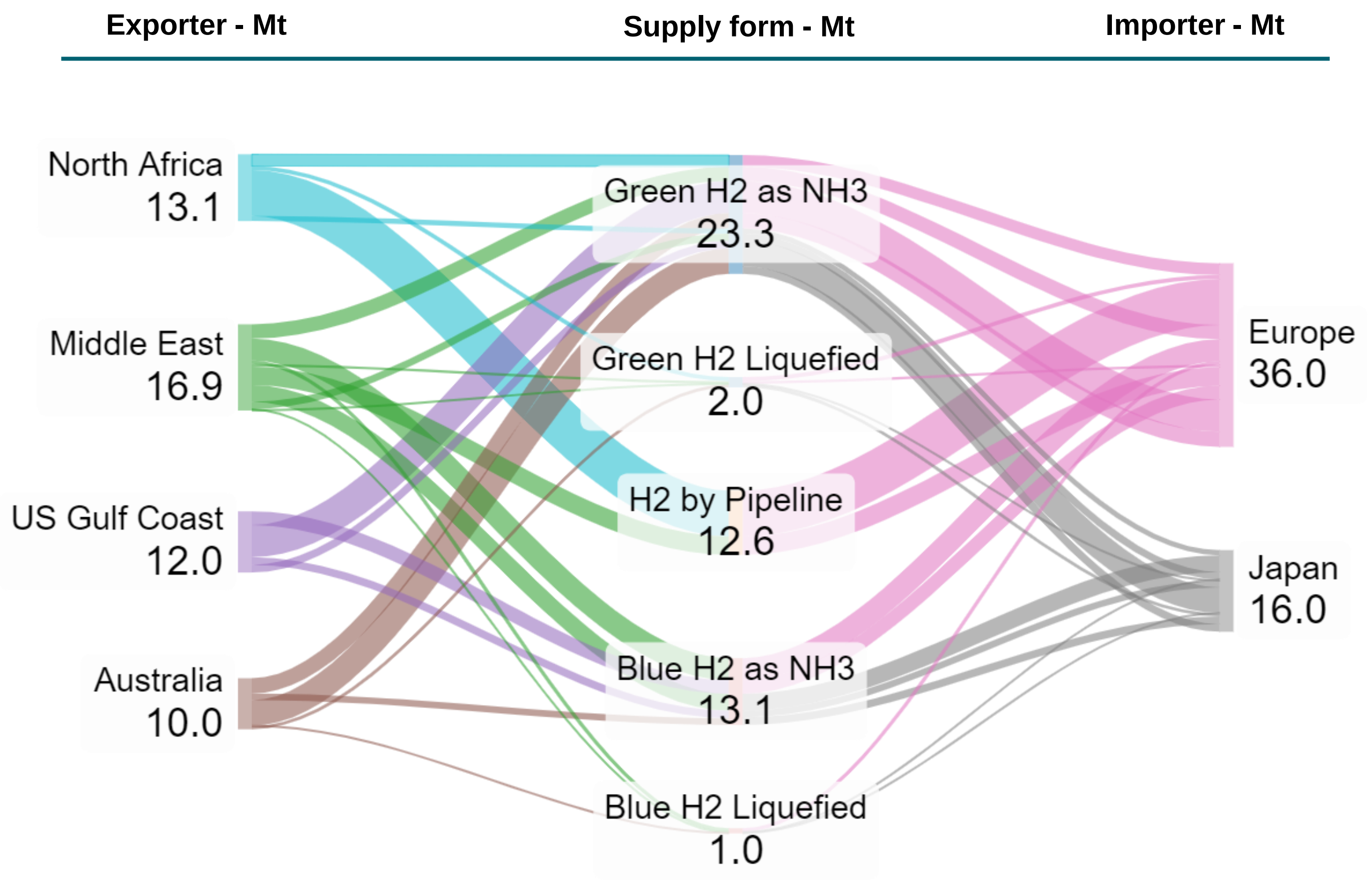
Key messages

- **Demand for clean hydrogen in Europe is ramping up in 2030**, based on early commercial scale hydrogen consumption mostly at steel plants, maritime and aviation sector, and existing refineries. Similarly to EU, **Japan's** h2 demand is driven by need in decarbonization of power sector, industry and transportation.
- A total of 10Mt of clean hydrogen demand is assumed in Europe with half assumed to be met by domestic demand including Norway, and **half imported by the exporting regions included in the study.**
- **Japan's Hydrogen strategy** is expecting demand of **3Mt** H2 by 2030, 40% of which could be met by imports from **Australia**
- Around 2030, **US Gulf Coast and Middle East are expected to begin** supplying mostly blue hydrogen (75% blue hydrogen) to Europe and Japan due to available and relatively cheap natural gas. **North Africa and Australia** are assumed to supply mostly green hydrogen, considering strong RES availability the announced production projects and strategies of these 2 countries.
- Over long distances, **hydrogen transportation** is mostly carried out as **ammonia reconverted into hydrogen**, as it is more efficient and cost-effective compared to the liquefied value chain.[1] This will depend on the commercialisation of ammonia cracking, which is expected to ramp up between 2030 and 2035.
- Hydrogen supply from North Africa towards Europe will be mostly performed via the **planned South H2 and H2Med pipeline leading to Germany via Italy and Spain respectively.**

Global H2 flow overview around 2050

By 2050, hydrogen trade capacities between corridors will increase significantly, reaching up to 50 Mt between MENA - Europe and Australia - Japan

