

Report

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Shipfuels Matrix - Merit Mapping of Maritime Alternative Fuels

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EXECUTIVE SUMMARY

Context and Objective

The decarbonisation of the maritime sector represents a challenge in the global transition to a low carbon energy system. As a key enabler of international trade, maritime shipping underpins global economic activity while contributing to greenhouse gas (GHG) emissions that must be significantly reduced in line with the objectives of the Paris Agreement. Achieving deep reductions by 2050 requires the large-scale deployment of alternative fuels, supported by transformation of fuel production, supply chains, infrastructure and vessel technologies. A wide range of alternative fuel options is under development, but these pathways differ significantly in terms of GHG performance, energy efficiency, feedstock requirements, technological maturity and operational characteristics. At the same time, available information is often fragmented, making it challenging for stakeholders to compare options and make informed decisions.

In this context, the Shipfuels Matrix has been developed as a common, data driven framework to support the consistent evaluation of alternative maritime fuel pathways. Jointly commissioned by Concawe, Aramco and CMA CGM, it provides a structured basis for comparing fuels across multiple criteria and use cases.

Approach

The Shipfuels Matrix enables a comprehensive well to wake assessment, covering the full value chain from feedstock production to end use in marine applications. It allows comparison of pathways based on key performance indicators, including GHG emissions, process efficiency, feedstock availability, technology maturity and fuel properties. By integrating these dimensions, the tool supports both high-level comparisons and more detailed analysis of individual pathways, including the influence of feedstock, conversion process and application. It provides a consistent analytical framework at a screening level, while more detailed techno economic analysis remains necessary for specific deployment decisions. Importantly, the tool is not intended to rank fuels. Suitability depends on factors such as operational requirements, technology maturity, infrastructure availability, regional context and regulatory environment.

Key Findings

While the main focus of this work was on establishing a curated compendium and data-rich repository, the use of the Shipfuels Matrix was demonstrated with several use cases.

GHG Performance

GHG performance varies widely across fuel pathways and is determined by the combination of feedstock, conversion process and energy input. The use of an alternative fuel does not inherently guarantee emissions reductions, as some pathways can approach or exceed the emissions of conventional fuels, particularly when based on energy intensive processes, unfavourable farming practices or fossil inputs.

Conversely, many pathways enable substantial GHG reductions, particularly those based on biogenic wastes/residues or low carbon energy sources. Pathways combining renewable or nuclear electricity with electrolysis and synthesis processes can achieve very low emissions. These results highlight that GHG performance must be assessed at pathway level rather than by fuel alone.

Efficiency and Feedstock Considerations

Process efficiency varies significantly across pathways. Direct processing routes generally exhibit higher efficiencies, while multi step synthetic pathways tend to incur higher energy losses. Feedstock availability is a key determinant of scalability. Biomass residues and waste streams are relatively widely available, albeit constrained in scale and dispersed, creating supply chain challenges.

Technology Maturity and Deployment

Technology maturity differs across pathways, with conventional refining and many biofuel routes already commercially established. In contrast, e-fuel and advanced thermochemical pathways require further scale up. This suggests a progressive transition, with near term deployment relying on mature technologies and the phase-in of more advanced solutions over time. Infrastructure, standards and supply chains will be critical to foster this evolution.

Operational and Fuel Characteristics

Fuel properties and operational characteristics play a key role in determining suitability. Differences in energy density influence vessel range and storage requirements, while storage and safety characteristics affect fuel handling and infrastructure. Propulsion system compatibility and fuel consumption also vary across engine types and vessel categories. Some fuels can be used in existing technologies, while others require new propulsion systems. This highlights that fuel selection must consider operational feasibility in addition to environmental performance.

Insights from Case Studies

The case studies demonstrate how the Shipfuels Matrix can be applied to explore different perspectives. Feedstock driven analysis highlights the influence of resource choice, conversion driven analysis shows variability within a given technology, and fuel driven analysis compares production pathways and applications for fuels such as ammonia and methanol. Across all cases, performance is context dependent, and robust decision making requires a holistic assessment of technical, environmental and operational factors.

Use of the Shipfuels Matrix to support the Maritime Energy Transition

The results confirm that there is no single optimal fuel solution. A range of pathways will be required to address different vessel types, operating conditions, resource availability and infrastructure constraints. The transition will therefore require a multi pathway approach supported by coordinated development of technologies, supply chains and regulatory frameworks.

The Shipfuels Matrix provides a flexible framework and definitive source to support this transition by enabling consistent comparison of alternative fuel pathways. As a “living” tool, it will be updated periodically to reflect technological developments, new data and evolving regulatory frameworks. By establishing a shared information base, the tool supports informed dialogue and evidence-based decision making, contributing to the decarbonisation of the maritime sector.

1. BACKGROUND AND OBJECTIVE

1.1. BACKGROUND

The Paris Agreement (2015) calls for substantial reductions in greenhouse gas emissions across all sectors by 2050 to limit the impacts of climate change. As a key enabler of global trade, the maritime sector plays a central role in this transition and is actively advancing lower-carbon fuel options. While progress is being made in both fuel production and regulatory frameworks, the sector is characterised by a wide range of potential pathways and fragmented, sometimes inconsistent information. This creates challenges for stakeholders in assessing options and aligning on future fuel strategies.

Against this backdrop, global energy and shipping stakeholders have collaborated to develop a common information base – the Shipfuels Matrix – to support a more consistent and transparent evaluation of alternative maritime fuel pathways.

1.2. OBJECTIVE

The Shipfuels Matrix, jointly commissioned by Concawe, Aramco, and CMA CGM, is designed as an up-to-date, “living” source of information on alternative maritime fuel pathways. It provides users with access to a coherent set of data across a broad range of topics, supporting a consistent assessment of fuel options.

The matrix aims to support the development of the maritime sector’s decarbonisation strategies and implementation roadmaps by enabling transparent comparison of key performance indicators (KPIs). These include well-to-wake greenhouse gas (GHG) emissions, technological readiness levels (TRL), and fuel properties.

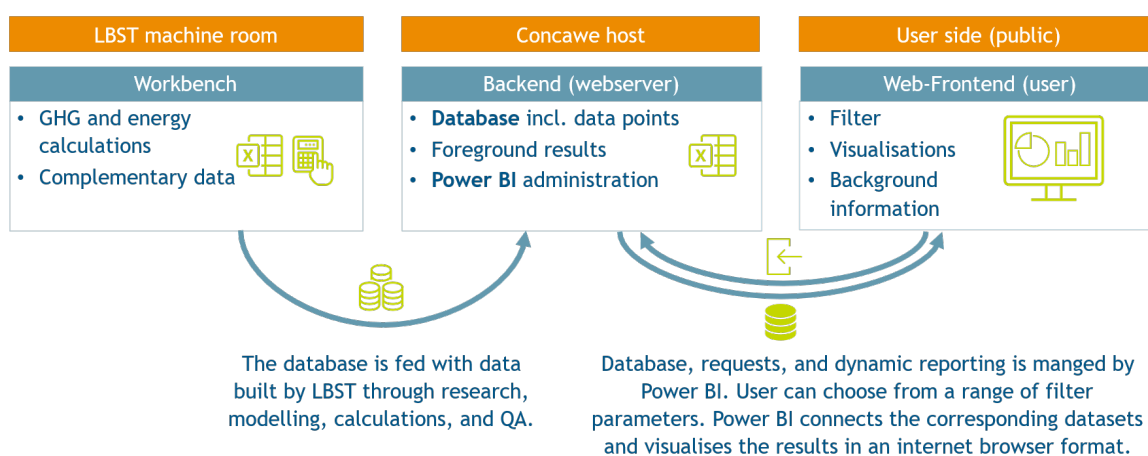
In addition to comparing different fuels, the tool allows users to analyse individual fuels across multiple production pathways and feedstocks. It also enables more detailed exploration of underlying factors, including feedstock availability and regional potential, as well as application-related aspects such as fuel use efficiency across different propulsion technologies.

2. DYNAMIC AND EDITABLE DATABASE - DESCRIPTION OF DATASET

2.1. OVERVIEW: DATASETS AND BACKGROUND CALCULATIONS

The underlying database has been supplied with data researched and developed in background analyses by Ludwig-Bölkow-Systemtechnik GmbH (LBST). The results, key assumptions and references are consolidated into a final dataset and serve as the data source for the Power BI dashboards. Further details regarding the data consolidated in the final database can be found below.

Figure 1 Data flow within the project



2.2. DETAILS ON DATASETS

In the subsections following, the respective final datasets are described in more detail and explained with regard to:

- Dataset structure
- Information covered in the respective table columns, and how they are visualised

2.2.1. Pathways

2.2.1.1. Dataset structure

In the dataset PATHWAYS, all alternative fuel pathways are listed on a well-to-wake (WtW) basis and pathway-related information is included for each pathway.

The pathways carry a respective unique pathway ID and are defined by:

- Final fuel
- Conversion processes
- Raw feedstock if applicable (e.g. sunflower seeds for sunflower oil as primary feedstock)
- Primary feedstock (feedstock used in conversion process 1)
- Secondary feedstock (renewable electricity for hybrid Biomass- / Power-to-Liquid (B/PtL) pathways, and CO₂ from different sources) if applicable

- Fuel transport mode and distance (i.e. import vs. domestic EU)
- Fuel use (i.e. the type of propulsion)

2.2.1.2. Creation of unique pathway ID

Each pathway considered is attributed a unique identifier (ID), which has the following format:

[Fuel ID] - [feedstock ID] - [consecutive numbering on conversion processes] - [inside EU/imported]¹ - [propulsions type ID]²

2.2.1.2.1. Final fuel codes

The following fuel codes are used:

Table 1 Final fuel codes for pathway ID

Final fuel	Fuel ID
Ammonia (NH ₃)	NH ₃
Cashew nutshell liquid (CNSL)	CNSL
Diesel via hydrothermal liquefaction (HTL)	HTL_diesel
Diesel (pyrolysis)	Pyrol_diesel
Electricity	Electricity
Ethanol	EtOH
Fatty Acid Ethyl Esters (FAEE)	FAEE
Fatty Acid Methyl Esters (FAME)	FAME
FAME residues	FAME_res
Heavy Fuel Oil (HFO)	HFO
Liquid Hydrogen (LH ₂)	LH ₂
Liquefied methane	LiqCH ₄
Marine Diesel Oil (MDO)	MDO
Methanol	MeOH
Paraffinic diesel* (e.g. HVO)	Paraffinic_diesel
Straight vegetable oil	SVO
Very Low Sulfur Fuel Oil (VLSFO)	VLSFO

*Paraffinic diesel includes hydrotreated vegetable oil (HVO), hydrotreated animal fats/waste cooking oil, Fischer-Tropsch (FT) diesel, and diesel produced via the methanol-to-diesel (MTD) process.

2.2.1.2.2. Raw Feedstock codes

The feedstocks included in the Shipfuels Matrix were selected to provide representative rather than exhaustive coverage of the range of biomass, waste, fossil and renewable feedstocks currently considered for maritime fuel production. The selected feedstocks include both conventional feedstocks, such as food and feed crops, and advanced feedstocks, including feedstocks listed under Annex IX of the Renewable Energy Directive, with future updates potentially incorporating

¹ For import-pathways, the suffix “imp” is used, and the suffix “EU” for the corresponding pathways with final fuel transport inside of the EU. If no suffix is used, it implies by default a domestic “inside of the EU” pathway. Import paths only for pathways with ammonia, ethanol, liquefied methane, liquid hydrogen, methanol or paraffinic diesel as final fuel.

² Propulsions type ID is only used, where more than one option is possible (i.e., for Ammonia, Liquefied methane)

additional feedstocks as they emerge and gain relevance. The following feedstock codes are used:

Table 2 Feedstock codes for pathway ID

Raw feedstocks	Feedstock ID
Agricultural prunings	AgriPrun
Bagasse	Bagasse
Burnt forest wood	Brntwood
Camelina (intermediate oil crop)	Camelina
Cashew nutshell	CNS
Coal	Coal
Corn	Corn
Corn stover	CornStov
Crude glycerol	Glycerol
Crude oil	CrudeOil
Concentrated Solar Power (CSP)	CSP
Food waste	FoodW
Hydro	Hydro
Lignocellulosic energy crop (proxy miscanthus)	Miscant
Lignocellulosic energy crop (proxy short rotation forestry (SRF))	SRF
Macroalgae ³	Algae
Manure	Manure
Molasses	Molasses
Municipal solid waste	MSW
Natural gas	NG
Nuclear fuel	Nuclear
Oil seed crop field residues	OilRes
Palm oil mill effluent (POME)	POME
Primary forest residues	ForestRes
Photovoltaic (PV)	PV
Rapeseed	Rapeseed
Renewable electricity (unspecified ⁴)	RE
Residues from FAME production	FAMERes
Secondary forest residues	2ForestRes
Sewage sludge	Sewage
Soybeans	Soybeans
Stem wood	Stemwood
Sugar beet	SugBeet

³ Macroalgae is not included in Annex IX of DIRECTIVE (EU) 2018/2001 (Renewable Energy Directive) but there are projects for the use of macroalgae as feedstock for anaerobic digestion plants to produce biogas (e.g. COASTAL Biogas, <https://www.coastal-biogas.eu/>)

⁴ Renewable electricity (unspecified) assumes a mix of renewable energy source such as wind and solar. Ratio varies, depending on flexibility of synthesis process/plant components and time horizon, based on [Soler et al. 2024]

Raw feedstocks	Feedstock ID
Sugar cane	SugCane
Sunflower seed	Sunflower
Tallow oil	TallowOil
Used cooking oil	UCO
Vegetable waste	VegetW
Waste plastics	Wplastic
Waste tyres	Wtyres
Waste wood	Wwood
Wheat	Wheat
Wheat straw	Wstraw
Wind offshore	WindOff
Wind onshore	WindOn

2.2.1.2.3. Transport codes

With regard to transport modes and distances for delivering the final fuel, two versions of some pathways exist, namely production outside of the EU and import to the EU, and production and transport inside the EU. Import pathways were included where production outside the EU is considered a plausible and commercially relevant supply route (e.g. sugar cane ethanol from Brazil), as well as for selected ammonia, liquefied methane, liquid hydrogen, methanol and paraffinic diesel pathways. If no suffix is used, it implies an inside-of-the-EU pathway; for import pathways the suffix “import” is used, and “EU” for the corresponding inside-of-the-EU pathway.

2.2.1.2.4. Propulsion type codes

The following table indicates the type of propulsion that can be used for each final fuel⁵. A propulsion ID is only used in the pathway ID if there is more than one possible propulsion type for the final fuel reference for differentiation. Here, only for Ammonia and liquified methane a Propulsion ID is used.

⁵ The propulsion technologies included in the Shipfuels Matrix were selected based on their technological and commercial readiness and are intended to provide representative rather than exhaustive coverage of available fuel-propulsion combinations. Future updates may incorporate additional propulsion technologies as they mature and gain commercial deployment.

Table 3 Overview of propulsion types used for final fuels and respective code in pathway ID

Final fuel	Propulsion type	Propulsion ID
FAME	Slow speed Diesel Internal Combustion Engine (ICE)	
FAEE	Slow speed Diesel ICE	
Straight vegetable oil	Slow speed Diesel ICE	
CNSL (Cashew nutshell liquid)	Slow speed Diesel ICE	
FAME residues	Slow speed Diesel ICE	
Paraffinic diesel (e.g. HVO)	Slow speed Diesel ICE	
Diesel (pyrolysis)	Slow speed Diesel ICE	
Diesel (HTL)	Slow speed Diesel ICE	
Ethanol	2-stroke Diesel cycle dual fuel ICE	
Methanol	2-stroke Diesel cycle dual fuel ICE	
LH ₂	Fuel cell (Proton Exchange Membrane Fuel Cell)	
Liquefied methane	Otto dual fuel, medium speed	Otto_medium
	Otto dual fuel, slow speed	Otto_slow
	2-stroke Diesel cycle dual fuel ICE	DF_ICE
	Lean-burn spark ignited (LBSI)	LBSI
Ammonia	2-stroke Diesel cycle dual fuel ICE	DF_ICE
	Catalytic NH ₃ electrolysis + Fuel cell + electric motor	FC
Electricity	Battery electric propulsion	
MDO	Slow speed Diesel ICE	
HFO	Slow speed Diesel ICE	
VLSFO	Slow speed Diesel ICE	

2.2.1.3. Information covered in the “PATHWAYS” dataset

Overall, 46 feedstocks, 33 processes, 17 final fuels and 8 propulsion systems are combined within the Shipfuels Matrix to represent a broad range of maritime fuel pathways. The following table gives an overview of the feedstocks, conversions, final fuels and propulsion system forming these pathways.

Table 4 Overview of Feedstocks, processes, final fuel and propulsion systems

Feedstocks	Conversion and conditioning processes	Final fuel/electricity	Propulsion systems
- Vegetable oil from oil crops (4 crops) - Waste oils (5 oil sources) - Sugar & starch crops (4 crops) - Agricultural residues (3 sources) - Residues for anaerobic digestion (4 sources) - Algae for anaerobic digestion - Woody biomass incl. SRF (6 sources) - Other residues (5 sources) - Non-bio-waste (2 sources) - Sewage sludge - Lignocellulosic energy crop (i.e. Miscanthus) - PV electricity - Wind electricity (onshore) - Wind electricity (offshore) - CSP electricity - Hydro electricity - Nuclear fuel - Coal - Natural gas - HFO and diesel for electricity (2 sources)	- Transesterification - Hydrotreating - Raw Glycerol conversion (2 types) - Alcohol Fermentation - Methanol synthesis - Methanol-to-Diesel (MTD) - Fischer-Tropsch synthesis - Haber-Bosch synthesis (HB) - Pyrolysis & upgrading - HTL & upgrading - Anaerobic digestion (AD) - Gasification, Pyro-gasification, hydrothermal gasification (3 types) - Water electrolysis - Co-electrolysis of water and CO₂ - H₂ & CH₄ liquefaction (2 types) - Methanation - SMR w CCS, ATR w CCS (2 types) - CO₂ capture technologies (3 types) - Biomass power stations (4 types) - Fossil power stations (4 types)	- Ammonia - Electricity - Ethanol - FAME - FAEE - HTL-based diesel - LH₂ - Liquefied methane - Methanol - Paraffinic diesel (e.g. HVO) - Pyrolysis-based diesel - Straight vegetable oil - FAME residues - CNSL	- Slow speed Diesel ICE 2-stroke Diesel cycle dual fuel ICE - Proton Exchange Membrane Fuel Cell (PEMFC) - Otto dual fuel, medium speed - Otto dual fuel, slow speed - Lean-burn spark ignited (LBSI) - Catalytic NH₃ electrolysis + Fuel cell + electric motor - Battery electric propulsion
Number of feedstocks: 46	Number of conversion processes: 33	Number of final fuels/electricity: 17	Number of propulsion systems: 8

Table 5 provides an overview of the information covered in the PATHWAYS dataset and the related visualisations in the Power BI dashboard. Underlying literature sources and assumptions are displayed within the visualisation where applicable.

