REPORT FOR THE STUDY ON SUSTAINABILITY CRITERIA AND LIFE CYCLE GHG EMISSION ASSESSMENT METHODS AND STANDARDS FOR ALTERNATIVE MARINE FUELS

Final Report

Report for: IMO Low Carbon GIA

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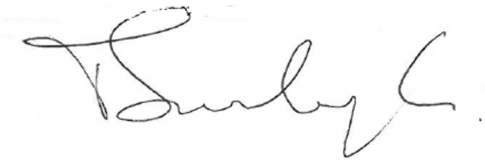

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Executive summary

Introduction and background

This report seeks to increase understanding of existing sustainability criteria and life cycle greenhouse gas (GHG) emission assessment/calculation methods that are of relevance to marine fuels and identifying areas where further work could be undertaken. This work, for the Global Industry Alliance to Support Low Carbon Shipping (Low Carbon GIA), is with a view to promoting the production and uptake of low carbon fuels and supporting IMO Member States and the wider maritime sector in gaining a better understanding of the environmental impacts of alternative fuel options for the maritime sector. The analysis and recommendations in this study are the sole responsibility of the authors of this study. This exploratory work is policy neutral, although it is recognised that recommendations for applying certain methods and standards may indirectly influence policy decisions. It does not prejudge any future policy developments at IMO and does not constitute IMO’s views on the development of lifecycle GHG/carbon intensity guidelines for maritime fuels.

The use of fossil fuels is almost universal across the shipping industry, although in recent years vessels with alternative energy sources have started to be successfully introduced in small numbers. While a range of low-carbon and zero-carbon energy sources are potentially available for shipping, currently there is no clear decarbonisation path or paths, and is likely that in the future a range of solutions will be adopted according to different vessel and operational requirements. Although such fuels may have low, net-zero, or zero GHG emissions in-use (Tank to Wake, or TtW) their emissions from production and distribution (Well-to-Tank or WtT) vary greatly. If future regulations or legislation for these fuels is adopted, it will be missing significant emissions sources unless GHG emissions are calculated and taken into account on a Well-to-Wake (WtW) basis.

Currently, the emissions from shipping are calculated by applying the appropriate fuel CO_2-equivelent factor by the amount of fuel used. For traditional liquid fossil fuels such as HFO, this method could be considered sufficient albeit incomplete. For other fuels, from LNG to hydrogen, ammonia or biofuels, important emissions may occur elsewhere in the supply chain, and may not even be in the form of CO_2. A practical use of this study and subsequent WtW studies could be to generate a number of CO_2-equivelent factors reflecting the production and use of future fuels from various pathways, which could be used to calculate the total emissions from vessels using these fuels.

GHG calculation methodologies and fuel pathway case studies

The study has identified existing standards, regulations and calculation methods and tools related to WtT and WtW, including ‘well to wake’ (or ‘well to wheel’ for road vehicle) methodologies. The review of the landscape of regulations, standards, and methods covering GHG emissions and environmental impacts was carried out across transport sectors and territories to understand the coverage and approaches used. With most being based on the use of fossil fuels, their focus is on CO_2 emissions released TtW, although a small number of methods reflect the increasing use of alternative fuels with coverage of WtT or WtW, and environmental sustainability considerations.

From this, **four GHG calculation methods and tools were identified** which had sufficient coverage and relevance to be worthy of deep study. The methods and tools identified were:

- That built into the **GREET** model, which was developed to simulate energy use and emissions for a range of vehicle and fuel combinations
- That resulting from the application of the calculation rules and emission factors specified in the **RED II** policy directive, which sets targets for EU Member States to increase the use of energy from renewable sources
- That specified in the **CORSIA** certification scheme, originally developed for Sustainable Aviation Fuels (SAF) and Lower Carbon Aviation Fuels (LCF)
- That used in the **JEC** Well-to-Wheel study, which was co-developed by the JRC, EUCAR and Concawe to assess the sustainability of the European vehicle and oil industry

In order to evaluate these methods and tools, they were applied to three case study fuel pathways. The fuel pathways selected by GIA members were:

- **Green synthetic methane (e-LNG) using renewable energy**
- **Blue ammonia (that is, utilising carbon capture and storage (CCS))**

- **Renewable diesel fuel from Hydrogenated Vegetable Oil (HVO)**

These pathways were chosen so that, together, they would provide a sufficient range of fuel types and production processes to fully evaluate the methodologies used. Their selection does not imply they are expected or recommended to be significant future marine fuels (a subject that is beyond the scope of this study), but merely that they represent very different potential fuel pathway scenarios. Production, distribution, in-use, and fugitive emissions appropriate to the scenarios were included in their evaluation. For a clear comparison of the methods and tools the WtW assessment excluded vessel-specific factors, applying a boundary at the powertrain output shaft, and used a common input dataset for each fuel across all methods where relevant.