2050 Hydrogen supply to chosen geographies (Hydrogen, Mt)



Source : Guidehouse Analysis

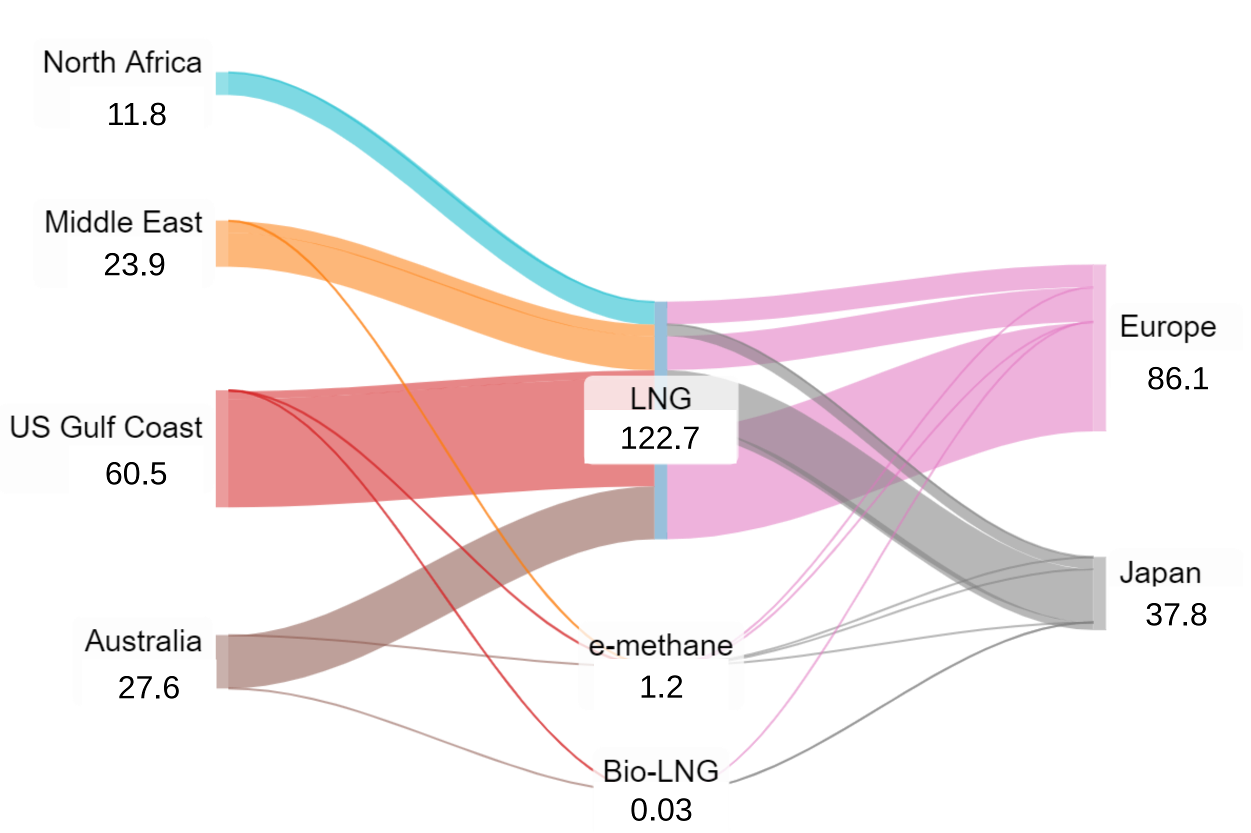
Key messages

- Europe's aggressive shift away from natural gas further increases the role for clean gasses such as hydrogen due to many traditionally gas fired processes becoming hydrogen powered – ie. Gas fired power, metals production, heat production, transport etc.
- **North Africa** and **Middle East** will be the two main suppliers of hydrogen, mostly green, to Europe by 2050 due to high solar resource potential and proximity leading to high-cost effectiveness.
- For **long distance** routes, priority will be given to the shipment of H2 in the **form of ammonia**, which will be dominant form of hydrogen transported due to **expected commercialisation of ammonia cracking technology.**
- **The Middle East will likely deliver most of its hydrogen via shipping as ammonia and reconversion**, as it will be the cheapest option for transport. Some could be delivered through a potential hydrogen pipeline, but economics at the distance of around 3,500km between the EUA and Greece for example begin to deteriorate for piped hydrogen due to high leakage.
- Supply to **Japan** will mainly come **from Australia, followed by the Middle East and US Gulf Coast due to their proximity.**

CH4 flow overview (LNG, Bio-LNG, e-methane), 2030

Around 2030, reliance on LNG will persist in 2 selected geographies, US Gulf Cost playing an important role in its delivery

2030 LNG, Bio-LNG and e-methane supply to chosen geographies (Mt)



Source : Guidehouse Analysis.