Table 5 Information covered in dataset PATHWAYS and related visualisation

Information	Tab included	Details	Visualisation
Possible pathways	Pathway category	Each pathway is categorised into one of the following pathway categories: - Biofuel - Power & Biomass-to-Liquid (PBtL) - Mix of bio- and non-biowaste derived fuel - Non-biowaste derived fuel - Power-to-Gas (PtG) - Power-to-Liquid (PtL) - Direct electrification - Bio-electricity - Fossil electricity - Nuclear electricity - Fossil fuel with CCS - Fossil fuel	- Overview table - Pathway diagram visualisation (data from Pathway diagram dataset)
	Final fuels	Final fuel produced from pathway	
	- Feedstocks - Raw feedstock - Primary Feedstock - Secondary feedstocks - CO₂ source - Process description of primary feedstock supply - References of primary feedstock supply	For each pathway, the supply of the primary feedstocks from the raw feedstock is modelled with regard to GHG emissions and energy flows where applicable (e.g. processing of energy crops in oil mills). Secondary feedstocks cover renewable electricity for hybrid (B/PtL) pathways as well as CO₂ from different sources.	
	- Conversion and conditioning processes: - Process descriptions - References	The overall conversion and conditioning processes to produce a final fuel are separated into up to three conversion steps.	
	- Fuel transport: Import vs. inside of EU - Description of assumptions - References	Depending on the final fuel and transport distance, different assumptions on the transport modes are made.	
	- Fuel use: Propulsion type - Description of assumptions - References	The final fuels are assumed to be used in maritime applications. For Ammonia and liquified methane, more than one propulsion type can be applied.	

Information	Tab included	Details	Visualisation
GHG emissions	- GHG emissions (in $g_{CO2eq}/MJ_{Final\ fuel}$): - From primary feedstock supply CO_2 absorbed from atmosphere and bound in renewable final fuel - From conversion 1-3 - From transport of the final fuel - From the use of the final fuel - Total GHG emissions	For each supply chain element, the GHG emissions were calculated (well-to-wake in g_{CO2eq}/MJ_{fuel})	- Bar chart on total emissions - Waterfall chart
Efficiency	- Efficiency - Efficiency related to the feedstock input - Energy input of feedstocks ($MJ/MJ_{Final\ fuel}$) - External energy inputs ($MJ/MJ_{Final\ fuel}$) - Energy output of main products ($MJ/MJ_{Final\ fuel}$) - Energy output of by-products ($MJ/MJ_{Final\ fuel}$)	- For each pathway, the efficiency has been calculated with regard to - overall energy input and outputs: $\sum (LHV^6 \text{ (main product)} + LHV \text{ (by-products)}) / \sum (LHV \text{ (feedstock)} + LHV \text{ (external energy inputs)})$ - feedstock input: $LHV \text{ (main product)} / LHV \text{ (feedstock)}$ - Detailed assumptions on the efficiency related to the feedstock input are included in the Power BI dashboard directly.	- KPI table - Bar Chart on total efficiency and Efficiency related to feedstock input

2.2.1.4. Information covered in the “ENERGY FLOW” dataset

The **ENERGY FLOW** dataset provides information on the energy flows of each pathway on a well-to-tank (WtT) basis, which are displayed as a Sankey diagram in the Power BI dashboard. This visual requires the specific dataset structure as follows:

- Source
- Destination
- Value of the energy flow ($MJ/MJ_{Final\ fuel}$)

The energy flows are linked to the respective pathways by using the pathway ID (see section 2.2.1.2). References and information on assumptions which have been applied for the calculation of the energy flows are included in the PATHWAYS dataset. The efficiencies in the PATHWAYS dataset have been calculated from the energy flows of this dataset.

⁶ LHV = lower heating value

Table 6 Energy flows required per pathway in ENERGY FLOW dataset

Value chain steps	Source (Energy Inputs)	Destination	Comment
Feedstock supply	Diesel and electricity for farming machines		
	Electricity required for cultivation	(<Feedstock cultivation/ collection/ extraction and/or processing>)	
	Agrochemicals, seeding material		
	Crops handling and processing		Covering crop transport, crop drying and auxiliary energy for oil mill
	(<Feedstock cultivation/ collection/ extraction and/or processing>)	Feedstock supply (<Bio feedstock or electricity>) Oil cake Losses from feedstock supply	
Conversion	Feedstock supply (<Bio feedstock> or electricity)		
	Methanol or ethanol		For transesterification only
	Hydrogen	<Conversion process 1>	
	Electricity for electrolysis for e-BtL		For electrolysis for e-BtL
	Auxiliaries		Includes electricity for auxiliaries, natural gas and process chemicals
	<Conversion process 1>	<<Conversion process 2> or <Conversion process 3> or Fuel transport and distribution> By-products Losses from conversion	If no conversion 2 is defined, then conversion 3. If no conversion 3 is defined, then "Fuel transport and distribution"
	Methanol		
	Hydrogen		
	Auxiliaries	<Conversion process 2>	Includes electricity for auxiliaries, natural gas and process chemicals
	Energy for carbon capture (net)		
	<Conversion process 2>	<<Conversion process 3> or Fuel transport and distribution> By-products Losses from conversion	If no conversion 3 is defined, then "Fuel transport and distribution"
		Co-electrolysis	Heat from FT synthesis for co-electrolysis
	Auxiliaries	<Conversion process 3>	Includes electricity for auxiliaries, natural gas and process chemicals
Transport of final fuel	Fuels & electricity	Fuel transport and distribution	
		<Final fuel>	
		Losses from transportation & bunkering	
	Fuel transport and distribution		

2.2.1.5. Information covered in the “Pathway diagram” dataset

The Pathway Diagram dataset serves to dynamically display each pathway later in the Power BI dashboard. It relates value chain steps and their respective icons to a specific matrix position element to build the diagram:

Table 7 Description of function of respective columns for the generation of the dynamic pathway diagrams

Type of information	Details	
Location of pathway elements in diagram	Pathway step Nr	Numbered pathway steps ensure the correct order along the value chain from the left to the right
	ROW Level	The main pathway is located in the third/lowest row of the matrix (ROW Level = 3_Diagram Level 1). Secondary feedstocks are located in the second row of the matrix (ROW Level = 2_Diagram Level 2). They are further matched with the relevant pathway step⁷. The CO₂ sources / the carbon capture process is located in the first row of the matrix and matched with the relevant pathway step⁸ (ROW Level = 1_Diagram Level 3).
	Icons	Respective icons of the pathway elements in base 64 code (image URI format).
Names	Pathway element (name)	Name of each pathway element for reference
	Pathway element name for display in diagram (4_Diagram Level 0)	The names of the pathway elements are displayed below the pathway matching the respective pathway steps. This is only applied for⁹ • Feedstock cultivation and processing • Conversions 1-3 • Transport of final fuel • Use of final fuel / Propulsion type

2.2.2. Feedstocks

2.2.2.1. Feedstock dataset structure and general information

The **Feedstocks** dataset and the **Feedstocks_bioenergy_potentials** dataset include all information on complementary characteristics for the **raw feedstocks** and the **secondary feedstocks** covered in the list of pathways. For a better overview, the feedstocks are classified into the following feedstock classes:

Table 8 Feedstock classes

Feedstock classes	
1. Animal fats	2. Non-biowaste/residue
3. Aquatic biomass	4. Nuclear
5. Bio-waste/residue	6. Primary agricultural waste/residue
7. Energy crop	8. Primary forest residues
9. Food crop	10. Renewable electricity (solar, wind, hydro)
11. Forestry product	12. Secondary agricultural waste/residue
13. Fossil	14. Secondary forest residues
15. Mixed waste/residue	

⁷ i.e. Conversion 2 („20_Conversion 2“) for renewable electricity in hybrid (B/PtL)-pathways and Conversion 3 („30_Conversion 3“) for CO₂.

⁸ i.e. Conversion 3 („30_Conversion 3“)

⁹ The icons of the product flows are arrows with the respective naming already.

2.2.2.2. Information covered in the “Feedstock” dataset

The **Feedstocks** dataset includes the following complementary characteristics of feedstocks, which are independent of the fuel pathways:

Table 9 Information covered in dataset “Feedstocks” and related visualisation

Information	Details	Note	Visualisation
Seasonality of feedstocks	No seasonality/ Mild seasonality/ Seasonal/ Pronounced seasonality		Matrix with checks
Limitation of production by industry	Classification: – Dependent on single industry – Dependent on few industries – Diversified		Matrix with red/yellow/green flags
Impact on gross water consumption from feedstock culture and crop	• Indicative range for gross water demand from feedstock culture and crop ($\text{m}^3/\text{GJ}_{\text{Feedstock}}$) • References	Applicable for energy crops only	Bar chart with ranges
Impact on biodiversity	Rating of positive (+) / neutral (0) and negative (-) impact of these factors on bio-diversity: – Pest control – Fertilizer input – Irrigation – Humus balance – Invasive species – Tillage & rotation practices	Applicable for energy crops only	Matrix with red/yellow/green flags

2.2.2.3. Information covered in the “Feedstocks_bioenergy_potential” dataset

The **Feedstocks_bioenergy_potential** dataset covers data on the bioenergy potentials from bio-feedstocks in different world regions. This dataset is handled separately for better visibility and is structured as the matrix Feedstocks x World regions with the bioenergy potential entries in PJ/year. For reference, the calculation basis is further included, i.e. the minimal and maximal recoverability factor, the energy content ($\text{MJ}/\text{kg}_{\text{dry feedstock}}$), and the gross production of the feedstocks per world region ($\text{kt}_{\text{dry feedstock}}/\text{year}$).

The bioenergy potentials are displayed in the dashboard via a map, indicating the size of the bioenergy potentials as clustered columns per feedstock in each world region as well as ranges with best estimates per world region or the world. Best estimate refers to the reference value reported in the underlying source and should not be interpreted as the most likely or preferred outcome, as it may reflect a medium, baseline, or other reference scenario depending on the source.

2.2.3. Conversions

2.2.3.1. Conversion dataset structure and general information

The **Conversions** dataset and the **Conversions_large plants** dataset provide the information on the complementary characteristics for all single conversion processes covered in the **PATHWAYS** dataset. The information is considered independently of the fuel pathways.

2.2.3.2. Information covered in the “Conversions” dataset

The **Conversions** dataset provides the complementary characteristics of all conversion processes covered in the **PATHWAYS** dataset as provided below:

Table 10 Information covered in dataset Conversions and related visualisation

Information	Details	Visualisation
Technological readiness level (TRL)	- Min. and max. TRL - Background information - References	Ranges in column chart for each conversion process

Via the link of the Conversions dataset with the **PATHWAYS** dataset, furthermore, a Sankey diagram displays the possible production processes involved to produce different final fuels.

2.2.3.3. Information covered in the “Conversions_large plants” dataset

The **Conversions_large plants** dataset provides a list of examples of existing large plants (incl. name, conversions process, location, production volume (t/year), relevant assumptions and references). The production volumes, together with the TRLs for the different conversion technologies serves as a basis for the visualisation of the state of technology by mapping them in a x-y-scatter graph.

2.2.4. Final Fuels

2.2.4.1. Final Fuel dataset structure and general information

The **Final Fuels** dataset lists all covered final fuels in the **PATHWAYS** dataset and provides their pathway-independent complementary characteristics.

2.2.4.2. Information covered in dataset “Final Fuels”

The following complementary characteristics are covered:

Table 11 Information covered in dataset “Final Fuels” and related visualisation

Information	Details	Visualisation
Energy density	- Energy density by mass (LHV, MJ/kg) - Energy density by volume (LHV, MJ/l)	x-y-chart for different fuels
Refueling duration	- Classification based on fuel properties and conclusion on refueling durations: - liquefied fuels - may achieve similar bunkering performance as conventional fuels, but with additional efforts - liquid hydrocarbons - refuelling times similar to diesel-type fuels	Matrix with checks in the “Applications” tab
Storage conditions	- Storage temperature [°C] - Storage pressure [MPa(a)]	Table
Consideration in standards and maximal blending ratio	- Max. blending ratio (according to relevant ISO standard) - Rating of regulatory readiness: Included in SOLAS, MARPOL and other standards	Table with conditional formatting
Co-activities during bunkering	Co-bunkering status and rationale	Traffic-light table in the “Applications” tab

2.2.4.3. Information covered in dataset “Final Fuels x Propulsion”

The following complementary characteristics are covered regarding the use of final fuels:

Table 12 Information covered in dataset “Final Fuels x Propulsion” and related visualisation

Information	Details	Visualisation
Pollutant emissions - default values	• Engine efficiencies • g/MJ and g/kWh_{mech} of pollutant in fuel: CO₂, CH₄, N₂O • Comparison to VLSFO	Clustered bar charts
Pollutant emissions - threshold values	• SO_x (g/MJ and g/kWh_{mech}), • TIER III limit <130 rpm for NO_x (g/kWh_{mech})	Table in “Applications” tab

2.2.5. Applications

2.2.5.1. Application dataset structure and general information

The dataset “Applications” provides pathway-independent information on the application of the final fuels in certain ship types. The ship types considered include:

Table 13 Ship types considered

Ship types
Deep container ships
Chemical tankers
Bulk carriers
RoPax/Passenger ferries

2.2.5.2. Information covered in dataset “Applications”

The dataset includes the complementary characteristics related to the application of the final fuels in different ship types:

Table 14 Information covered in dataset “Applications” and related visualisation

Information	Details	Visualisation
Fuel consumption	- Fuel consumption in $\text{g}_{\text{Final Fuel}}/\text{kWh}_{\text{mechanical work per final fuel}}$ - Assumptions & References	Bar chart
Pros and cons for onboard carbon capture	- General: Effect on fuel consumption - References	- Infobox - Table with bullets per category
Importance of fuel attributes for different ship types	- Rating of importance per ship type (Low/Medium/High): - Range - Fuel safety (flammability + combustibility) - Toxicity + Health - Environmental impact (emissions during use + environmental toxicity) - Refueling duration	Table with conditional formatting

2.3. UNDERLYING BASIC ASSUMPTIONS FOR THE DATASET

2.3.1. Feedstock

2.3.1.1. Bio-feedstock availability & Geographical area of availability

General

Here, the technical potential in PJ/year is displayed for each feedstock. The technical potential shows the potential supply of the feedstock in view of limiting agronomic and other factors that impact yield levels, account for competition from other uses and land requirements for non-agricultural use. For example, wheat is not considered outside of Europe due to food supply security considerations. The technical potential refers to the amount of energy available from the feedstock that can be used for fuel production. Additional sustainability constraints such as those relating to nature conservation and biodiversity, soil and water are considered, resulting in the sustainable potentials of the crop.

The gross production (kt/yr) and bioenergy potential (PJ) are calculated for the regions: Middle East and North Africa, Sub-Saharan Africa, Latin America and Caribbean, North America, South Asia, Europe, Central Asia, East Asia, and Pacific.

References and Assumptions

[Silesh et al. 2025] provide agricultural residue production data per continent based on FAOSTAT from 2023 [FAO 2023]. The data for Europe includes Eastern Europe, Northern Europe, Southern Europe, and Western Europe based on the United Nations geo-scheme (including Belarus, Ukraine, and Russia). The share of agricultural residues available for bioenergy (40 to 50%, average 45%) is derived from [Concawe 2025]. The gross production data for municipal solid waste and other waste

categories are derived from [World Bank Group 2024]. The full list of references utilised for determination of the feedstock potentials are documented in the database.

Calculation methodology

The **Technical potential** (PJ/yr) or sustainable potential for each feedstock is calculated by multiplying the gross production (kt/year), energy content (MJ/kg_{dry matter}), recoverability factor (RF) and ratio of product residue (RPR) if applicable. The energy content indicates the calorific value of the feedstock, reflecting the amount of energy that can be obtained per unit mass. The recoverability factor indicates the fraction of feedstock that can realistically be used to generate bioenergy (biofuel) after some of it has been used because of variations in nature, competitive uses and technical limitations. The ratio of product residue (RPR) is used to calculate how much unused crop residue might be left after harvesting a particular crop. The RPR varies for different crop levels. Gross production including food production, where applicable, is provided in kilo ton dry substance per year for 2023.

The technical potential for **agricultural residues** (includes wheat straw, corn stover, bagasse, oil seed crop field residue) is calculated as follows:

*Technical potential (agricultural residues) = [Gross production] * [RF] * [Energy content]*

Here the gross production indicates the residue available (for some feedstock with no data for residue, the gross production of residue is calculated by multiplying the gross production of crop with RPR).

For **food and energy crops** (including sugarcane, wheat, corn, soybean, rape seed, camelina and sunflower seed), the following formula is used to calculate the technical potential:

*Technical potential (ethanol, VO) = [Crop production] * [Yield] * [RF] * [Energy content]*

Here, yield (in l/t) represents the ethanol/ vegetable oil (VO) yield from the crop. The recoverability factor (RF) considers only the fraction utilized for biofuel production excluding other competing uses. Energy content of the fuel (ethanol/vegetable oil) is considered. For wheat 2% of total wheat harvest is considered to be used for ethanol production in Europe. For other regions the potential is considered zero due to competition with food production. For corn 31% of the harvest is utilized for ethanol production in the USA. In other regions, incl. China, India, and most African countries, food supply security is a critical issue. Hence, the potential is considered zero.

For **waste** (Sewage sludge, Manure, Vegetable waste, Food waste, waste wood, municipal solid waste), the technical potential is calculated as follows:

*Technical potential (waste) = [Gross production] * [RF] * [Energy content]*

Here, the recoverability factor indicates the share of the product which can realistically be collected for biofuel use (according to [Imperial College London 2021]).

For primary forest residues the technical potential is calculated as follows:

*Technical potential (primary forestry residues) = [Gross stemwood production] * [RPR] * [Energy content]*

For primary forestry residue the RPR is the ratio to roundwood which is assumed to be 40% as indicated in [Konstantinavičienė 2023].

For secondary forestry residue, **short-rotation forestry (SRF)**, and **miscanthus chaff**, the feedstock potential is directly derived from cited literature source.

2.3.1.2. Seasonality of availability

Fuel producers need a stable supply of feedstocks. This can be impacted by the seasonality of the feedstock. All feedstocks are categorised, based on the harvest cycles, into one of the four categories:

- **0 - No seasonality** (year-round): Feedstock available continuously; stable and reliable supply.
- **1 - Mild seasonality**: Feedstock available year-round but with seasonal variation, e.g. PV.
- **2 - Seasonal** (2-3 harvests/year): Biomass available multiple times a year; more frequent harvests but still seasonal.
- **3 - Pronounced seasonality** (1 harvest/year): Biomass available once a year after the main crop harvest; common in agriculture.

The main source for this categorisation is [Imperial College London 2021], while others are based on the knowledge of LBST experts.

2.3.1.3. Production limitations by industries

The production of fuels can be more secure and stable, if the source of supply of feedstocks is more diversified. This analysis categorizes feedstocks as follows:

- **Dependent on a single industry**: The feedstock comes mainly from one specific industry. Supply is vulnerable if that industry faces disruption.
- **Dependent on a few industries**: The feedstock is sourced from a limited number of industries. Supply is more stable but still somewhat exposed to sector-specific risks.
- **Diversified**: The feedstock is produced across various industries or sectors. This ensures a more secure and reliable supply. One example of diversified industry is plastic waste, which can come from several industries, including building and construction, consumer and institutional products, electrical or electronics, industrial or machinery, textile sector, etc.

2.3.1.4. Consequences on water consumption from crop cultivation

The data on water consumption of each food and energy crop is mainly obtained from [Gerbens-Leenes et al. 2008], [Govoni et al. 2024] and [Zhang et al. 2024].