Consideration of wider sustainability criteria

The evaluation of the existing methods and tools showed a focus on GWP aspects, and the methods' specific coverage of feedstock sourcing and fuel production categories is described below. Overall, this study highlighted the need to comprehensively account for all GHG emissions, including:

- Contribution to global warming potential (GWP) from fuel feedstock sourcing – especially through land use change (LUC) for non-waste biofuels
- Contribution to GWP from fuel production – such as the effectiveness of carbon capture and storage (CCS), fugitive emissions, and the carbon intensity of electricity sources

Additionally, this study also identified the need to consider additional environmental sustainability criteria for several impact categories. The following were assessed to have significant impact potential for fuel WtW pathways:

- Eutrophication Potential – from land use for non-waste biofuels
- Particulate Matter Formation Potential – for liquid hydrocarbon fuels (e.g., biodiesel), which may be similar to some existing fossil fuels
- Ecological and Human Toxicity and Abiotic Depletion – potentially large concerns from material demands associated with electricity as an energy carrier and input to green fuels, and the demand for electric motors, batteries, and fuel cells.

Methodological differences identified

The differences identified between the studied methodologies are, in no particular order:

- **GREET** was found to be a flexible tool with broad coverage, and although there was a North American regional focus it provides a sound platform for the analysis of alternative marine fuels.
- **RED II** has limited TtW coverage (TtW CO_2 emissions from biofuels are assumed to be zero, and it omits other GHG emissions), so it cannot be applied to a WtW analysis for all fuels without additional consideration of TtW emissions. Coverage of LUC and fugitive emissions was limited and there was no provision for CCS, so the method is incomplete for marine fuels. It is recognised that RED II is currently undergoing revision.
- **CORSIA** also has no CCS and limited fugitive emissions coverage, limiting its suitability to certain marine fuel types. However, it has the most comprehensive approach to LUC and is an example of an international emissions standard.
- The **JEC** report method has no LUC coverage at all, as well as lacking CCS and comprehensive fugitive emissions coverage, and so it is not suitable for the range of alternative marine fuels.

The most significant differences were found to be due to how the methods and tools dealt with LUC, co-product allocation, and fugitive emissions from production and use. The coverage of LUC and fugitive emissions for the four methods and tools is broadly summarised above. The methodologies differ in their treatment of co-products. While system expansion and economic allocation are highly complex, it is noted that RED II and CORSIA are both international legislative measures and both use energy allocation. Furthermore, WtW analysis did not always include all TtW emissions with global warming potential; notably RED II omitting in-use emission of CH_4 and N_2O as well as CO_2.

For blue fuels (relying on CCS to reduce their carbon intensity) the GHG emissions are sensitive to the effectiveness of CCS; at the time of writing there are still relatively few established CCS facilities in the world, most of which are only operating at pilot plant scale (Global CCS Institute, 2021). Consequently, a large degree of uncertainty remains on the actual feasibility and effectiveness of this technology at large scale. As carbon capture rates may vary with time, it is possible that monitoring or regulation may be required for carbon capture plants.

Quantifying fugitive emissions from production and use is also difficult, yet for methane can have a significant GHG impact. The GWP of methane is around three times higher over a 20-year timeframe than the typically considered 100-year timeframe. Therefore, when considering shorter-term climate impacts, the use of a 20-year timeframe for GWP is more scientifically appropriate, whereas when considering longer term climate impacts, the use of a 100-year timeframe is more scientifically appropriate. Whether to prioritise shorter- or longer-term climate effects is ultimately a policy decision, which falls outside the scope of this report. However, it is noted that the choice between using 20-year or 100-year timeframes for GWPs will affect the WtW calculation of GHG emissions from different fuels differently.

The application of life cycle principles to calculating the GHG impacts for all alternative marine fuels requires a means of accounting for the emissions of the fuel production and distribution (WtT), along with the in-use exhaust and fugitive emissions (TtW), including non-CO_2 emissions with GWP. This could be implemented through the way the GHG intensity of the fuel is calculated. Because of variations in feedstocks, production plants, and local distribution, the WtT element of the GHG intensity needs to be calculated for each fuel pathway and potentially each process or batch of fuel, while the exhaust emissions may require engine or vessel certification to reflect the powertrain technology and any exhaust catalysts. Even then, exhaust emissions may depend on the engine operational profile.