Key messages

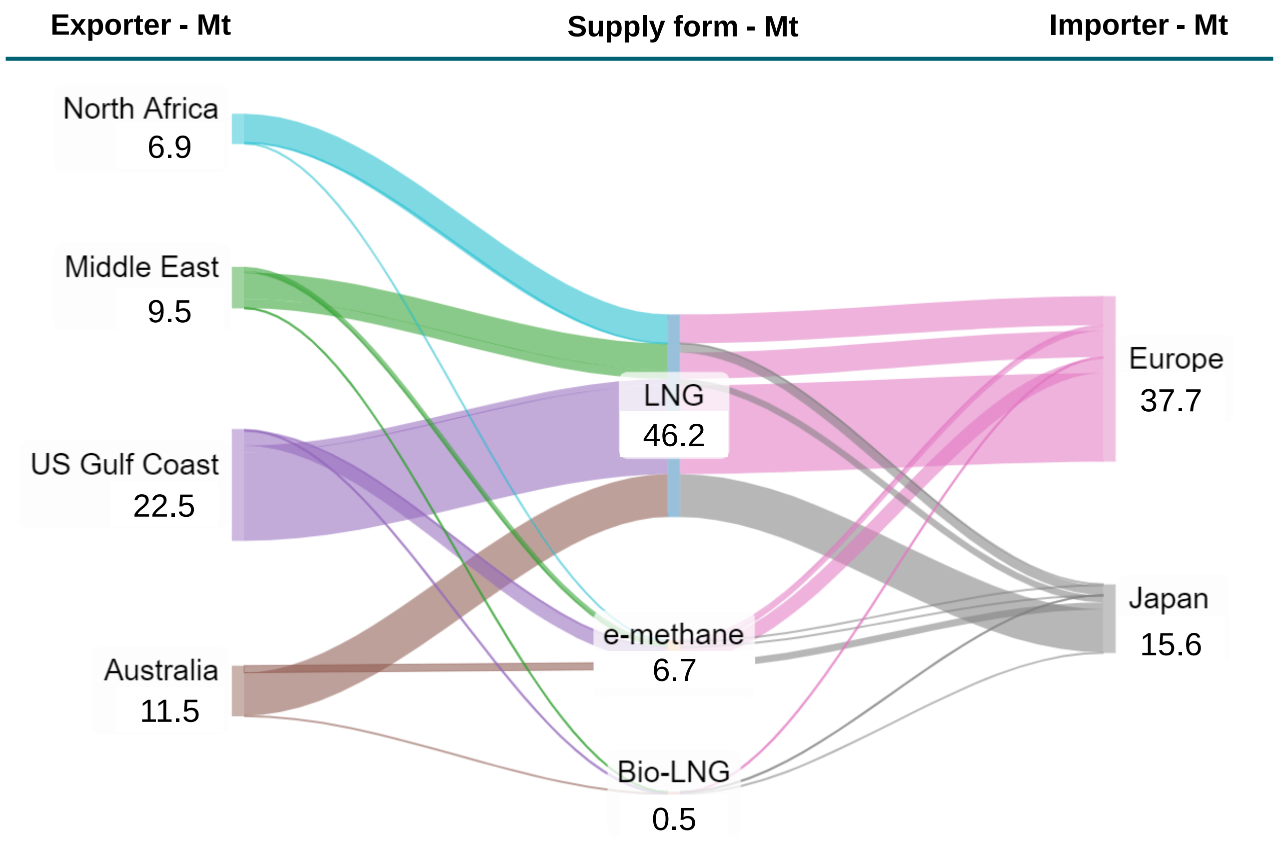
- Around 2030, the two importing geographies will continue their reliance on LNG, however with **lesser demand**, following announced climate transition plans.
- **US Gulf Coast** could play an important role as a supplier of clean gases for the EU, mostly as e-methane based on biogenic CO_2 availability and available subsidies for CO_2 capture in the IRA.
- Existing infrastructure for import of liquefied CH4 based gases in importing geographies facilitate the earliest imports of e-methane and bio-LNG.
- **Australia and US Gulf Coast could supply the earliest quantities of Bio-LNG** to EU and Japan, potentially via blending in existing LNG cargos as quantities of biomethane will be limited and likely consumed domestically to meet emissions reduction demands.
- **E-methane** will be traded in much greater quantities than Bio-LNG, as required feedstock for production is believed to be higher than biomethane.
- In 2030, **North Africa will not deliver** Bio-LNG nor e-methane, as no intentions have been announced and due to the lack of required biogenic CO2.

Estimates were made to calculate proportion of e-methane and Bio-LNG of the total LNG that can be delivered. It was assumed that for the corridor US Gulf Coast – Europe, Bio-LNG proportion represent 3% and for Japan – 3% as well. The overall proportion of clean gases from LNG is 0.5%.

CH4 flow overview (LNG, Bio LNG, E-methane), 2050

By 2050, reliance on LNG will decrease, however proportion of delivered clean gases will increase considerably

2050 LNG, Bio-LNG and e-methane supply to chosen geographies (Mt)



Key messages

- **In 2050**, demand for LNG will **continue reducing**, following the introduced policies and rapid electrification of sectors that are currently reliant on natural gas.
- **Proportion** of supplied methane based **clean gases** is estimated to represent up to 15% between chosen corridors.
- **North Africa** is expected to join Middle East, Australia and US Gulf Coast in delivering of clean gasses (**e-methane**) **towards Europe**.
- **US Gulf Coast** will continue leading in delivering e-methane and Bio-LNG considering **scale-up** of their production.
- **Australia** is following UGC in delivering of e-methane and Bio-LNG, mostly **towards Japan**, using the established infrastructure.

Source : Guidehouse Analysis

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Immediate next steps, Q&A

?

Q&A session
We will be happy to answer all of your questions

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Thank you