2.3.1.5. Feedstock impact on biodiversity

The impacts per food and energy crops are rated for different categories as follows:

- **0**: Can be positive or negative, depending on cultivation practice
- **+**: Positive impact on biodiversity
- **-**: Negative impact on biodiversity

The biodiversity categories considered include:

- **Pesticide control:** For pest control, the following thresholds for pesticide use were applied:
 - > 4 kg/(ha.year): negative impact
 - > 0 - 4 kg/(ha.year): medium impact
 - = 0 kg/(ha.year): positive impact
- **Fertilizer input:** For fertilizer input, the following thresholds for N-fertilizer use were applied:
 - 100 kg/(ha.year): negative impact
 - ≤ 50 kg/(ha.year): positive impact
- **Irrigation:** Inadequate irrigation practices can have a negative impact on rivers and lakes nearby the energy crop cultivation or plantation site
- **Humus balance:** Depending on the agricultural practice and the type of energy crops the humus content of the soil can be balanced, decreased or increased.
- **Use of degraded land:** Assessment whether the energy crops can improve soil properties e.g. increase the content of organic matter or the carbon content of the soil.
- **Invasive species:** Assessment whether the energy crop is invasive.
- **Tillage and rotation practices:** Tillage and crop rotation practices have an impact on biodiversity. Crop rotation systems consisting of only a few crops or only one type of crop lead to a decrease of biodiversity directly or indirectly e. g. due to higher demand of pesticides.

The conclusions on biodiversity impacts are drawn based on [European Commission 2022]; [Giuntoli et al. 2017]; [JEC 2020]; [JRC 2019]; [JRC 2025]; [Karlsson Potter et al. 2023]; [Lask 2019]; [LfULG 2014]; [Nature Geoscience 2021]; [Taheripour & Tyner, 2013]; [Valin et al. 2015]; [Zanetti et al. 2024].

2.3.2. Conversion

2.3.2.1. Process technical maturity

The technological maturity of processes is typically assessed via the technology readiness level (TRL) scale¹⁰. The values are assigned for all relevant processes from 1 to 9 (e.g. 5 being "laboratory testing of integrated system" and 9 meaning "System proven in operational environment"). TRL can depend on associated technology and also on feedstock used. The data is obtained from LBST expert knowledge based on [UBA 2022], [Sher et al. 2025] and [Ramboll 2024]. The TRL values reported in the Shipfuels Matrix relate to individual conversion processes. The maturity of a complete fuel pathway may be lower, depending on the specific feedstock, process configuration and degree of integration demonstrated at commercial scale.

¹⁰ See <https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/>

2.3.2.2. Opportunities of scaling up process units

The state of technology development of production process to produce the final fuels considered can be gauged by mapping the technological readiness level (TRL) of production processes and the corresponding currently largest sizes of production plants. This indicates whether the technology development is advanced and whether commercial-scale production sites have so far been constructed.

Largest unit sizes based on the output of final fuel or intermediate product are considered according to [IEA 2024] data and data provided by original equipment manufacturers (OEMs). If the data on production capacity was originally expressed in metric tons of final fuel or intermediate product per day, it was converted to metric tons per year, assuming 365 days of operation while accounting for a 10% reduction in total operational hours for maintenance.

2.3.3. Final Fuel

2.3.3.1. Fuel consumption for transport of final fuel

Energy efforts per MJ of fuel transport and distribution are calculated and displayed in the Sankey diagrams representing energy flows of the fuel pathways.

2.3.3.2. Energy consumption related to transport & storage of molecule including chemical conversion factors

Throughout the production and transport of a fuel, energy is consumed in processes that convert the fuel into different physical or chemical states, with associated energy losses at each step. The overall production efficiencies for each fuel are calculated by dividing the fuel's energy content by the feedstock's energy content. The energy flows and losses have been gathered from literature cited for each pathway.

2.3.3.3. Energy density (by volume and by mass)

The energy density is an important characteristic of a fuel and has implications on vessel range, available cargo space, bunkering times, etc. As maritime fuels differ in density, a fuel change affects either the range or the payload of a vessel. Assuming constant storage parameters, the final fuel's energy density serves as a proxy to provide a basic overview of how substitution by different fuels influences vessel range. Two types of density values are provided for the fuels:

1. **Gravimetric density** (specific energy content per unit of mass) expressed in MJ LHV/ kg
2. **Volumetric density** (mass per unit of volume) expressed in kg / m³

2.3.3.4. Fuel hazard and handling considerations

The suitability of a fuel for maritime applications depends not only on its environmental performance, but also on its physical, health and environmental hazards and the operational requirements associated with its storage, transport, bunkering and use on board ships. Maritime fuels may present different challenges, including flammability, toxicity, cryogenic or pressurised storage requirements, material compatibility and environmental risks. These characteristics can influence vessel design, crew training, fuel storage systems, bunkering infrastructure, port operations and overall risk management.

The classification and labelling of substances and mixtures placed on the European Union market are governed by EU Regulations on Classification, Labelling and Packaging of Substances and Mixtures¹¹ (CLP). The classification of a specific maritime fuel may vary depending on its substance identity, composition, manufacturing pathway and relevant fuel specifications. For finished maritime fuels and fuel blends, classification may also vary according to the types and concentrations of the components used, including feedstocks, additives and blending practices. Maritime fuels marketed under the same general fuel name may therefore require different classifications.

Concawe publishes annually the report Hazard Classification and Labelling of UVCB Hydrocarbon Substances in the European Economic Area, covering substances within the Concawe REACH portfolio. The report is available from the Concawe¹² website and provides recommendations for the classification and labelling of hydrocarbon substances based on available dossier data and updated regulatory information. These recommendations are intended as guidance only and do not replace the obligation of suppliers to conduct their own assessment in accordance with applicable legislation.

Under the CLP Regulation, manufacturers, importers and downstream users placing substances or mixtures on the EU market are responsible for classification, while suppliers are responsible for ensuring that the associated labelling, packaging and Safety Data Sheet information comply with the applicable legal requirements. Distributors must also fulfil the obligations applicable to their role in the supply chain. Where relevant and where the applicable conditions are fulfilled, CLP Notes or Oil Industry Notes may be taken into account. Hazards not covered by a harmonised classification must be assessed by the responsible duty holder and, where appropriate, addressed through self-classification.

A classification assigned to an individual substance or mixture should therefore not be automatically transferred to a finished maritime fuel without assessing its complete composition and applying the relevant CLP rules.

Before placing a maritime fuel on the EU market, the responsible suppliers should verify its classification against the latest applicable versions of:

- the CLP Regulation and its Adaptations to Technical Progress;
- Annex VI harmonised classification entries and applicable notes;
- ECHA Guidance on the Application of the CLP Criteria¹³;
- relevant REACH registration dossiers and supplier Safety Data Sheets;
- fuel-specific compositional and analytical information; and
- any other legislation or regulatory requirements applicable to the specific maritime fuel.

2.3.3.5. Compatibility with existing standards

The availability of relevant regulations for each fuel within **IMO SOLAS**¹⁴ (International Convention for the Safety of Life at Sea), **IMO MARPOL**¹⁵ (International Convention for the Prevention of Pollution from Ships), **external**

¹¹ EUR-Lex - 02008R1272-20260701 - EN - EUR-Lex

¹² www.concawe.eu

¹³ [ECHA Guidance on the Application of the CLP Criteria](https://echa.europa.eu/en/guidance-documents/guidance-on-the-application-of-the-clp-criteria)

¹⁴ <https://imorules.com/SOLAS.html>

¹⁵ <https://imorules.com/MARPOL.html>

standards (such as ISO), and **EN/ASTM standards** is assessed. The results are categorized on a scale of "no marine standards available" to "high regulatory readiness" and summarize and update the overview provided in [Green Voyage 2050, 2025], which entails more in-depth background information.

MARPOL governs the prevention of marine pollution from ships, while SOLAS sets international standards for ship safety and the protection of life at sea. ISO marine standards define globally harmonized specifications for marine fuel quality, testing, and handling, whereas EN and ASTM marine standards provide regional (European and American) benchmarks. MARPOL, e.g. does not forbid fuels specifically. For fuel blends, however, high biofuel shares, chemical tanker standards, segregation, etc. (Annex II, NSL) are required, which means that explicit risk approval would be required, effectively restricting co-activities. SOLAS does not explicitly forbid co-activities either. Fuels with flash points below 60 °C (e.g., methanol, ethanol, FAME-rich blends), however, fall under the International Code of Safety for Ships using gas (IGF Code)¹⁶, requiring additional safety measures for co-activities.

2.3.3.6. Maximum blending ratios

Maximum fuel blending ratios are defined in the recently updated ISO 8217 standard (ISO8217:2024). The availability and provision on blending ratios of the considered final fuels are summarised by the below categories:

- **‘Established’** fuels are those which are included in this ISO standard with defined blending ratio.
- **‘Unestablished’** fuels are those that have not been included in ISO standards and information on blend percentages is not given. For these fuels, there needs to be a planned sequence leading to recognition that the fuel product in question does not in itself represent a risk when used as a ‘drop-in’ fuel (i.e. can be used in existing machinery without adjustment).

Information on blending ratios is provided in ISO8217:2024 and [Lloyd’s Register 2024].

2.3.3.7. Storage conditions

The storage conditions of final fuels are provided by specifying the typical **storage temperatures** and **pressures** required.

2.3.3.8. GHG emission default values (tank-to-wake)

In its **Guidelines on Life Cycle GHG Intensity of Marine Fuels** [IMO 2024] (Annex 10), the International Maritime Organization provides default values for greenhouse gases such as CO₂, CH₄, and N₂O. These default values are provided for each fuel type (in g/MJ_{Final fuel}) and dependent on the propulsion technology (in g/kWh_{Mechanical work}).

2.3.4. Application

2.3.4.1. Possibility of co-activities

Co-activities are all supporting activities that occur alongside the main process of bunkering fuel. Whether co-activities are allowed at a port depends on the fuel’s properties, infrastructure preparation, and safety regulations (e.g., IGF Code). Several fuels are restricted due to toxicity, volatility, or incompatibility risks that

¹⁶ <https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx>

could lead to leaks, fire, or chemical reactions. For example, fuels with flash points below 60 °C (e.g., methanol, ethanol, FAME-rich blends) fall under the IGF Code, requiring additional safety measures for co-activities.

Based on relevant standards (see 2.3.3.5) and the categorization within the GHS framework, the status for co-bunkering activities is concluded.

2.3.4.2. Fuel consumption

The efficiency of the propulsion of different ship types is analysed using the values for the fuel consumption (in g of VLSFO equivalent per kWh of mechanical work (LHV)) for different ship types. Values of [Ramboll 2022] are applied, providing proxy values for different ship types considering the ship properties and the auxiliary energy demands of the ships.

2.3.4.3. Onboard carbon capture

Integrating systems for onboard carbon capture of engine emissions is a challenge for which different ship types are differently suited. The collected data lists the pros and cons per ship type for handling the integration of carbon capture components. Overall, carbon capture onboard a ship reduces the carbon emissions but increases the energy demand (i.e., additional fuel demand). Example projects are provided. Mainly based on [DNV 2024], [OGCI 2024], and [GCMD 2025].

2.3.4.4. Engine GHG emissions

CO₂ emissions depend on the carbon content of the fuel and the efficiency of the engine. CO₂ emitted from the combustion of renewable fuels is absorbed from the atmosphere e.g. during growth of the biomass in case of biofuels or via direct air capture (DAC) in case of renewable fuels of non-biological origin (RFNBO). Non-CO₂ engine GHG emissions consist of methane (CH₄) and nitrous oxides (N₂O). Table 15 shows the engine efficiency and the engine GHG emissions.

Table 15 Engine efficiency and engine emissions (GHG)

Fuel	Ship propulsion	Engine efficiency	CO ₂ g/kWh _{mech}	CH ₄ g/kWh _{mech}	N ₂ O g/kWh _{mech}	Source
VLSFO	Slow speed Diesel ICE	51.1%	548	0.009	0.031	[IMO 2021]
MDO	Slow speed Diesel ICE	51.1%	529	0.008	0.030	[IMO 2021]
FAME	Slow speed Diesel ICE	51.1%	537	0.009	0.034	[IMO 2021]
FAEE	Slow speed Diesel ICE	51.1%	527	0.009	0.033	[IMO 2021]
FAME residues	Slow speed Diesel ICE	51.1%	540	0.010	0.034	[IMO 2021]
Straight vegetable oil	Slow speed Diesel ICE	51.1%	540	0.010	0.034	[IMO 2021]
Paraffinic diesel incl. HVO	Slow speed Diesel ICE	51.1%	499	0.008	0.029	[IMO 2021]
Diesel (HTL), diesel (pyrolysis)	Slow speed Diesel ICE	51.1%	524	0.008	0.029	[IMO 2021]
CNSL	Slow speed Diesel ICE	51.1%	495	0.009	0.031	[IMO 2021]
Ethanol	2-stroke Diesel cycle dual fuel ICE	51.1%	503	0.0009*	0.0031*	[IMO 2021]
Methanol	2-stroke Diesel cycle dual fuel ICE	51.6%	481	0.0009*	0.0031*	[IMO 2021]

Fuel	Ship propulsion	Engine efficiency	CO ₂ g/kWh _{mech}	CH ₄ g/kWh _{mech}	N ₂ O g/kWh _{mech}	Source
Liquefied methane	Otto dual fuel medium speed	48.1%	412	4.64	0.016	[IMO 2021]
Liquefied methane	Otto dual fuel slow speed	50.7%	391	2.42	0.016	[IMO 2021]
Liquefied methane	2-stroke Diesel cycle dual fuel ICE	55.6%	356	0.26	0.014	[IMO 2021]
Liquefied methane	Lean-burn spark ignited (LBSI)	48.1%	412	3.89	0.016	[IMO 2021]
Ammonia	2-stroke Diesel cycle dual fuel ICE	48.8%	0	0	0.100	[Kanchiralla et al. 2023]; [IMO 2021]
Ammonia	Catalytic NH ₃ electrolysis + Fuel cell + electric motor	24.9%**	0	0	0	
LH ₂	Fuel cell (PEMFC) electric	54.5%	0	0	0	[Kanchiralla et al. 2023]
Electricity	Battery electric	85.5%	0	0	0	[McKinlay et al. 2024]

*CH₄ and N₂O emissions amount to about 10% of those of VLSFO [IMO 2021]

**Ammonia (NH₃) is split on board of the ship via electrolysis. The ammonia consumption is derived from the chemical reaction (2 NH₃ → N₂ + 3 H₂) leading to about 5.632 kg of NH₃ per kg of H₂. The electricity consumption for NH₃ electrolysis amounts to 9.7 kWh per kg of H₂ [Barbar & Botte 2024]. The H₂ is converted to electricity in a fuel cell power plant with an efficiency of 52% including all auxiliaries [McKinlay et al. 2024]. A part of electricity generated by the fuel cell is required for NH₃ electrolysis. The efficiency of the electric motor is assumed to be 95%.

2.3.4.5. Pollutant emission limits (NO_x and SO_x)

For emissions during use, the IMO has established pollutant emission limits (Tier III limits) differentiated by engine speed class in IMO Regulation 13 for NO_x, and IMO Regulation 14 for SO₂ of [IMO 2021] (Table 16).

Table 16 Engine emissions (NO_x)

Fuel	Ship propulsion	TIER III NO _x g/kWh _{mech}	Comment
VLSFO, MDO	Slow speed Diesel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
FAME, FAEE, straight vegetable oil	Slow speed Diesel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
FAME residues	Slow speed Diesel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
Paraffinic diesel incl. HVO	Slow speed Diesel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
Diesel (HTL), diesel (pyrolysis)	Slow speed Diesel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
CNSL	Slow speed Diesel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
Ethanol, Methanol	2-stroke Diesel cycle dual fuel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)

Fuel	Ship propulsion	TIER III NO _x g/kWh _{mech}	Comment
Liquefied methane	Otto dual fuel medium speed	2.41	IMO regulation 13: NO _x emission limits for an engine speed of 720 rounds per minute (rpm) as an example for a medium speed Otto engine
Liquefied methane	Otto dual fuel slow speed	3.40	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
Liquefied methane	2-stroke Diesel cycle dual fuel ICE	3.40	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
Liquefied methane	Lean-burn spark ignited (LBSI)	2.08	According to IMO regulation 13 for an engine speed of 130 to 1999 rounds per minute (rpm), the maximum allowable NO _x emissions are calculated by $E_{NOx} = 9 \cdot n^{(-0.2)}$ n = speed in rounds per min (rpm). (4-stroke) lean burn spark ignition (LBSI) engines are designed for medium (130-1999 rpm) and high (2000 rpm and above) speed [SINTEF 2017]. Medium speed 4-stroke LBSI are typically used for liquefied methane fueled ro-ro vessels. As an example, a LBSI engine with a speed of 1500 rpm has been selected
Ammonia	2-stroke Diesel cycle dual fuel ICE	3.4	IMO regulation 13: NO _x emission limits for engine speed of <130 rounds per minute (rpm)
Ammonia	Catalytic NH ₃ electrolysis + Fuel cell + electric motor	0	
LH ₂	Fuel cell (PEMFC) electric	0	
Electricity	Battery electric	0	

The SO₂ emissions depend on the sulfur content of the fuels and the engine efficiency. According to IMO regulation 14 inside emission control areas (ECA) the maximum sulfur content is 0.1% m/m since 2015. Outside ECA the maximum sulfur content is 0.5% m/m since 2020.

2.3.4.6. Refuelling duration

The refuelling or bunkering duration of maritime fuel differs between fuels. Alternative maritime fuels can be classified, depending on their refuelling times, into the following three types:

1. **liquid hydrocarbons:** refuelling times similar to diesel-type fuels
2. **liquefied gaseous fuels:** may achieve similar bunkering performance as liquid hydrocarbons, but with additional efforts
3. **Electricity:** refuelling time partly depending on the capacity of the charger. Charging time: 4-6 h

2.3.4.7. Range, suitability of operations and customer acceptance

Priorities concerning desirable technical fuel properties differ across commercial ship types. The relative **importance of each fuel attribute across vessel categories** is rated as “highly important”, “important” and “less important”. For example, a fuel having low toxicity and health risks is especially important for RoPax/Passenger ferries due to higher numbers of passengers that would be affected from a fuel safety incident. The technical fuel attributes assessed include:

- **Range:** Container ships transport more expensive cargo than e.g. bulk carriers. Substituting cargo space for fuel space comes with higher opportunity costs. RoPax/Passenger ferries typically travel shorter distances between destinations and have been among the first vessel segments to adopt fuels with lower energy density.
- **Fuel safety (flammability + combustibility):** The damage potential from a fuel safety incident is higher for RoPax/Passenger ferries with higher numbers of affected passengers. A fuel safety incident on a chemical tanker could lead to a chain reaction, affecting the fuel cargo. The damage potential from affecting the cargo of bulk carriers is far lower.
- **Toxicity and health:** Generally, health and safety are very relevant both for crew and passengers. For passenger ships release of toxic substances has more impact because large numbers of passengers are difficult to reliably equip with personal protective equipment (gasmask).
- **Refueling duration:** The deep-sea container shipping industry is very volatile and highly competitive, resulting in tight control of costs and the preservation of sailing schedules.
- **Environmental impact:** Some passenger ship operators show higher environmental awareness and prefer vessels with better environmental performance to allow for a higher willingness to pay in passengers. Cargo ship operators need to consider the customer acceptance as well [del Saz-Salazar & Tovar 2024].