Boundaries for WtW evaluation of marine fuels

When applying life cycle assessment (LCA) principles, consideration should be given to the boundaries to include all relevant factors and allow a fair comparison at the lowest possible complexity level of the calculation. This report considered the appropriate boundaries for assessing marine fuels in different contexts.

- When considering the WtW GHG emissions of marine fuels the system boundary may include:
  - Fuel/electricity production including sourcing of feedstock, production, and fugitive emissions.
  - Fuel distribution and storage, including losses and energy consumption from compression and liquefaction (where applicable), and fugitive emissions.
  - Vessel operation phase including fuel conversion/combustion and exhaust and fugitive emissions, covering all fuel use (such as for auxiliary power and multi-fuel systems) and shore power electricity, and including non-CO_2 combustion emissions such as CH_4 and N_2O.

Recording of individual vessel fuel consumption and transport measures is already established through IMO DCS and for some vessels EU MRV regulations. To evaluate the WtW GHG impact of a vessel from its fuel consumption a GHG intensity factor can be applied.

- A WtW GHG intensity factor comprises the following elements:
  - A WtT factor for the fuel, established for each fuel type and production pathway, including the fuel distribution and bunkering processes.
  - A TtW emissions factor for the exhaust and fugitive emissions of the fuel in-use. While for today's engines and fuels, the GHG emissions are broadly proportional to the fuel used, in future, there may be marked differences in performance. An example would be for LNG engines, where some engines may have lower methane slip than others.

It is not unusual for vessels to use more than one type of fuel, whether alternatively or in combination (such as a pilot fuel), for propulsion or otherwise, and this is likely to become more common with the adoption of alternative fuels. Therefore:

- A WtW GHG methodology for the maritime sector should be able to fully accommodate dual-fuel systems for monitoring usage of all fuels used (whether for propulsion or otherwise) with their appropriate WtT and TtW emissions factors.

The use of shore power to remove the need to run auxiliary engines in ports may in future be mandated through legislation as is proposed in the EU, and already in place in China and California, for various larger vessel types. While this means less fuel is consumed on the vessel, it may not mean there are no net GHG emissions. Indeed, the evaluation of the GHG emissions of the electricity used may need to consider whether renewable, grid average or marginal factors are appropriate. Therefore:

- The GHG impact of electricity supplied for shore power or battery charging could be evaluated by measuring the energy provided and the use of an appropriate GHG factor for the electricity source.

With increasing uptake of lower/zero carbon fuels, the proportion of the lifecycle emissions associated with the vessel (construction, modification, and use) increase. This is particularly true for electrified and battery vessels, and not just for GHG but also wider sustainability criteria. In addition, the effect of future lower density fuels on the "utility" of the vessel (more space used by fuel, less available for cargo), and therefore its sustainability, may not be clear. This can only be assessed for a specific vessel design and usage.

- It is recommended to further study the relative emissions across lifecycle stages for a number of vessel types and energy vectors. This would inform whether guidance or legislation may be required in future.

Possible methodological approaches to calculating GHG emissions

The case studies shared a common input dataset for each fuel scenario to evaluate the differences resulting from the methods and tools. That there were differences reflects differing assumptions in the methods and tools, and the fuels and regions they were designed to cover.

The scope of this project cannot compare the benefits or demerits to the various land use change options. However, the CORSIA approach to LUC is an existing example of a framework covering international emissions and has the most comprehensive coverage of LUC among the methods and tools assessed.

- CORSIA represents a relevant model for how a maritime WtW method could treat LUC, though a mid-point between GTAP and GLOBIOM ILUC models could be used.
- Further work could identify appropriate approaches to LUC that address the required sustainability criteria, and which apply to the range of potential alternative marine fuels available globally.

The most appropriate approach to co-product assessment is a subject of debate, since it relies on artificially defined boundaries and which sub-system is deemed responsible for which share of the total emissions. System expansion is the preferred LCA approach according to the recommendations given by ISO (ISO 14044, 2006), and it also recommended by the ILCD handbook (JRC, 2010) for "consequential" LCAs (where the emphasis is on system-level change rather than on individual product units). However, energy allocation is a less complex and subjective approach. It is noted that of the methods and tools studied, RED II and CORSIA are both international legislative measures and both adopt the simpler energy allocation approach.

- In principle, system expansion is the preferred approach to co-product allocation, but given the complexities associated with system expansion, and to a lesser extent also with economic allocation, an energy allocation approach as set by RED II and CORSIA could be used.

The GHG impact from fugitive emissions can be significant for certain fuels (such as those containing methane). These can occur e.g., from leaks or boil-off venting of storage vessels. While such emissions can be difficult to accurately quantify (as discussed below), there is no justification to disregard them.