2.3.5. GHG emissions

The GHG emissions of all fuel pathways are calculated **according to FuelEU Maritime**, adding data from EU RED, IMO and GREET where necessary. The life cycle **scopes** include well-to-tank (WtT), tank-to wake (TtW) and well-to-wake (WtW), with

$$GHG_{WtW} = f_{wind} * (GHG_{WtT} + GHG_{TtW})$$

Where

f_{wind} : Reward factor for wind-assisted propulsion (note that f_{wind} is not considered in this study)

FuelEU Maritime (Regulation (EU) 2023/1805) requires using **GWP 100** according to the IPCC Assessment Report 4 (AR4):

- CO₂: 1 g CO₂eq/g
- CH₄: 25 g CO₂eq/g
- N₂O: 298 g CO₂eq/g

Emission allocation is based on energy (by-products such as oilseed cake or DDGS) and exergy (heat export). According to this methodology, **capex-related (grey) emissions**¹⁷ are not considered. **CH₄ savings from avoided wet manure storage are considered.**

¹⁷ 'CAPEX-related', 'grey', or 'embedded' emissions are those emissions attributed with the manufacturing (incl. upstream production of materials and components thereof) of e.g. the solar panels, wind power plants, or other factories/production facilities.

Data for energy inputs and GHG emissions of different processes and agricultural practices have been derived from various literature sources and datasheets by technology providers (see references of respective pathways directly).

3. POWER BI DASHBOARD

3.1. STRUCTURE OF THE POWER BI DASHBOARD

3.1.1. General

The Shipfuels Matrix comprises 46 feedstocks, 33 processes, 17 final fuels and 8 propulsion systems, providing representative coverage of a wide range of maritime fuel pathways. It consists of separate tabs with different foci, namely:

- **Intro:** Background and Objective of the Shipfuels Matrix
- **User Guide:** Detailed description on how to use the Shipfuels Matrix Dashboard
- **Pathways:** Overview of KPIs regarding different maritime fuel pathways (incl. GHG emissions, energy flows, pathway TRLs and efficiencies) with the option of in-depth information for a single selected pathway.
- **Feedstocks:** Information about various feedstocks for maritime fuel production
- **Conversions:** Information about various conversion processes for maritime fuel production
- **Final Fuels:** Information about various maritime fuels
- **Applications** Application of different maritime fuels in various ship and engine types
- **Background Information:** Assumptions and background information
- **References:** Literature sources used

By default, all data is shown. On each page, filter settings can be applied which then apply to all other pages.

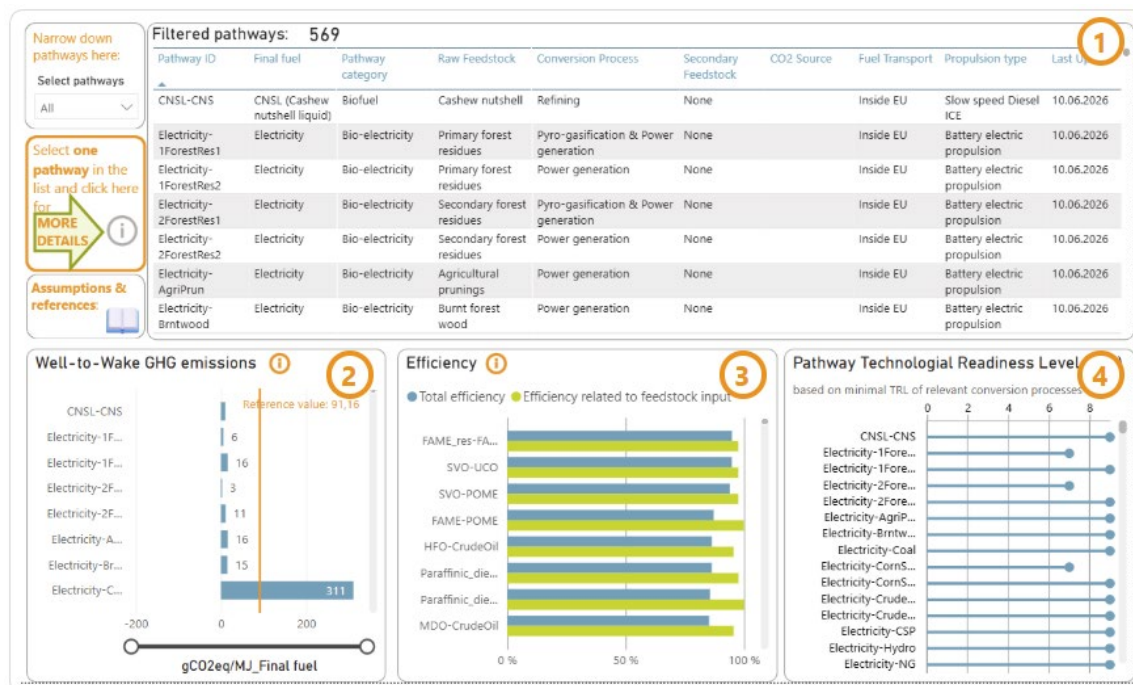
For example, pathways can be filtered via final fuels, feedstock inputs, conversion processes and others. When applying filter settings in one slicer, the other slicers then show only eligible options corresponding to the pathways list.

3.1.2. Pathways page

This page is using information from the dataset **PATHWAYS**. It provides an overview of KPIs regarding different maritime fuel pathways, including:

1. Pathway Description Table (incl. Feedstocks, Conversion Processes, Final Fuel, Application)
2. GHG Emissions
3. Efficiency
4. Pathway TRL

Figure 2 Basic structure of the Pathways page



You can also filter one or more specific pathways with the additional filter "Further select Pathways here" on the top left to compare these selected pathways.

For more detailed information (see Figure 3), select one pathway and click on the info button on the top left. This page is using information from the datasets **PATHWAYS**, **ENERGY FLOW** and **Pathway diagram**. It gives an overview of KPIs (key performance indicators) regarding different maritime fuel pathways, including:

1. Selected Pathway Description Table
2. Pathway Visualisation
3. KPIs
4. Energy Flow Diagram
5. GHG Emissions (split into process steps)

Basic structure of the deep-dive information page for a selected pathway

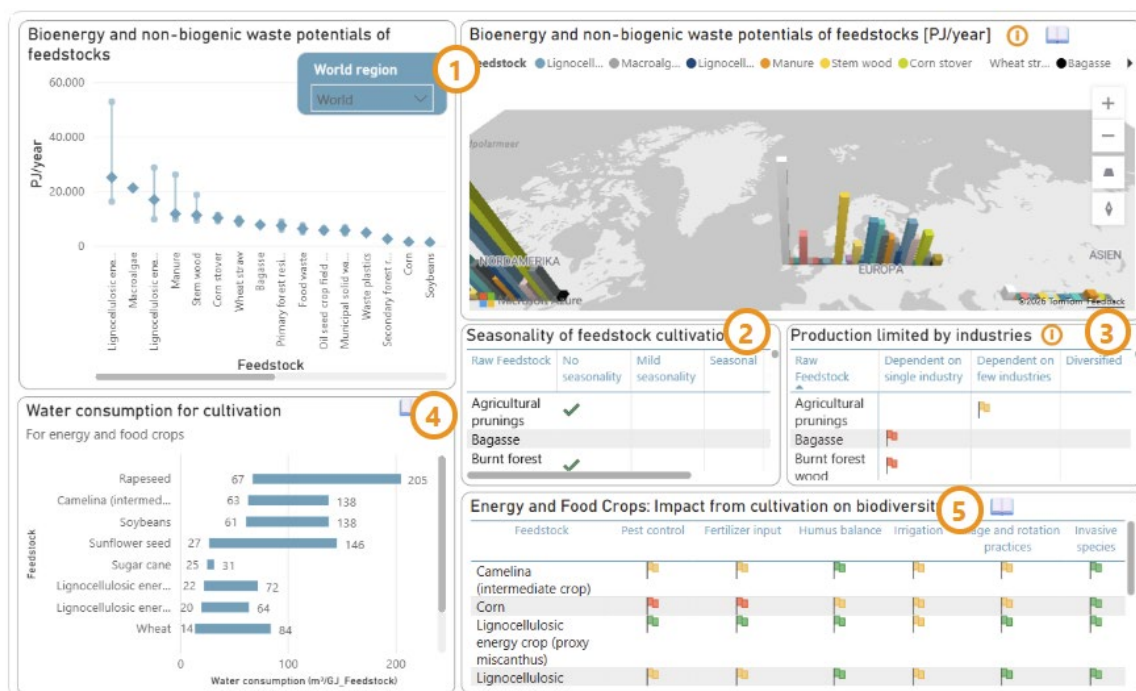


3.1.3. Feedstocks page

This page shows all visuals related to feedstocks, independent of pathways. It uses inputs from the datasets **Feedstocks** and **Feedstocks_bioenergy_potentials**. Detailed information about various feedstocks for maritime fuel production are shown, including:

1. Global Bioenergy Potentials
1. Seasonality of feedstock cultivation
2. Production limited by industries
3. Water consumption for cultivation
4. Impact on biodiversity from energy and food crop cultivation

Figure 4 Basic structure of the Feedstock page



3.1.4. Conversions page

This page shows all visuals related to conversion processes, independent of pathways, using inputs from the **Conversion** and **Conversions_large plant** datasets. It contains detailed information about various conversion processes for maritime fuel production, including:

1. State of technology development
2. Conversion Process options for the production of Final Fuels
3. Technological Readiness Level (TRL) of different conversion processes

Figure 5 Basic structure of the Conversion page



3.1.5. Final fuels page

All visuals related to final fuels, independent of pathways are shown on this page, using inputs from the **Final Fuels** and **Final Fuels x Propulsion** dataset. It covers detailed information about various maritime fuels:

1. Energy density
2. GHG emission default values (tank-to-wake)
3. Storage conditions
4. Maximum blending ratios
5. Regulatory readiness

Figure 6 Basic structure of the Final fuels page

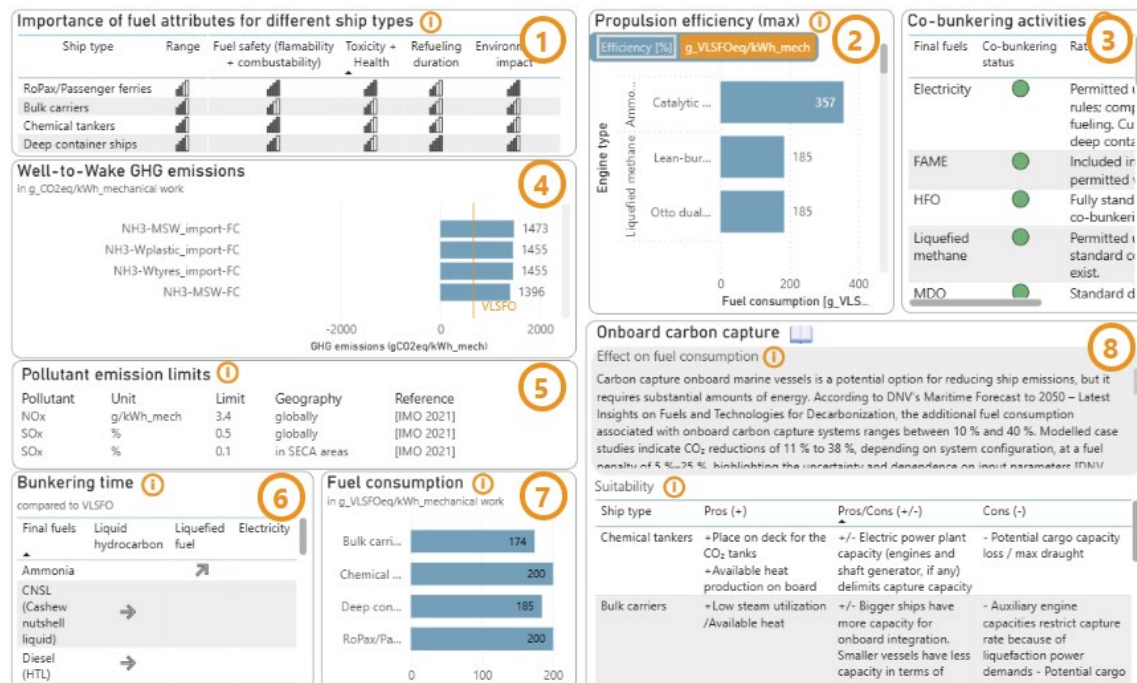


3.1.6. Applications page

All visuals related to final fuels and applications, i.e. ship and engine types, independent of pathways, are shown on this page using inputs from the **Final Fuels** and **Applications** dataset.

1. Importance of fuel attributes for different ship types
2. Propulsion efficiency
3. Co-bunkering activities
4. Well-to-Wake GHG emissions
5. Pollutant emission limits
6. Bunkering time compared to VLSFO
7. Fuel consumption of different fuel types
8. Pros and Cons of onboard carbon capture

Figure 7 Basic structure of the Application page



3.1.7. Background information and References

The page “Background information” shows all information related to all process steps regarding one pathway and is using inputs from the **PATHWAYS** dataset. To show all assumptions and background information, select one pathway from the pathway table above. Then, information clustered in the different process steps including the references used is displayed.

The page “References” shows a list of all sources used to gather all information shown in the database.

Figure 8 Overview of Background information for a selected pathway

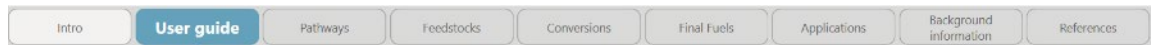
Filtered pathways									
Select one pathway for further details									
Pathway ID	Final fuel	Pathway category	Raw Feedstock	Secondary Feedstock	CO2 Source	Conversion 1	Conversion 2	Conversion 3	Propulsion ty
							methane reforming)	synthesis	electrolysis + + electric mo
NH3-Biofuel-6-EU_a	Ammonia	Biofuel	Food waste	None		Aerobic digestion	SMR (Steam methane reforming)	Haber-Bosch synthesis	2-stroke dies dual fuel ICE
NH3-Biofuel-6-EU_b	Ammonia	Biofuel	Food waste	None		Aerobic digestion	SMR (Steam methane reforming)	Haber-Bosch synthesis	Catalytic NH3 electrolysis + + electric mo
NH3-Biofuel-6-imp_a	Ammonia	Biofuel	Food waste	None		Aerobic digestion	SMR (Steam methane reforming)	Haber-Bosch synthesis	2-stroke dies dual fuel ICE
NH3-Biofuel-6-imp_b	Ammonia	Biofuel	Food waste	None		Aerobic digestion	SMR (Steam methane reforming)	Haber-Bosch synthesis	Catalytic NH3 electrolysis + + electric mo
NH3-Biofuel-7-EU_a	Ammonia	Biofuel	Sewage sludge	None		Aerobic digestion	SMR (Steam methane reforming)	Haber-Bosch synthesis	2-stroke dies dual fuel ICE

Feedstock Supply - Transport via truck: 20 km as in [Giuntoli et al. 2017]	[Giuntoli et al. 2017] Reference: Feedstock supply
Conversion 1 - Waste is converted to biogas via anaerobic digestion - Input and output data from [Giuntoli et al. 2017] (same data as in [JEC 2020]) - Heat for fermenter supplied by biogas - Electricity: EU electricity mix (10-20 kV; 110 gCO2eq/MJ according to [JEC 2020])	[Giuntoli et al. 2017], [JEC 2020] Reference: Conversion 1
Conversion 2 - Biogas to hydrogen via steam methane reforming (SMR) - Input and output data based on smaller SMR plant (560 Nm³ hydrogen/h) derived from [JEC 2020] - In contrast to [JEC 2020], biogas (mix of CH4 and CO2) is directly fed into SMR without upstream biogas upgrading	JEC 2020 Reference: Conversion 2
Conversion 3 - 178 kg_H2/t_ammonia [Dechema 2017] - Electricity consumption: 2.16 MJ/kg_ammonia (= 0.1162 MJ/MJ_ammonia; LHV_ ammonia =18.59 MJ/kg)	DECHEMA 2017, Sphera 2024 Reference: Conversion 3
Fuel Transport - Same assumptions as for the import of LNG in [JEC 2020] - Import via refrigerated LPG carriers to EU: 4000 nautical miles (7408 km) incl. return voyage (empty) - Payload: 50,000 t of NH3 [ICI 2018] and [Adland et al. 2020] - Speed: 14 knots - Electricity consumption import terminal from [Fraunhofer ISI 2022] incl. electricity for boil-off gas management - Transport from import terminal to dispensing site: 10 km.	[Adland et al. 2020], [Fraunhofer ISI 2022], [ICE 2018], [JEC 2020] Reference: Fuel Transport
Fuel Use Ammonia (NH3) is split on-board of the ship via electrolysis. The ammonia consumption is derived from the chemical reaction (2 NH3 => N2 + 3 H2) leading to a bout 5.632 kg of NH3 per kg of H2. The electricity consumption for NH3 electrolysis amounts to 9.7 kWh per kg of H2 [Barbar & Botte 2024]. The H2 is converted to electricity in a fuel cell power plant with an efficiency of 52% including all auxiliaries [McKinlay et al. 2024]. A part of electricity generated by the fuel cell is required for NH3 electrolysis. The efficiency of the electric motor is assumed to be 95%.	[Barbar & Botte 2024], [McKinlay et al. 2024] Reference: Fuel use

3.2. NAVIGATION AND FILTERING OF THE POWER BI DASHBOARD

3.2.1. Navigation

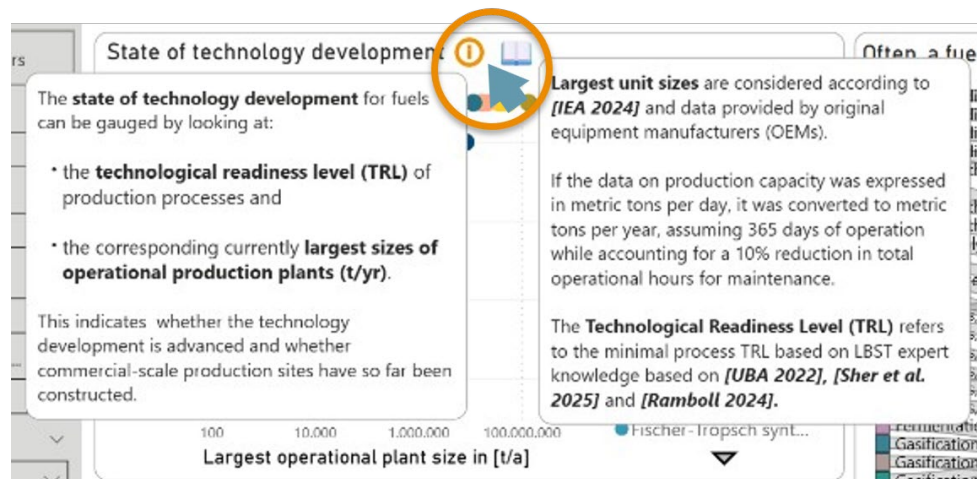
Navigate through the tool using the Buttons on the top. The page you are currently viewing will be highlighted in colour.



3.2.2. Navigation around visuals

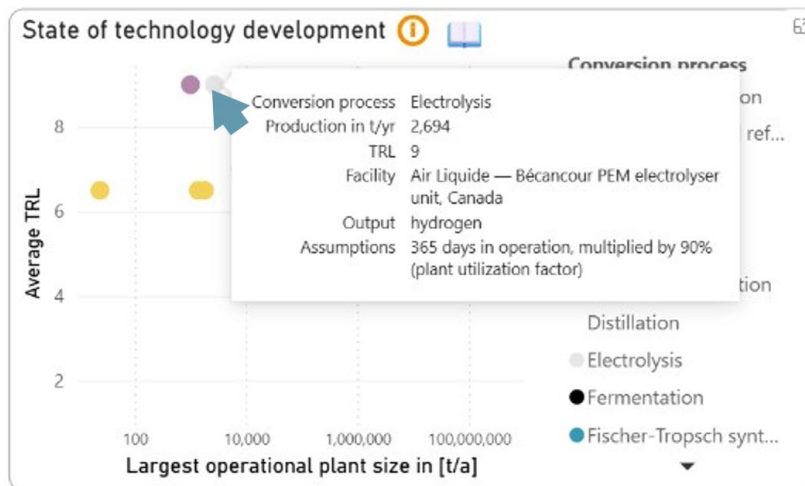
Click on  to display more information on the data shown. Click on  for relevant references used, and assumptions and calculation details. Click on the symbols again to hide the info boxes again.

Figure 9 Navigation around visuals: More information and references



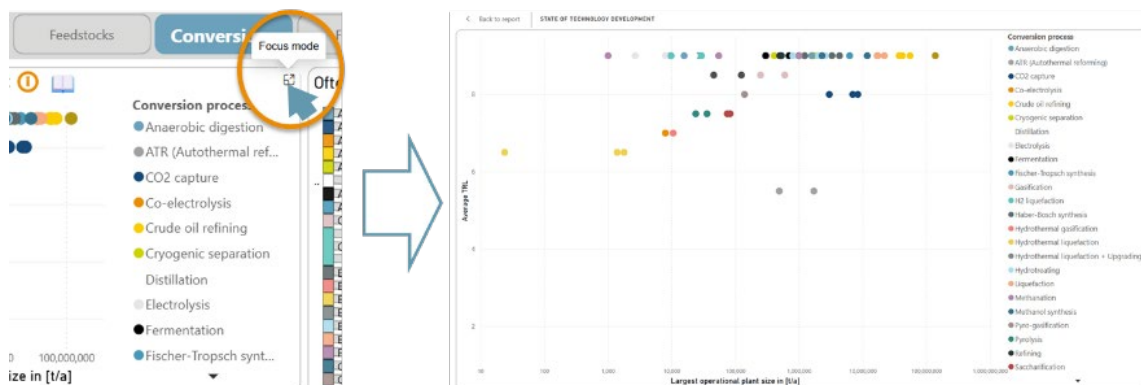
Hover over the data points to display the underlying data, assumptions and references.

Figure 10 Navigation around visuals: Display underlying data



Click on the "Focus mode" symbol when hovering over a visual to expand it to full screen.

Figure 11 Navigation around visuals: Focus mode



3.2.3. Filtering

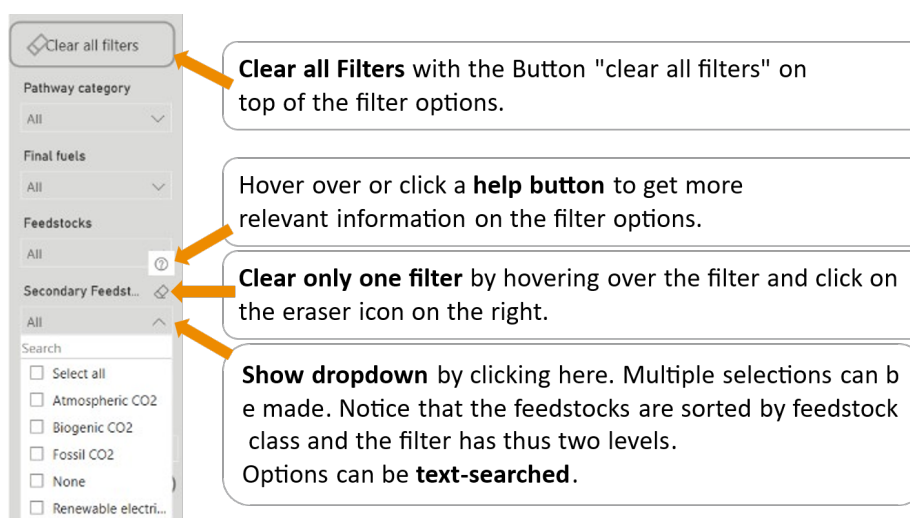
Filter information using the filter options on the left of each dashboard page. The filter selection is applied across all tabs. You can filter by:

1. **Pathway category** - Biofuels vs. e-fuels vs. direct electrification vs. fossil fuels w/ CCS vs. fossil fuels vs. hybrid fuels
2. **Final fuel**
3. **Feedstocks** - raw primary feedstock input sorted by feedstock class
4. **Secondary feedstocks** - CO₂ feedstocks and renewable electricity for e-BTL pathways
5. **Conversion process** - single processes
6. **Pathway TRL** - defined by minimal TRL of included processes per pathway
7. **Import vs. Inside EU** of fuel transport
8. **Propulsion type** - depending on final fuel used
9. **Ship type** - relevant for the applications tab

The filter options available are according to the shipfuels pathways considered in this dashboard.

Applying a selection in one filter narrows down the pathway options and thus affects the available options in the other filters accordingly.

Figure 12 Overview of filters and how to use them



4. MERIT COMPARISON OF PATHWAYS

This section presents the results of the comparative analysis of alternative maritime fuel pathways using the Shipfuels Matrix. The results are structured along key performance indicators, including well-to-wake (WtW) greenhouse gas emissions, process efficiency, feedstock availability, technology maturity, fuel and application characteristics. The analysis highlights both the range of performance across pathways and the key drivers influencing outcomes.

4.1. WELL-TO-WAKE GHG EMISSIONS COMPARISON OF PATHWAYS

4.1.1. Fossil fuel pathways

To provide context for interpreting the results, Table 17 presents well-to-wake (WtW) GHG emissions for selected fossil fuel pathways.

Table 17 Well-to-wake GHG emissions of selected fossil fuel pathways

Final fuel	Total GHG emissions (gCO _{2eq} /MJ _{Final fuel})
VLSFO	94.3
HFO	91.6
MDO	90.6
Ammonia - From natural gas	117
Liquefied hydrogen - From natural gas	128.1 [JEC 2020]
Methanol - From natural gas	93.5-110
Paraffinic diesel - From natural gas - From coal	94.0 [JEC 2020] 201.1 [JEC 2020]
Electricity - From coal - From natural gas	310.9 144.4

A reference value of 91.16 gCO_{2eq}/MJ is used throughout this report, corresponding to the average GHG intensity of the energy used on board ships in 2020, as determined under the FuelEU Maritime Regulation¹⁸.

4.1.2. Pathways above reference value

A subset of pathways exceeds the reference value illustrating that not all alternative fuel pathways deliver GHG reductions and highlighting the importance of both feedstock and conversion pathway selection. Pathways exceeding the reference value are primarily driven by energy-intensive conversion processes and the use of fossil-based or carbon-intensive inputs.

¹⁸ Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC

Table 18 Pathways above reference value

Final fuel	Conversion process	Feedstock	Total GHG emissions (gCO _{2eq} /MJ _{Final fuel})
Liquid H ₂	Gasification, H ₂ liquefaction	Municipal solid waste, waste tyres, waste plastics	99.2-100.7
Ammonia	Gasification, Haber-Bosch synthesis	Municipal solid waste, waste tyres, waste plastic	95.4-100.7 (depending on engine)
Liquefied methane	Gasification & Methanation, Liquefaction	Municipal solid waste, waste tyres, waste plastics	92.6-96.3 (depending on engine)
Diesel (pyrolysis)	Pyrolysis & upgrading	Waste plastics	110.7

4.1.3. Pathways with low GHG emissions

While the Shipfuels Matrix provides results for the full set of pathways, this section focuses on pathways achieving substantial GHG reductions relative to the reference value of 91.16 gCO_{2eq}/MJ. To facilitate interpretation, pathways have been categorised according to their level of GHG reduction relative to this reference value as follows:

1. Pathways with GHG reduction of 70-80% (equivalent to 18.2 to 27.3 gCO_{2eq}/MJ)
2. Pathways with GHG reduction of 80-85% (equivalent to 13.7 to 18.2 gCO_{2eq}/MJ)
3. Pathways with GHG reduction of 85-90% (equivalent to 9.1 to 13.7 gCO_{2eq}/MJ)
4. Pathways with GHG reduction of more than 90% (equivalent to less than 9.1 gCO_{2eq}/MJ)

4.1.3.1. Pathways with GHG reduction of 70-80%

This category is characterised by pathways based primarily on residual and waste biomass feedstocks. These pathways demonstrate significant GHG reductions while maintaining relatively mature conversion technologies. Biomass such as wood chips plays an important role, acting as a versatile feedstock across multiple conversion processes (e.g. gasification, pyrolysis, hydrothermal liquefaction).

Table 19 Pathways with GHG reduction of 70-80%

Final fuel	Conversion process	Feedstock	Total GHG emissions (gCO _{2eq} /MJ _{Final fuel})
Ammonia	AD, SMR, Haber-Bosch synthesis	Vegetable waste, residues from FAME production, food waste	25.8-27.1 (Catalytic NH ₃ electrolysis + Fuel cell + electric motor)
Ammonia	Gasification, Haber-Bosch synthesis	Bagasse pellets, cashew nutshell, corn stover, miscanthus chaff bales, oil seed crop field residues, wheat straw, wood chips	23.1-27.1 (Catalytic NH ₃ electrolysis + Fuel cell + electric motor or 2-stroke Diesel cycle dual fuel ICE)
Diesel (HTL)	HTL & upgrading	Wood chips	23.5-25.0
Diesel (Pyrolysis)	Pyrolysis & upgrading	Wood chips	19.9-24.7
Electricity	Power generation	Wood chips	26.2
Ethanol	Fermentation & Distillation	Sugar beet	20.4
Ethanol	Saccharification & Fermentation & Distillation	Wood chips, bagasse	20.3-24.8
Liquid H ₂	Electrolysis, H ₂ liquefaction	Renewable electricity, water	26.3 (of which 25.5 attributed to liquefaction step)
Liquefied methane	AD, Cryogenic separation	Sewage sludge, residues from FAME production, vegetable waste, food waste	22.4-25.6 (2-stroke Diesel cycle dual fuel ICE)
Liquefied methane	Electrolysis, CO ₂ capture & Methanation, Liquefaction	Nuclear electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	22.8-23.3 (Otto dual fuel, medium speed)
Liquefied methane	Electrolysis, CO ₂ capture & Methanation, Liquefaction	Nuclear electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	20.3-20.8 (Lean-burn spark ignited engine)
Liquefied methane	Gasification & Methanation, Liquefaction	Wood chips, cashew nutshell, corn stover, oil seed crop field residues, wheat straw, miscanthus chaff bales, bagasse pellets	19.4-26.9 (2-stroke Diesel cycle dual fuel ICE or Otto dual fuel, slow speed or Lean-burn spark)
Liquefied methane	Hydrothermal gasification & methanation, CH ₄ liquefaction	Food waste, vegetable waste	20.4-22.9 (Otto dual fuel, medium speed or Lean-burn spark ignited)
Liquefied methane	Pyro-gasification & Methanation, Liquefaction	Miscanthus chaff bales, wood chips	21.1-25.9 (Otto dual fuel, slow speed or 2-stroke Diesel cycle dual fuel ICE)
Methanol	AD, SMR (Steam methane reforming) & Methanol synthesis	Sewage sludge, food waste, vegetable waste, residues from FAME production	21.5-26.6
Straight vegetable oil	Refining	Camelina	27.0

4.1.3.2. Pathways with GHG reduction of 80-85%

Compared to the previous category, these pathways reflect incremental improvements in lower GHG emission feedstock and process efficiency, supported by increased use of low-carbon energy inputs.

Table 20 Pathways with GHG reduction of 80-85%

Final fuel	Conversion process	Feedstock	Total GHG emissions (gCO _{2eq} /MJ _{Final fuel})
Diesel (HTL)	HTL & upgrading	Corn stover, oil seed crop field residues, wheat straw	15.6
Diesel (Pyrolysis)	Pyrolysis & upgrading	Wood chips, cashew nutshell	17.2-18.2
Electricity	Power generation	Wood chips	14.9-15.7
FAME	Transesterification	Cashew nutshell, tallow oil, palm oil mill effluent (POME)	15.1-17.4
Liquefied methane	Electrolysis, CO ₂ capture & Methanation, Liquefaction	Renewable electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	16.5 (Otto dual fuel, medium speed)
Liquefied methane	Electrolysis, CO ₂ capture & Methanation, Liquefaction	Nuclear electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	15.8-16.3 (Otto dual fuel, slow speed)
Liquefied methane	Gasification & Methanation, Liquefaction	Cashew nutshell	15.8 (2-stroke Diesel cycle dual fuel ICE)
Liquefied methane	Hydrothermal gasification & methanation, CH ₄ liquefaction	Food waste, vegetable waste	15.9 (Otto dual fuel, slow speed)
Liquefied methane	Pyro-gasification & Methanation, Liquefaction	Miscanthus chaff bales, wood chips	16.5-18.0 (2-stroke Diesel cycle dual fuel ICE)
Paraffinic diesel (e.g. HVO)	Hydrotreating	Cashew nutshell liquid (CNSL), tallow oil	16.4-16.9

4.1.3.3. Pathways with GHG reduction of 85-90%

This category reflects further optimisation in both feedstock selection and energy sourcing. Pathways combine biogenic or waste feedstocks with low-carbon energy inputs, enabling deeper emission reductions. Synthetic fuel processes based on electrolysis and carbon capture also begin to play a more prominent role. The results indicate that high GHG reductions can be achieved through multiple pathways, provided that both the energy input and carbon source are decarbonised.

Table 21 Pathways with GHG reduction of 85-90%

Final fuel	Conversion process	Feedstock	Total GHG emissions (gCO _{2eq} /MJ _{Final fuel})
Ammonia	Electrolysis, Haber-Bosch synthesis	Nuclear electricity, water	10.4 (2-stroke Diesel cycle dual fuel ICE)
CNSL (Cashew nutshell liquid)	Refining	Cashew nutshell	9.9
Electricity	Power generation	Wood chips, corn stover, oil seed crop field residues, wheat straw	10.9-13.3
Electricity	Pyro-gasification & Power generation	Wood chips	12.9
Ethanol	Saccharification & Fermentation & Distillation	Wheat straw, oil seed crop field residues, corn stover	11.1-11.2
FAME/FAEE	Transesterification	Cashew nutshell, used cooking oil	10.1-13.7
Liquefied methane	Electrolysis, CO ₂ capture & Methanation, Liquefaction	Renewable electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	9.5 (Otto dual fuel, slow speed)
Methanol	Gasification & Methanol synthesis	Wood chips	12.1
Paraffinic diesel (e.g. HVO)	Electrolysis, CO ₂ capture & Methanol synthesis, Methanol-to-diesel (MTD) process	Nuclear electricity, water, CO ₂ source (atmospheric)	9.7
Paraffinic diesel (e.g. HVO)	Electrolysis, CO ₂ capture & Reverse water gas shift (RWGS) & Fischer-Tropsch synthesis	Nuclear electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	9.6-10.4
Paraffinic diesel (e.g. HVO)	Gasification & Fischer-Tropsch synthesis	Wood chips	12.0
Paraffinic diesel (e.g. HVO)	Hydrotreating	POME, used cooking oil	13.0

4.1.3.4. Pathways with GHG reduction of more than 90%

Pathways achieving more than 90% GHG reduction are predominantly characterised by the use of renewable electricity and nuclear power. Electrolysis-based pathways, in combination with CO₂ capture and synthesis processes, enable the production of low-carbon fuels such as e-methanol, e-ammonia and synthetic hydrocarbons.

Table 22 Pathways with GHG reduction of more than 90%

Final fuel	Conversion process	Feedstock	Total GHG emissions (gCO _{2eq} /MJ _{Final fuel})
Ammonia	Electrolysis, Haber-Bosch synthesis	Nuclear electricity, water	6.3 (Catalytic NH ₃ electrolysis + Fuel cell + electric motor)
Ammonia	Electrolysis, Haber-Bosch synthesis	Renewable electricity, water	4.2* (2-stroke Diesel cycle dual fuel ICE)
Ammonia	Electrolysis, Haber-Bosch synthesis	Renewable electricity, water	0.2 (Catalytic NH ₃ electrolysis + Fuel cell + electric motor)
Ammonia	AD, SMR, Haber-Bosch synthesis	Manure	-206.2 (2-stroke Diesel cycle dual fuel ICE)
Ammonia	AD, SMR, Haber-Bosch synthesis	Manure	-210.3 (Catalytic NH ₃ electrolysis + Fuel cell + electric motor)
Electricity	Hydrothermal gasification & Power generation	Sewage sludge	0.3
Electricity	Power generation	Nuclear electricity	4.4
Electricity	Power generation	Renewable electricity (PV, CSP, wind onshore, wind offshore, hydro)	0
Electricity	Pyro-gasification & Power generation	Wood chips, wheat straw, oil seed crop field residues, corn stover	2.5-5.8
FAEE	Transesterification	POME, used cooking oil	5.8-7.8
FAME residues	Refining	FAME residues	3.2
Liquefied H ₂	AD, SMR, H ₂ liquefaction	Manure	-126.8 (Fuel cell)
Liquefied methane	Electrolysis, CO ₂ capture & Methanation, Liquefaction	Nuclear electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	8.3-8.8 (2-stroke Diesel cycle dual fuel ICE)
Liquefied methane	Electrolysis, CO ₂ capture & Methanation, Liquefaction	Renewable electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	2.0 (2-stroke Diesel cycle dual fuel ICE)
Liquefied methane	Hydrothermal gasification & methanation, CH ₄ liquefaction	Food waste, vegetable waste	8.4 (2-stroke Diesel cycle dual fuel ICE)
Liquefied methane	AD, Cryogenic separation	Manure	-86.4 (2-stroke Diesel cycle dual fuel ICE)
Methanol	Electrolysis, CO ₂ capture & Methanol synthesis	Nuclear electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	7.8-8.6 (2-stroke Diesel cycle dual fuel ICE)
Methanol	Electrolysis, CO ₂ capture & Methanol synthesis	Renewable electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	1.7 (2-stroke Diesel cycle dual fuel ICE)

Final fuel	Conversion process	Feedstock	Total GHG emissions (gCO _{2eq} /MJ _{Final fuel})
Methanol	Gasification & Methanol synthesis	Bagasse, lignocellulosic energy crop (proxy miscanthus), corn stover, oil seed crop field residues, wheat straw, cashew nutshell, wood chips	4.2-8.8
Methanol	AD, SMR & Methanol synthesis	Manure	-136.5 (2-stroke Diesel cycle dual fuel ICE)
Paraffinic diesel (e.g. HVO)	Co-electrolysis, CO ₂ capture & Reverse water gas shift (RWGS) & Fischer-Tropsch synthesis	Nuclear electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	8.5-9.0
Paraffinic diesel (e.g. HVO)	Co-electrolysis, CO ₂ capture & Reverse water gas shift (RWGS) & Fischer-Tropsch synthesis	Renewable electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	2.3
Paraffinic diesel (e.g. HVO)	Electrolysis, CO ₂ capture & Methanol synthesis, Methanol-to-diesel (MTD) process	Nuclear electricity, water, CO ₂ source (fossil, or biogenic)	8.9-9.1
Paraffinic diesel (e.g. HVO)	Electrolysis, CO ₂ capture & Methanol synthesis, Methanol-to-diesel (MTD) process	Renewable electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	2.3
Paraffinic diesel (e.g. HVO)	Electrolysis, CO ₂ capture & Reverse water gas shift (RWGS) & Fischer-Tropsch synthesis	Renewable electricity, water, CO ₂ source (atmospheric, fossil, or biogenic)	2.3
Paraffinic diesel (e.g. HVO)	Gasification & Electrolysis & Fischer-Tropsch synthesis	Corn stover, oil seed crop field residues, wheat straw, cashew nutshell, wood chips, water	2.6-8.0
Paraffinic diesel (e.g. HVO)	Gasification & Fischer-Tropsch synthesis	Bagasse, lignocellulosic energy crop (proxy miscanthus), corn stover, oil seed crop field residues, wheat straw, cashew nutshell, wood chips	2.8-8.8
Straight vegetable oil	Refining	POME, tallow oil, used cooking oil	3.9-8.0

*Attributed to higher N₂O emissions during combustion

4.2. TOTAL PROCESS EFFICIENCY AND FEEDSTOCK EFFICIENCY

In addition to GHG performance, the overall efficiency of fuel pathways is a key metric influencing energy demand and resource utilisation. Two efficiency metrics are considered in the Shipfuels Matrix. Total process efficiency reflects the conversion of all energy inputs into useful energy outputs and is calculated as the sum of the energy content of the main product and any by-products divided by the sum of the energy content of the feedstock and external energy inputs. In contrast, efficiency related to feedstock input reflects the conversion of feedstock energy into the main product and is calculated as the energy content of the main product divided by the energy content of the feedstock.

The efficiency analysis highlights significant variation across pathways. Thermochemical pathways generally exhibit moderate efficiencies, while electro-based pathways display a wider range due to the energy intensity of hydrogen production and subsequent processing steps. Higher efficiencies are typically observed for direct processing technologies, whereas multi-step synthetic pathways incur greater conversion losses. In particular, conversion efficiency in power generation varies significantly depending on the feedstock. Renewable power generation systems can achieve efficiencies of over 80%, whereas fossil fuel-based systems typically range between 33% and 48%, and nuclear power around 27%. In comparison, biomass-to-power pathways generally achieve efficiencies of approximately 25%.

The results also indicate that efficiency related to feedstock input can differ significantly from total process efficiency, highlighting the importance of considering resource utilisation alongside absolute energy performance. For pathways requiring substantial external energy inputs, feedstock-related efficiency can exceed total process efficiency because part of the energy embodied in the final fuel originates from sources other than the primary feedstock, such as electricity, hydrogen or process heat. Efficiency should therefore be assessed alongside GHG performance, feedstock availability and technology maturity, as low-emission pathways may involve higher energy losses.

Table 23 Comparison of total process efficiency and efficiency related to feedstock input across different pathways

Final fuel	Conversion process	Total process efficiency (%)		Efficiency related to feedstock input (%)	
		Min	Max	Min	Max
Ammonia	ATR/SMR of natural gas, Haber-Bosch synthesis	43.0	46.6	50.2	55.2
	AD, SMR, Haber-Bosch synthesis	16.7	28.7	22.0	33.5
	Gasification, Haber-Bosch synthesis	34.4	44.3	59.6	59.6
	Electrolysis, Haber-Bosch synthesis ¹	14.9 ¹	53.4	16.2	57.9
Diesel	Pyrolysis or HTL & Upgrading	41.2	65.9	46.8	83.9
Electricity	Power generation	25.4	82.1	25.9	82.1
	Pyro-gasification or Hydrothermal gasification of biomass & Power generation	18.6	70.7 ²	18.6	21.1
Ethanol	Fermentation & Distillation	38.4	61.1	53.8	60.8
	Saccharification & Fermentation & Distillation	31.0	39.2	28.3	37.0
FAEE/FAME	Transesterification	38.6 ³	87.2	33.5	99.9
FAME residues	Refining	94.9	94.9	97.6	97.6
HFO/MDO/VLSFO	Crude oil refining	83.1	86.4	93.8	95.6
Liq. H ₂	AD, SMR, H ₂ liquefaction	19.4	31.5	28.0	42.7
	ATR/SMR, H ₂ liquefaction	40.8	43.6	56.7	62.4
	Electrolysis, H ₂ liquefaction ¹	15.6	55.6	18.3	65.4
	Gasification, H ₂ liquefaction	33.5	41.5	67.3	67.3
	Pyrolysis & Gasification or Hydrothermal gasification, H ₂ liquefaction	28.1	48.7	68.1	78.7

Final fuel	Conversion process	Total process efficiency (%)		Efficiency related to feedstock input (%)	
		Min	Max	Min	Max
Liq. methane	AD, Cryogenic separation	29.5	49.2	41.7	63.6
	Electrolysis, CO ₂ capture & Methanation, Liquefaction ¹	13.5	52.3	15.4	55.2
	Gasification & Methanation, Liquefaction	40.9	53.5	66.4	66.4
	Pyro-gasification or Hydrothermal gasification & methanation, liquefaction	62.6	68.1	59.8	70.3
Methanol	AD, SMR & Methanol synthesis	21.5	37.0	28.7	43.7
	ATR/SMR of NG, CO ₂ capture & methanol synthesis	34.1	36.4	49.5	54.5
	Electrolysis, CO ₂ capture & Methanol synthesis ¹	13.3	53.3	16.0	57.2
	Gasification or Hydrothermal gasification & Methanol synthesis	32.5	55.9	58.8	63.0
Paraffinic diesel	ATR/SMR of NG, CO ₂ capture & RWGS & FT	29.7	31.8	41.1	45.2
	Electrolysis/Co-electrolysis, CO ₂ capture & RWGS & FT ¹	11.3	47.8	13.2	55.1
	Electrolysis, CO ₂ capture & Methanol synthesis, MTD	12.4	51.2	15.2	54.5
	Gasification & Electrolysis & FT	52.3	53.1 ⁴	81.1	81.1 ⁴
	Gasification & FT	33.0	50.1	42.5	45.1
HVO	Hydrotreating	45.6 ⁵	86.4	33.9	103.9
CNSL	Refining of CNSL	45.8	45.8	48.1	48.1

¹ The range reflects variations across electricity sources, with the lower bound associated with nuclear power and the upper bound corresponding to renewable electricity.

² Refers to a CHP plant where the heat is exported.

³ The lower value refers to FAEE/FAME derived from cashew nutshells with the efficiency based on the LHV of the final fuel versus the LHV of the cashew nutshell. The higher value refers to FAEE/FAME derived from waste vegetable oil with the efficiency based on the LHV of the final fuel versus the LHV of the waste vegetable oil.

⁴ The high feedstock-related efficiency is achieved through the addition of renewable hydrogen produced via electrolysis, which improves carbon utilisation during fuel synthesis and enables a larger fraction of the biomass-derived carbon to be converted into paraffinic diesel. The overall process efficiency is lower, as it includes the contribution of hydrogen from electrolysis as an input.

⁵ The lower value refers to HVO derived from cashew nutshells with the efficiency based on the LHV of the final fuel versus the LHV of the cashew nutshell. The higher value refers to HVO derived from waste vegetable oil with the efficiency based on the LHV of the final fuel versus the LHV of the waste vegetable oil.

4.3. FEEDSTOCK AVAILABILITY

4.3.1. Comparison of all bio-mass feedstocks at a global level

The distribution of global biomass resources varies significantly across feedstock types. Residues such as agricultural and forestry residues tend to offer the highest technical potential, while more niche feedstocks are limited in scale. These differences have direct implications for scalability. Pathways relying on widely available residues are likely to be more readily deployable than those dependent on geographically constrained feedstocks. Scalability also depends on the extent to which feedstocks can be integrated into existing conversion, refining and fuel distribution infrastructure, thereby reducing the need for new investments and facilitating more rapid deployment. As more vessels adopt these fuels, market uptake can accelerate, improving availability and enabling broader adoption across the maritime sector.

Figure 13 Bioenergy potential for biomass feedstocks at a global level



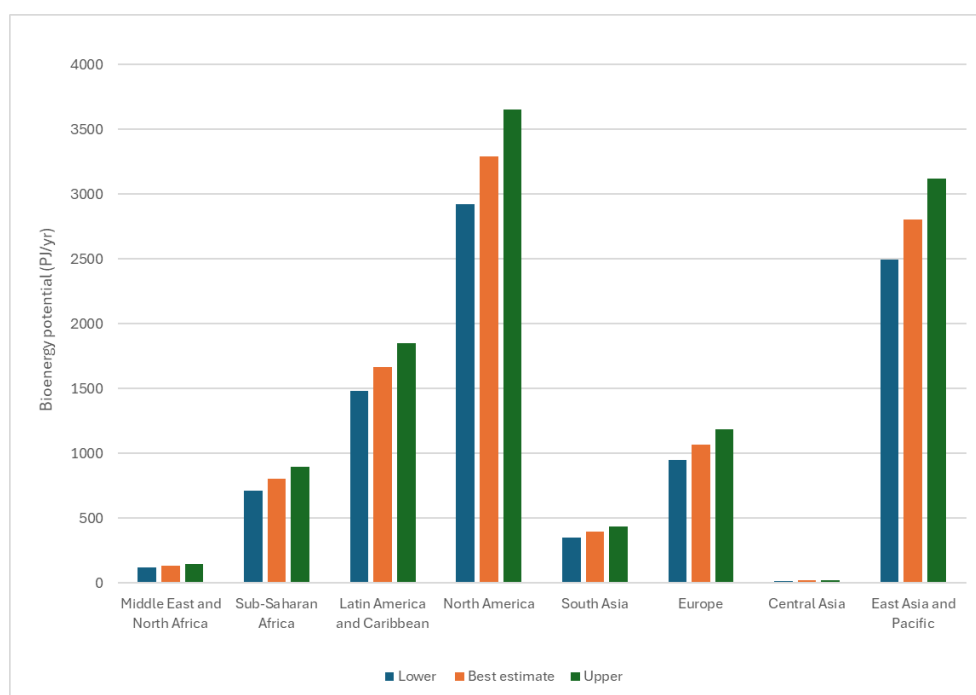
★ refers to grassy lignocellulosic crops, with miscanthus utilised as a proxy
 ★ refers to woody lignocellulosic crops, represented by short-rotation coppice species such as willow and poplar

4.3.2. Comparison of bioenergy potential of corn stover across different regions

As an example, the bioenergy potential for corn stover was analysed to understand the availability potential for different regions. It is observed that regions such as North America and East Asia and Pacific offer the highest potential for corn stover, while regions such as Central Asia and Middle East and North Africa have very limited potential for this feedstock.

This data reflects the availability potential, rather than deployment. The regional availability figures are used to contextualise pathway relevance based on localized resource abundance. They are not intended to rank options or indicate a preference for one region over another. The variations between the Lower, Best estimate and Upper values represent the inherent uncertainty and range of potential within the modelled datasheets.

Figure 14 Bioenergy potential for corn stover across different regions globally



4.4. TECHNOLOGY MATURITY

The analysis indicates that many conventional and biofuel production pathways are already technologically mature (TRL 8-9), with established deployment at demonstration or industrial scale. In contrast, several synthetic fuel pathways, particularly those involving CO₂ capture and advanced electrolysis pathways, are at lower TRL levels and require further development and scale-up. Plant scale data also shows significant variation, with conventional refining and SMR-based processes operating at much larger scales compared to emerging bio-based and electro-fuel technologies. In practice, technology maturity can vary depending on the specific technology configuration and feedstock used. To provide a consistent basis for comparison, the highest TRL identified for each pathway has been used in the Shipfuels Matrix.

Table 24 Comparison of technology readiness level and plant scale for range of conversion processes

Final fuel	Conversion process	TRL	Approximate Plant Scale (kt/yr)
Ammonia	Anaerobic Digestion	9	30
	Electrolysis	9	300
	Haber-Bosch Synthesis	9	4,300
	Steam Methane Reforming	9	138,500
	Gasification	9	600
	ATR (Autothermal Reforming)	6	1,700
Diesel	Pyrolysis	8	40
	Hydrothermal Liquefaction	7	2
	Upgrading of pyrolysis oil	8	-
Electricity	Power Generation	9	-
	Pyro-Gasification	8	140
	Hydrothermal Gasification	7	10
Ethanol	Distillation	9	40
	Fermentation	9	1,000
	Syngas Fermentation	9	120
	Saccharification	8	80
	Hydrothermal Gasification	7	10
FAEE/FAME	Transesterification	9	1,600
FAME residues	Refining of FAME residues	9	525
LH ₂	Anaerobic Digestion	9	30
	Electrolysis	9	300
	H ₂ Liquefaction	9	30
	Steam Methane Reforming	9	138,500
	Gasification	9	600
	Pyrolysis	8	1,700
	Hydrothermal Gasification	7	10
	ATR (Autothermal Reforming)	6	1,700
Liqefied methane	Anaerobic Digestion	9	30
	Cryogenic separation	9	1,800
	Electrolysis	9	320
	Liquefaction	9	21,900
	Methanation	9	1,000
	Gasification	9	600
	Pyro-Gasification	8	140
	Hydrothermal Gasification	7	10
Methanol	Anaerobic Digestion	9	30
	Electrolysis	9	300
	Methanol Synthesis	9	11,800

Final fuel	Conversion process	TRL	Approximate Plant Scale (kt/yr)
	Steam Methane Reforming	9	138,500
	Gasification	9	600
	Glycerol Reforming	7	-
	Hydrothermal Gasification	7	10
	ATR (Autothermal Reforming)	6	1,700
Paraffinic diesel (e.g. HVO)	Electrolysis	9	320
	Fischer-Tropsch Synthesis	9	6,300
	Hydrotreating	9	2,600
	Methanol Synthesis	9	11,800
	Methanol-to-Diesel (MTD) Process	9	-
	Steam Methane Reforming	9	138,500
	Gasification	9	600
	Co-Electrolysis	7	-
	Reverse Water Gas Shift (RWGS)	6	-
	ATR (Autothermal Reforming)	6	1,700
CNSL	Refining of CNSL	9	525

4.5. SELECTED FUEL PROPERTIES

4.5.1. Energy density

The energy density is an important characteristic of a fuel which has implications on aspects such as range, available cargo space and bunkering times. The following table highlights the trade-offs between fuels. Conventional liquid fuels exhibit high volumetric energy density, supporting long-range applications. In contrast, fuels such as hydrogen show high gravimetric but very low volumetric energy density, requiring significantly larger storage volumes. These differences have direct implications for vessel design and operational flexibility.

Table 25 Comparison of energy density of final fuels

Final fuels	Lower heating value (mass basis) (MJ/kg)	Lower heating value (volumetric basis) LHV (MJ/l)	Density (kg/m ³)
Ammonia	18.59	12.68	682
CNSL (Cashew nutshell liquid)	40.34	39.73	985
Diesel (HTL)	43.10	35.86	832
Diesel (pyrolysis)	43.10	35.86	832
Ethanol	26.81	21.29	794
FAEE	37.90	33.73	890
FAME	37.20	33.11	890
FAME residues	37.00	34.04	920
HFO	40.50	40.14	991
LH ₂	119.96	8.49	70.78

Final fuels	Lower heating value (mass basis) (MJ/kg)	Lower heating value (volumetric basis) LHV (MJ/l)	Density (kg/m ³)
Liquefied methane	50.00	21.00	420
MDO	42.70	38.00	890
Methanol	19.90	15.78	793
Paraffinic diesel	44.00	34.32	780
Straight vegetable oil	37.00	34.04	920
VLSFO	40.50	40.14	991

4.5.2. Storage conditions

The storage conditions of final fuels are provided by specifying the typical storage temperatures and pressures required. The following table shows that most liquid fuels can be stored under ambient conditions, while cryogenic fuels such as liquefied hydrogen and liquefied methane require very low temperatures. These storage requirements introduce additional considerations in fuel handling and infrastructure requirements.

Table 26 Comparison of storage conditions of final fuels

Final fuels	Storage temperature (°C)	Storage pressure (MPa) (absolute)
Ammonia	-48	0.125
CNSL (Cashew nutshell liquid)	15	0.1013
Ethanol	15	0.1013
FAEE	15	0.1013
FAME	15	0.1013
FAME residues	15	0.1013
HFO	15	0.1013
Diesel (HTL)	15	0.1013
LH ₂	-253.15	0.1
Liquefied methane	-161.5	0.1
MDO	15	0.1013
Methanol	15	0.1013
Paraffinic diesel (e.g. HVO)	15	0.1013
Diesel (pyrolysis)	15	0.1013
Straight vegetable oil	15	0.1013
VLSFO	15	0.1013

4.5.3. GHG Emissions

The IMO guidelines on life cycle GHG intensity of marine fuels provide default values for greenhouse gas emissions of CO₂, N₂O and methane emissions of maritime fuels. The following table illustrates that while fuels such as hydrogen and ammonia have zero CO₂ emissions at the point of use, non-CO₂ emissions, including methane and nitrous oxide, remain relevant for certain pathways. This emphasizes the importance of adopting a full lifecycle perspective when comparing fuels.

Table 27 Comparison of CO₂, N₂O and methane emissions of final fuels

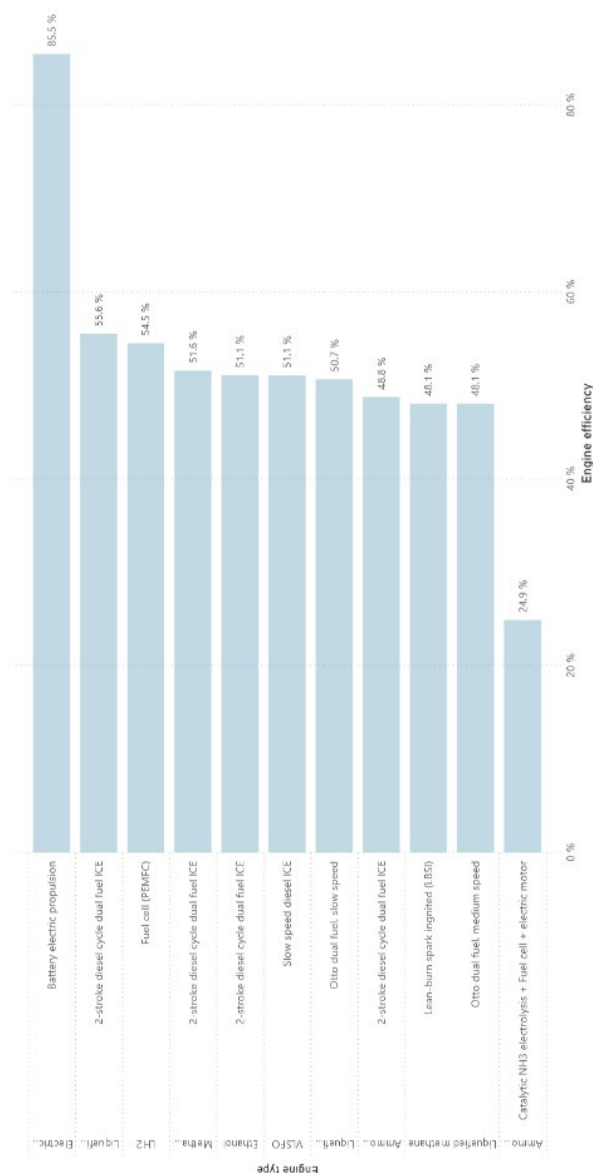
Final Fuels	CO ₂ (g/MJ)	N ₂ O (g/MJ)	CH ₄ (g/MJ)
Ammonia	0	0.0135	0.0000
CNSL (Cashew Nutshell Liquid)	70.25	0.0045	0.0001
Diesel (HTL)	74.39	0.0042	0.0001
Diesel (pyrolysis)	74.39	0.0042	0.0001
Electricity	0	0.0000	0.0000
Ethanol	71.35	0.0004	0.0000
FAEE	74.78	0.0047	0.0001
FAME	76.18	0.0048	0.0001
FAME residues	76.59	0.0049	0.0001
HFO	76.89	0.0044	0.0001
LH ₂	0	0.0000	0.0000
Liquefied Methane	55.00	0.0088	0.0190
MDO	75.08	0.0042	0.0001
Methanol	68.99	0.0004	0.0000
Paraffinic diesel (e.g. HVO)	70.80	0.0041	0.0001
Straight vegetable oil	76.59	0.0049	0.0001
VLSFO	77.80	0.0044	0.0001

4.6. APPLICATION PERFORMANCE (ENGINE TYPE, FUEL CONSUMPTION)

Application-level performance highlights the importance of engine compatibility and operational characteristics. Different propulsion systems exhibit varying efficiencies, with conventional combustion engines generally outperforming emerging technologies in absolute efficiency terms, although fuel-specific performance varies.

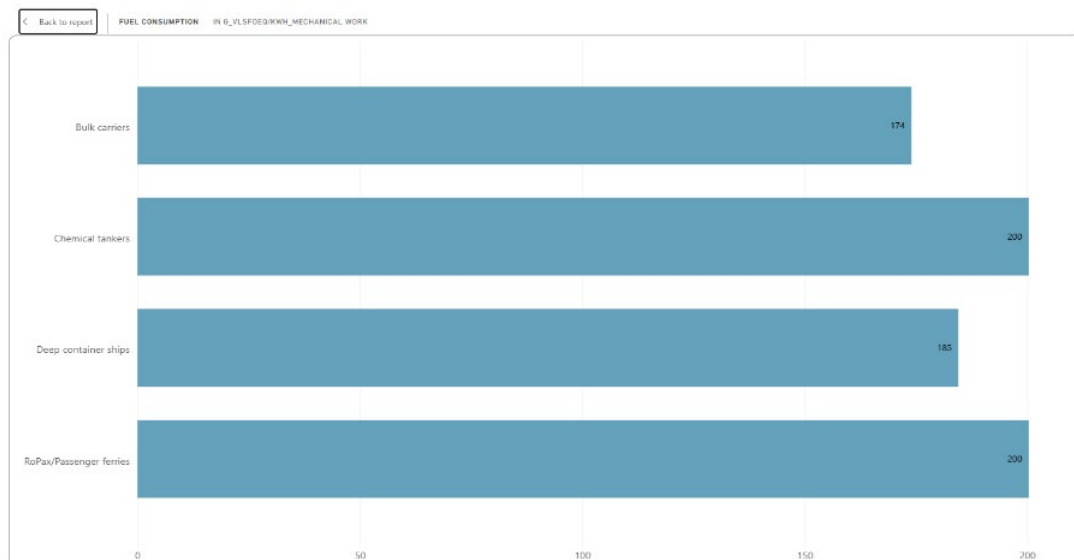
Figure 15

Comparison of propulsion efficiency of different engines for various final fuels



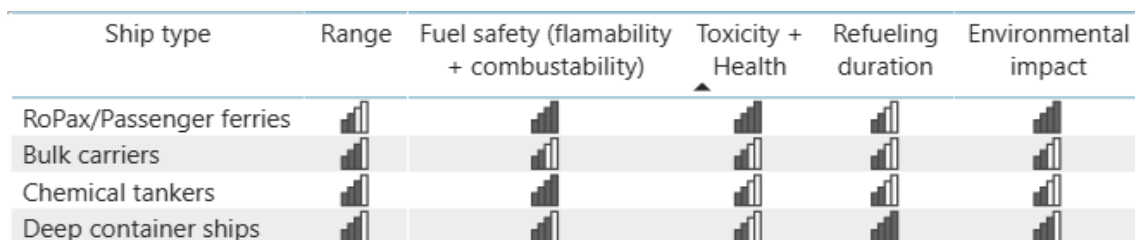
Propulsion performance and fuel consumption values are based on representative ship types, considering operational characteristics and auxiliary energy demand. Figure 15 indicates that fuel consumption varies considerably across vessel types, reflecting differences in operational profiles and energy demand. This suggests that fuel selection should be aligned with vessel-specific requirements.

Figure 16 Comparison of typical fuel consumption for different ship types



Priorities concerning desirable technical fuel properties differ across commercial ship types. The following figure presents the relative importance of each fuel attribute across vessel categories.

Figure 17 Comparison of relative importance of fuel attributes for different ship types



The comparison of fuel attribute priorities highlights that different ship types prioritise different characteristics, such as range, safety, or environmental impact. This reinforces that optimal fuel selection is context-specific and dependent on operational use cases.

5. CASE STUDIES

Building on the comparative analysis presented in the previous section, this section illustrates how the Shipfuels Matrix can be applied to explore specific questions across the value chain. Given the level of detail in the database, the tool enables users to analyse pathways from multiple perspectives, including policy assessment, technology development, and operational use cases.

Three case studies are presented to demonstrate different analytical approaches:

- **Case study 1:** A chosen feedstock, to compare different conversion processes, final fuels and propulsion types.
- **Case study 2:** A chosen conversion process, to investigate what are the options for feedstocks that can be used and what are the fuels that can be produced.
- **Case study 3:** Specific final fuels, to compare different conversion processes and feedstocks that could be used to produce the fuels, but also to understand what engines are suitable and what are the main characteristics of the fuels.

5.1. CASE STUDY 1: FOREST RESIDUES SELECTED AS FEEDSTOCK TO PRODUCE MARITIME FUELS

This case study illustrates how the Shipfuels Matrix can be used when a specific feedstock is selected, to identify: (i) feasible conversion processes, (ii) the range of resulting final fuels and propulsion options, and (iii) key performance indicators. Forest residue is used as an example because it supports multiple pathways and yields a range of candidate maritime fuels, including ammonia, liquefied methane, methanol, liquid hydrogen, diesel and electricity.

Two types of forest residues can be selected: primary residues (such as damaged trees, tree tops, branches) and secondary residues (such as saw dust and other sawmill by-products). By selecting both, 46 pathways are extracted from the database (23 for each, primary and secondary forest residues). Ten of these pathways represent production outside the EU with import to the EU, based on an assumed transport distance of 4,000 nautical miles including the empty return voyage. The 46 pathways also include variations (primary/secondary residues, electrolysis included or not) of:

- Ammonia produced from gasification and Haber-Bosch synthesis, transported and used in a 2-stroke Diesel cycle dual fuel ICE
- Ammonia used in a catalytic NH₃ electrolyser and fuel cell
- Methanol to be used in 2-stroke Diesel ICE
- Diesel produced from gasification and Fischer-Tropsch synthesis and other processes used in a slow speed Diesel ICE engine
- Liquid hydrogen to be used in a Fuel Cell
- Electricity to be produced directly or as co-product and used in an electric battery propulsion system.

5.1.1. GHG performance

For the ten import pathways, well-to-wake GHG emissions are reported in the range of 5-36 gCO₂eq/MJ of final fuel. For each of these pathways, import adds approximately +5.6 gCO₂eq/MJ relative to the corresponding pathway produced within the EU. Across all forestry residues pathways produced within the EU, WtW GHG emissions span approximately 3-38 gCO₂eq/MJ of final fuel. The difference in well-to-wake GHG emissions between primary and secondary forestry residues resides in the emissions accounted for the feedstock supply, which is 3.6 gCO₂eq/MJ for the primary forest residues and 1.6 gCO₂eq/MJ for the secondary forest residues.

This case study thus illustrates how the tool can be used not only to compare pathways, but also to quantify the influence of supply-chain configuration (e.g., import vs EU production, primary vs secondary residues) on lifecycle performance as illustrated in Figure 18.

Figure 18 Details of the pathway of ammonia produced from primary forestry residue to be used in a 2-stroke Diesel engine, produced outside EU and transported to EU

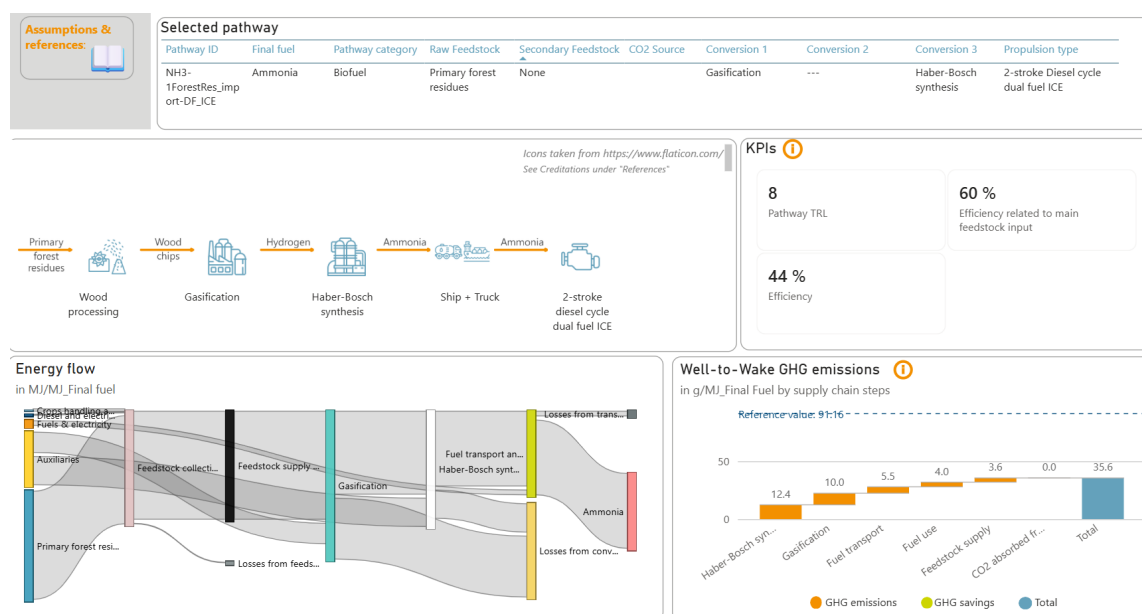
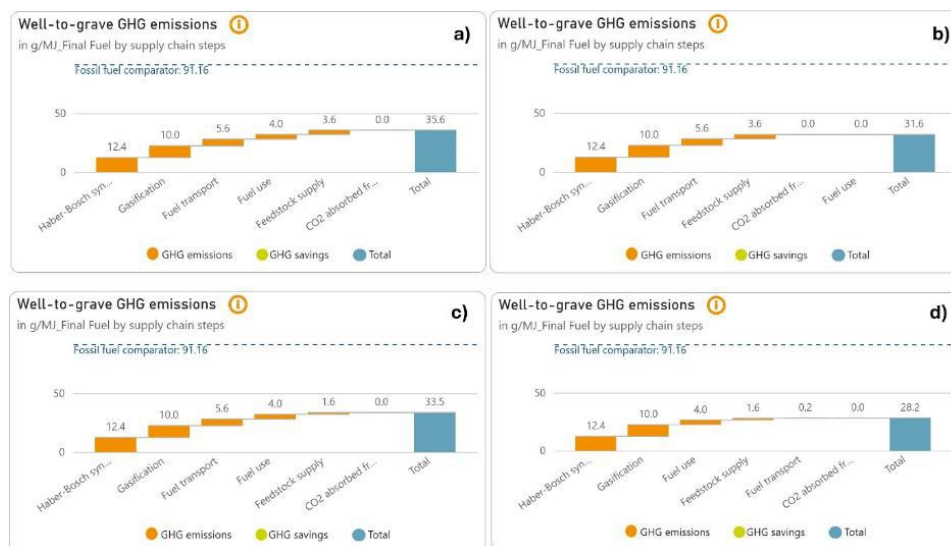


Figure 19 Waterfall diagram of well-to-wake GHG emissions for selected NH3 pathways



The well-to-wake emissions for the following selected pathways are depicted in Figure 19:

- Ammonia produced from primary forest residue to be used in a 2-stroke Diesel engine, produced outside EU and transported to EU
- Ammonia produced from primary forest residue to be used in a NH3 Fuel cell, produced outside EU and transported to EU
- Ammonia produced from secondary forest residue to be used in a 2-stroke Diesel engine, produced outside EU and transported to EU
- Ammonia produced from secondary forest residue to be used in a 2-stroke Diesel engine, produced in EU

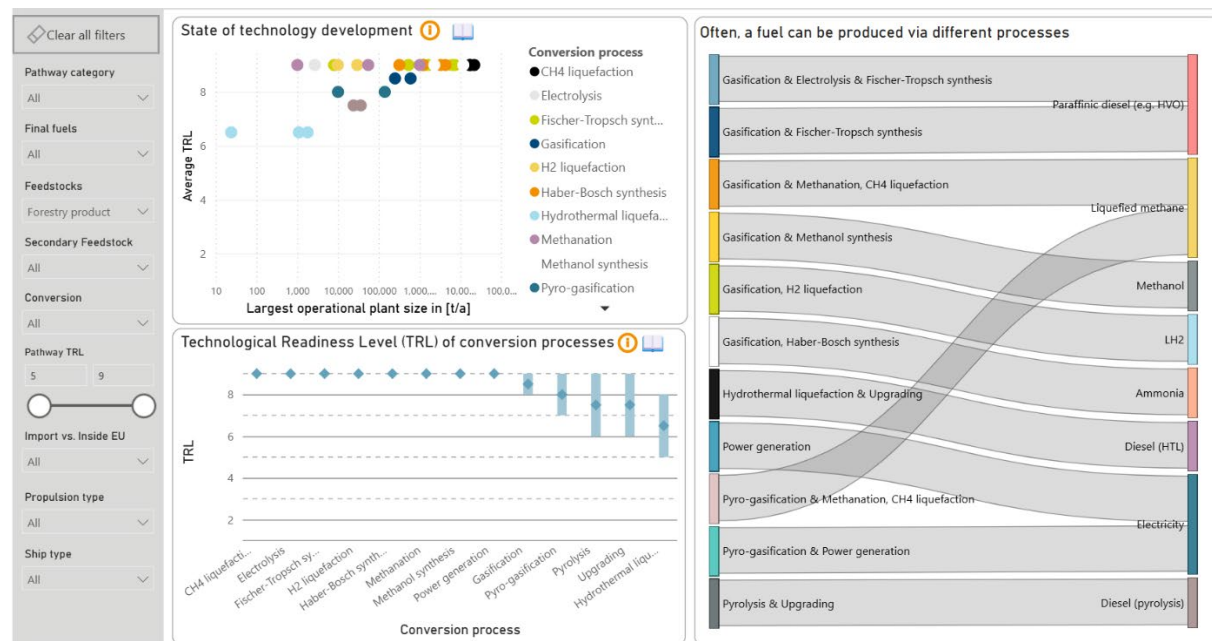
5.1.2. Conversions, technology maturity and efficiency

Forestry residues can be processed through several conversion processes to produce low carbon maritime fuels. The feedstock can be first gasified to generate a syngas that can then be upgraded toward Diesel, Methane or Methanol. Diesel can also be produced from hydrothermal liquefaction or pyrolysis of forestry residues. Pyro-gasification of forestry residues converts the feedstock either to methane, or electricity (which can be obtained directly from power generation as well). Hydrogen can be obtained from gasification and then liquefied.

Most of these conversion technologies are reported as having high technology readiness (TRL >8), beside hydrothermal liquefaction technology to produce Diesel which has a TRL of 6-7. The TRL values presented refer to the individual conversion technologies and should not be interpreted as the maturity of the complete fuel pathway, which may be lower depending on the degree of integration and commercial deployment achieved for specific feedstocks.

The total process efficiency and energy efficiency related to feedstock are, for most conversion paths, ranging between 40 and 70%; however, the forestry residues-to-electricity paths show relatively low conversion efficiencies, especially related to feedstock around 25%.

Figure 20 General information related to the pathways converting forestry residues into maritime fuels



5.1.3. Feedstock availability

Forestry residue as a feedstock presents a strong advantage as it doesn't depend on seasonality. However, it is dependent on specific single industry and it is difficult to assess the amount and accessibility of the feedstock from the different sites, that could induce possible constraints on the supply chain. Primary forest residue is available in many different parts of the world with high concentrations on each Continent, while secondary forest residue shows less supply potential and with availability mainly in East Asia / Pacific and in Europe. Overall, its bioenergy potential represents about 2,500 PJ per year while the bioenergy potential for primary forest residue can reach about 7,500 PJ per year.

Figure 21 Global bioenergy potential of primary and secondary forestry residues



5.1.4. Final fuel considerations

Most of the fuels produced from forest residues conversion pathways, are advanced in terms of regulatory readiness. Marine standards already exist for the use of paraffinic Diesel (produced via Fischer-Tropsch), liquefied methane (as it falls within existing biomethane/LNG-related regulations), and Methanol. Upgraded Diesel obtained from hydrothermal liquefaction and pyrolysis can comply with automotive standards EN 15940 or ASTM D975, while for ammonia some work is ongoing under ISO and CIMAC to define fuel grade specification for maritime use.

Regarding liquid hydrogen, despite the fact that no marine standards are available yet, maritime liquid hydrogen is handled under ISO 14687 / IMO IGF Code.

Regarding propulsion options that can be running on fuels and electricity produced from forestry residues and indicative maximum efficiencies reported in the database:

- The battery electric propulsion shows the highest propulsion efficiency with a maximum of 85.5%
- Liquid hydrogen via PEM fuel cell is reported at 54.5%
- Methanol and ammonia in a 2-stroke diesel cycle dual-fuel engine are reported at 51.6% and 48.8% respectively
- Ammonia can also be used to fuel a NH_3 fuel cell propulsion technology with a maximum propulsion efficiency of 24.9%
- Diesel oxidized in a slow speed Diesel ICE engine brings around 51% maximum propulsion efficiency
- Liquefied methane can be used in:
 - a 2-stroke diesel cycle dual-fuel engine showing a propulsion efficiency of 55.6%
 - an Otto dual fuel slow speed engine with around 51% maximum propulsion efficiency,
 - a lean-burn spark ignited and/or an Otto dual fuel, medium speed engines, with 48% maximum propulsion efficiency.

5.1.5. Discussion

This case study illustrates that forestry residues can support a diverse set of mature pathways and fuels with reduced lifecycle GHG reductions, while also highlighting system-level constraints. Import configurations increase emissions relative to EU production, and conversion efficiencies depend strongly on the pathways varying between 25 and 70%. From a resource perspective, the feedstock offers a substantial global bioenergy potential, suitable for the production of many different fuels and is widely available across regions. However, the dispersed and in some cases difficult accessibility of forestry residues generation may create supply chain constraints, potentially limiting large-scale deployment. Among the fuels considered, paraffinic Diesel, Methanol and liquefied Methane are quite advanced in regulatory readiness and propulsion flexibility, while other options such as Ammonia and liquid Hydrogen remain relevant depending on pathway configuration and use case.

5.2. CASE STUDY 2: PYROLYSIS SELECTED AS CONVERSION PROCESS

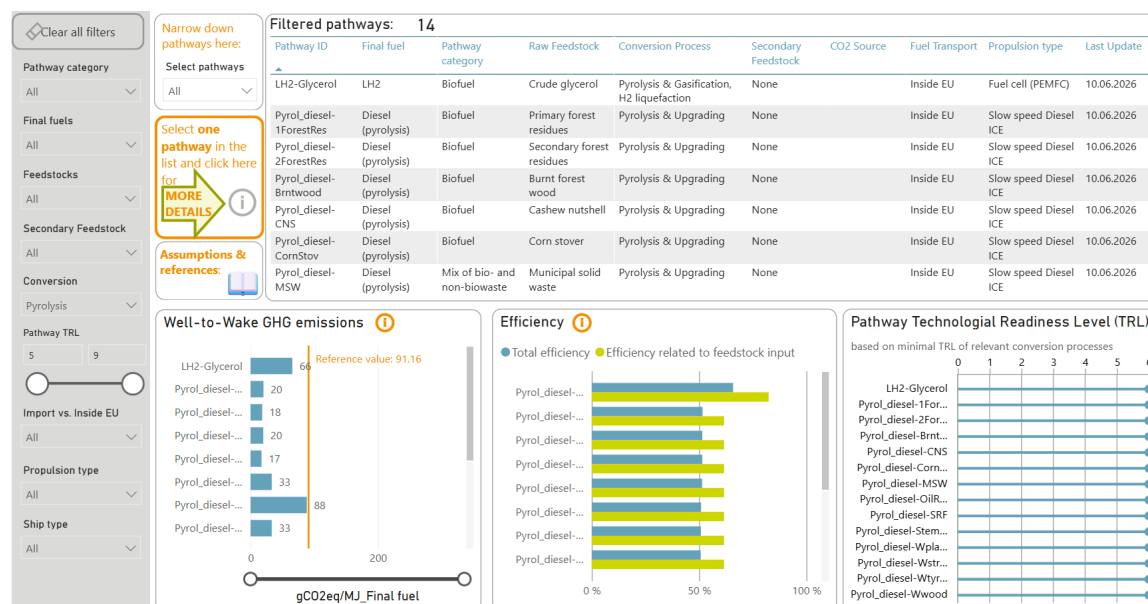
This case focuses on a conversion process-driven analysis to identify: (i) compatible feedstocks, (ii) resulting fuel outputs, and (iii) associated performance characteristics. Pyrolysis is used as an example due to its flexibility in processing a wide range of feedstocks and its relatively advanced stage of development.

Selecting pyrolysis as the conversion process yields 14 pathways in the database, including 13 pathways producing diesel and 1 pathway producing liquid hydrogen. All pathways considered are assumed to be produced within the EU.

5.2.1. GHG performance

Most pyrolysis pathways show well-to-wake GHG emissions below the reference value (91.16 gCO₂eq/MJ). The exception is diesel produced from waste plastics, which remains above the fossil benchmark. A subset of pathways achieves performance below the RFNBO threshold (28.2 gCO₂eq/MJ), primarily when using feedstocks such as lignocellulosic energy crops, forest residues, and cashew nutshells. These results indicate that GHG performance is strongly influenced by feedstock type, even when the conversion pathway remains constant.

Figure 22 Pathways KPIs for the selection of pyrolysis conversion



5.2.2. Efficiency

Most pyrolysis pathways exhibit total process efficiency around ~50%, and feedstock-related efficiency around ~60% with higher efficiencies observed for diesel from waste plastics (~66% total process efficiency), and hydrogen from crude glycerol (~79% feedstock-related efficiency).

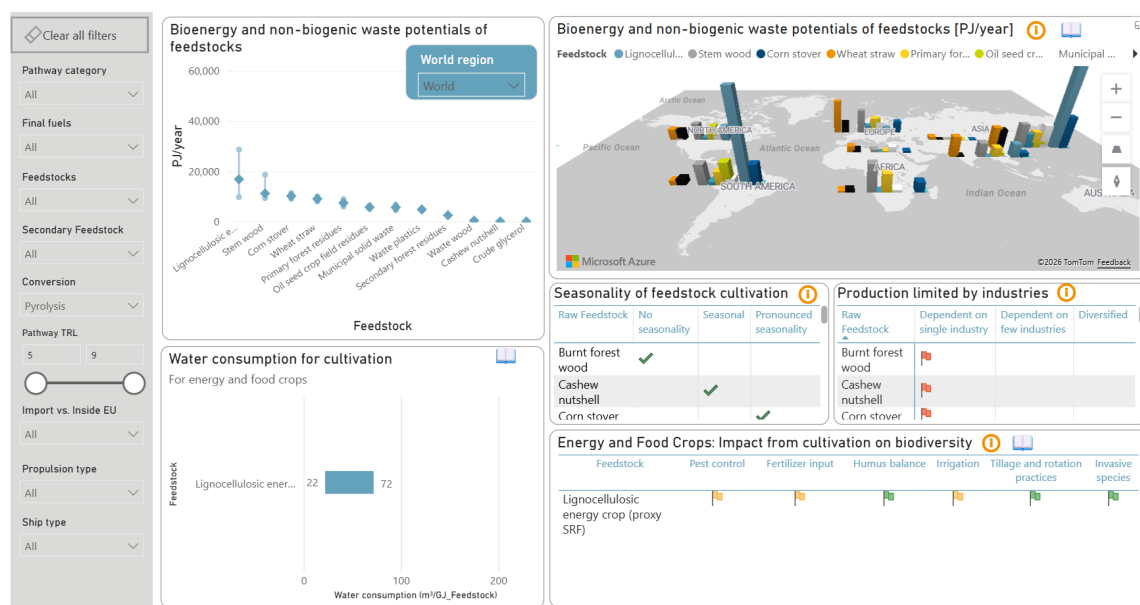
5.2.3. Feedstock availability

The pyrolysis pathways rely predominantly on residual and waste biomass feedstocks, including forestry residues, agricultural residues, lignocellulosic energy crops and municipal solid waste streams. The lignocellulosic energy crops show a

large potential of bioenergy supply with most of the production comes from the regions of East Asia & Pacific and South America.

Regarding the crude glycerol to produce hydrogen from pyrolysis, despite a diversified supply, the global estimated production is on the low range estimated about 588 kt per year, mainly in North America and Europe.

Figure 23 Feedstocks related information for the selection of pyrolysis conversion



5.2.4. Final fuel considerations

Currently, there are no maritime standards available for maritime fuels produced from pyrolysis. The obtained Diesel must get hydrotreated in order to meet the EN 15940 and / or ASTM D975 standards and the liquid Hydrogen for marine use is handled under ISO 14687/IMO IGF Code.

In terms of application:

- Diesel fuels are used in slow-speed diesel engines (propulsion efficiency ~51%)
- Liquid hydrogen is used in fuel cell systems (propulsion efficiency ~54.5%)

5.2.5. Discussion

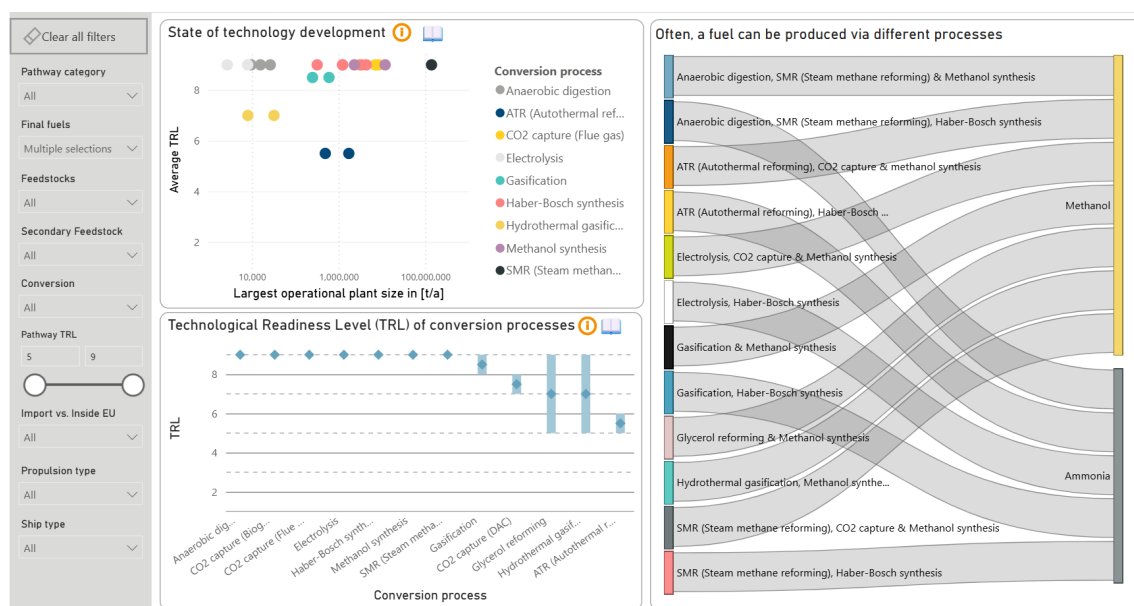
This case study demonstrates that pyrolysis provides a flexible and relatively mature pathway for converting a wide range of waste and residual feedstocks into maritime fuels. The analysis highlights that feedstock selection remains a key determinant of GHG performance, even when the conversion technology is fixed. From a deployment perspective, the reliance on widely available residual feedstocks supports scalability. At the same time, the absence of dedicated fuel standards and regulatory frameworks for pyrolysis-derived fuels require further development.

5.3. CASE STUDY 3: AMMONIA VS METHANOL AS FINAL FUEL

This case focuses on a fuel-driven comparison to compare: (i) alternative production pathways, (ii) feedstock options, and (iii) application characteristics. Ammonia and methanol are selected as widely discussed candidates for low-carbon maritime fuels, allowing for a comparison of their performance, maturity and deployment characteristics.

Selecting ammonia and methanol as final fuels yields a large number of pathways in the database, reflecting the diversity of conversion processes and compatible feedstocks. The pathways share several common upstream conversion steps, including anaerobic digestion, electrolysis, gasification, steam methane reforming (SMR) and autothermal reforming (ATR). The main differences between the pathways arise from the final synthesis step (ammonia vs methanol production), the energy source (fossil with CCS, biogenic, or electricity-based), and the end-use application (engine or fuel cell technologies).

Figure 24 Possible processes and technologies to produce ammonia and methanol



5.3.1. GHG performance

The analysis shows that both ammonia and methanol can achieve a wide range of well-to-wake GHG emissions, depending on feedstock and energy input.

For ammonia:

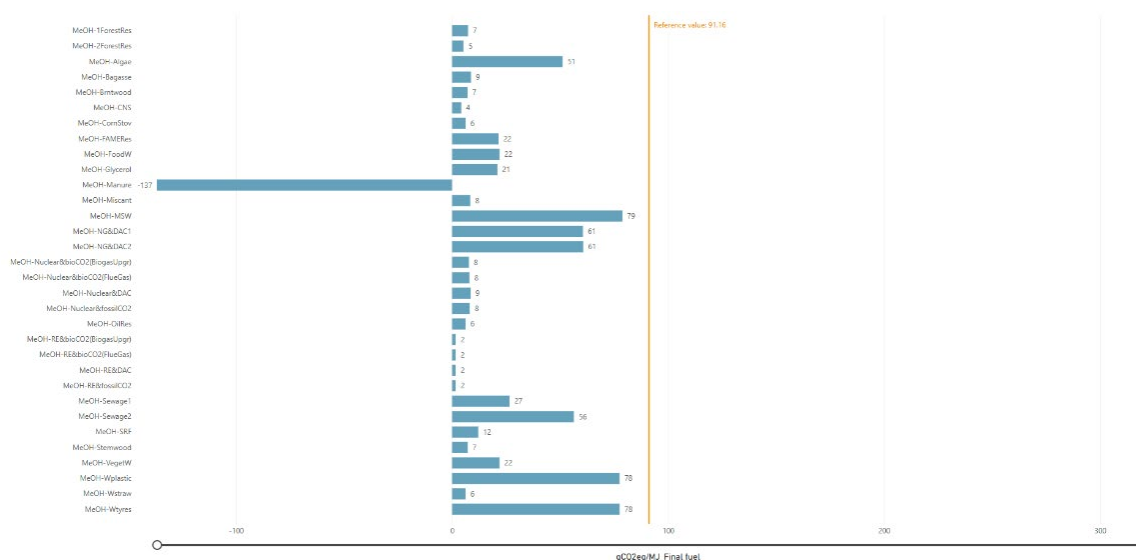
- certain pathways, particularly those based on waste-derived feedstocks (municipal solid wastes, waste tyres and waste plastics) via gasification, exceed the reference value (91.16 gCO₂eq/MJ)
- a subset of pathways achieves emissions below the RFNBO threshold (28.2 gCO₂eq/MJ) when based on biogenic feedstocks (lignocellulosic energy crop, agricultural and forest residues)
- electro-fuel pathways using nuclear, and renewable electricity can achieve emissions below approximately 10.5 gCO₂eq/MJ

For methanol:

- all pathways remain below the reference value.
- a significant number of pathways achieve very low emissions (<10 gCO₂eq/MJ), particularly for biomass gasification (using lignocellulosic energy crop, agricultural and forest residues) and power-to-liquid pathways (using the different sources of CO₂ and decarbonized electricity).

The results highlight that both fuels can deliver low-carbon outcomes, depending on the feedstock source and energy source.

Figure 25 *Well-to-wake GHG emissions of pathways to produce methanol inside the EU*



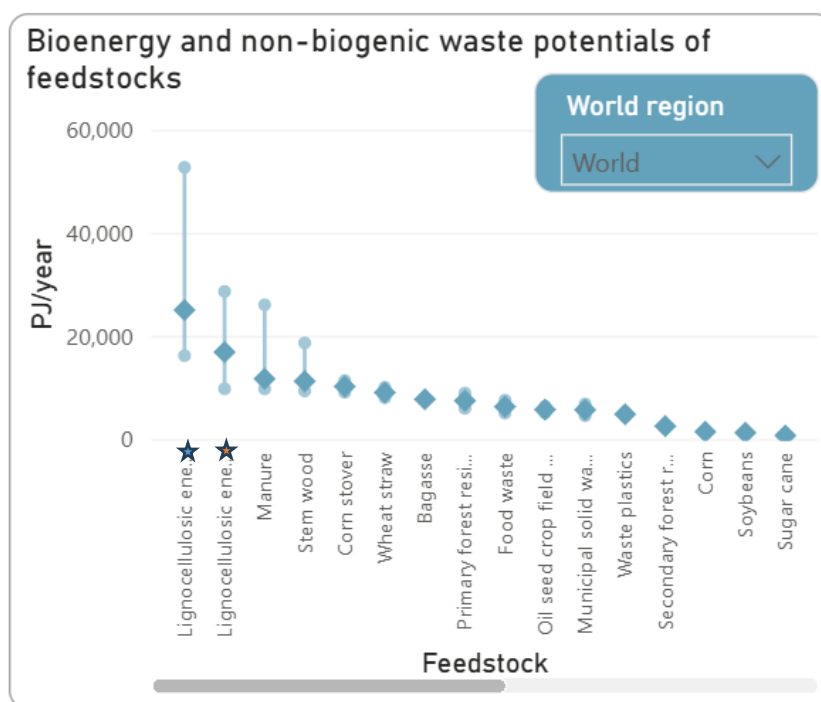
5.3.2. Technology maturity and pathways

Both ammonia and methanol are associated with relatively mature production technologies (TRL ≥ 8) for most pathways, although some pathways involving advanced reforming or hydrothermal processes remain at lower maturity levels. The diversity of pathways reflects the ability of both fuels to be produced from multiple feedstock and energy combinations, including biogenic feedstocks, fossil feedstocks with carbon capture and electricity-driven synthetic pathways.

5.3.3. Feedstock availability

The bio-based and waste-type feedstocks that can be used to produce ammonia and methanol are diversified as the first conversion step (gasification) can process many different types of feedstocks. The energy potential from the feedstocks is thus in the higher range, reaching more than 20,000 PJ/year for the lignocellulosic energy crops. The feedstocks by their diversification could be available and supplied within many different regions from all over the globe.

Figure 26 Bioenergy and non-biogenic waste potentials to produce ammonia and methanol



★ refers to grassy lignocellulosic crops, with miscanthus utilised as a proxy

★ refers to woody lignocellulosic crops, represented by short-rotation coppice species such as willow and poplar

5.3.4. Final fuel considerations

At the point of use, ammonia and methanol differ more significantly. Ammonia is compatible with multiple propulsion systems, including dual-fuel engines and fuel cell-based configurations. The regulatory framework for ammonia is under development, with ongoing work on fuel standards under ISO TC28/SC 4 and CIMAC to define fuel grade ammonia specifications.

Methanol can be used in conventional internal combustion engines (with modifications to the fuel supply system) and benefits from more established standards and specifications (IMPCA Methanol reference specification and ASTM D1152 standard), including existing fuel quality standards and marine guidelines as well as already supported by interim IMO guidance for bunkering. In terms of fuel properties, both fuels show relatively lower energy density compared to conventional fuels, implying potential implications for storage and vessel design.

5.3.5. Discussion

This case study demonstrates that both ammonia and methanol can achieve low-carbon performance across multiple pathways, supported by diverse feedstock options and relatively mature production technologies.

However, their deployment characteristics differ. Methanol has stronger regulatory and technical readiness, supporting near-term deployment. Ammonia offers greater flexibility in propulsion options, however, remains subject to ongoing regulatory and engine/fuel system development even if ammonia has obtained class approval and some ships are running on ammonia already.

From a resource perspective, both fuels benefit from broad feedstock availability, supporting scalability. At the same time, differences in infrastructure, standards, and end-use compatibility suggest that the choice between ammonia and methanol will depend on specific application requirements and deployment timelines.

6. CONCLUDING REMARKS

Taken together, both the comparative analysis and case studies demonstrate that pathway performance varies significantly across all evaluated dimensions, including greenhouse gas (GHG) emissions, efficiency, resource availability potential, scalability, and operational characteristics.

While substantial GHG emission reductions can be achieved across a range of pathways, no single fuel consistently outperforms others across all criteria. Instead, performance depends on the combination of feedstock, conversion pathway, and energy input.

The analysis highlights clear trade-offs between environmental performance, efficiency, resource availability, and operational feasibility, reinforcing the need for a multi-pathway approach to maritime decarbonisation.

7. ABBREVIATIONS

AD	Anaerobic Digestion
ASTM	American Society for Testing and Materials
ATR	Autothermal Reforming
B/PtL	Biomass-/Power-to-liquid
CCS	Carbon Capture and Storage
CH ₄	Methane
CNS	Cashew Nutshell
CNSL	Cashew Nutshell Liquid
CO ₂	Carbon Dioxide
DDGS	Distillers Dried Grains with Solubles
EU RED	European Union Renewable Energy Directive
FAEE	Fatty Acid Ethyl Esters
FAME	Fatty Acid Methyl Esters
FT	Fischer-Tropsch
GHG	Greenhouse gas
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
GWP	Global Warming Potential
H ₂	Hydrogen
HB	Haber-Bosch synthesis
HFO	Heavy Fuel Oil
HTL	Hydrothermal Liquefaction
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IGF Code	International Code of Safety for Ships using gas
IMO	International Maritime Organization
IMO MARPOL	International Convention for the Prevention of Pollution from Ships
IMO SOLAS	International Convention for the Safety of Life at Sea
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KPI	Key performance indicators
LBSI	Lean-burn spark ignited
LH ₂	Liquefied Hydrogen
LHV	Lower Heating Value
MDO	Marine Diesel Oil
MTD	Methanol-to-Diesel

N ₂ O	Nitrous oxide
NG	Natural gas
NH ₃	Ammonia
NO _x	Nitrogen oxides
PEMFC	Proton Exchange Membrane Fuel Cell
POME	Palm Oil Mill Effluent
PtG	Power-to-Gas
PtL	Power-to-Liquid
PV	Photovoltaic
SMR	Steam Methane Reforming
SO ₂	Sulfur dioxide
SRF	Short Rotation Forestry
TRL	Technological Readiness Level
TtW	Tank-to-Wake
RWGS	Reverse Water Gas Shift
VLSFO	Very Low Sulfur Fuel Oil
WtT	Well-to-Tank
WtW	Well-to-Wake

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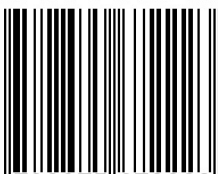
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