- Therefore, as far as practicable, marine fuel GHG calculation methods should account for fugitive emissions at all stages of the fuel pathway.

Consideration should be given to the appropriate time horizon over which to establish the CO_2e characterisation factors for all GHG emissions. The GWP of methane or black carbon emissions are much higher over a 20-year timeframe than the typically considered 100-year timeframe would indicate. The GHG emissions calculated for different types of fuels will be affected in different ways by the choice of timeframe.

- Further work could explore whether it is appropriate for GHG calculations for alternative marine fuels to capture short-term impacts as well as long-term ones, and how that may be achieved.

Establishing accurate data

While the use of common datasets allowed comparison of the methodological differences, the methods and tools also differed in the default data inventories provided. Given the global nature of the marine industry and the future diversity of fuels, production methods and geographies, a wider set of input data and emissions factors may need to be developed to allow more accurate evaluation of variation in WtW emission calculations. In some cases, this may be a relatively simple task, but in others such as land use change and upstream fugitive emissions, establishing widely accepted data could be challenging. Some data are specific to the fuel pathway, location or vessel and the use of default assumptions may be inappropriate.

- It is recommended that a future study reviews the differences between pathways, production method or locales for specific fuels to determine the differences in WtT emissions for a single fuel. This could then be used to determine whether different WtT factors are needed per pathway or supplier.
- Ongoing monitoring of certain aspects of fuel production is recommended due to differences in technology and process having a significant impact on the GHG intensity of the product.
- Further work could evaluate approaches to quantifying emissions (including fugitive) from alternative fuel production, storage, and distribution.

For future fuels, consideration of N_2O and CH_4 emissions from combustion or aftertreatment systems (including reagent consumption) will be critical, as these are expected to become a greater proportion of greenhouse gas emissions from shipping compared to today. This is likely to require some form of certification. It may also require monitoring of engine or ship, since emissions are likely to vary according to engine and exhaust emissions aftertreatment (catalytic converter) characteristics, use and indeed equipment health. On-board fugitive emissions should also be further evaluated.

- Further studies could evaluate approaches to establishing, certifying, and potentially monitoring non-CO_2 GHG emissions from vessels, including fugitive emission, as well as exhaust emissions from primary and any auxiliary powertrains.

Considerations for GHG emission assessment methods and standards for alternative marine fuels

From the analysis of existing GHG emission assessment methods and tools, Ricardo recommend that any WtW methodology applied to alternative marine fuels considers the following:

- Inclusion of in-use emissions of CO_2, CH_4 and N_2O, plus potentially black carbon.
- Inclusion of upstream emissions, particularly regarding methane leakage, energy used for production and carbon capture and storage rate.
- CORSIA represents a relevant model for the consideration of land use change, and RED II for considering co-product allocation.
- Any default data, assumptions, or emission factors provided should be conservative and the burden of proof for better values should be on the fuel producer or powertrain supplier.

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Glossary

Abbreviation	Definition
ADP	Abiotic Depletion Potential
AP	Acidification Potential
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use Change from Biofuels Production
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand
CH_3OH	Methanol
CH_4	Methane
CII	Carbon Intensity indicator (IMO)
C-LCA	Consequential Life cycle assessment
CNG	Compressed Natural Gas
Co	Cobalt
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
Cu	Copper
DCS	Data Collection System (IMO)
DLUC	Direct Land Use Change
EEDI	Energy Efficiency Design Index (IMO)
EEXI	Energy Efficiency Existing Ship Index
EN	European Committee for Standardisation
EP	Eutrophication Potential
EPA	Environmental Protection Agency (USA)
ETP	Ecological Toxicity Potential
ETS	Emissions Trading System (EU)

EU	European Union
FAME	Fatty Acid Methyl Esters
FU	Functional Unit
g	gram (unit of mass)
GHG	Greenhouse gas
GIA / Low Carbon GIA	Global Industry Alliance / GIA to Support Low Carbon Shipping
GLOBIOM	Global Biosphere Management Model
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model
GTAP	Global Trade Analysis Project
GTAP / GTAP-BIO	The Global Trade Analysis Project
GWP	Global Warming Potential
H_2	Hydrogen
HC	Hydrocarbon
HTP	Human Toxicity Potential
HFO	Heavy Fuel Oil
HVO	Hydrogenated Vegetable Oil
ICAO	International Civil Aviation Organization
ILUC	Indirect / Induced land use change
IMO	International Maritime Organization
IRP	Ionizing Radiation Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization (formerly International Standards Organisation)
JEC	Collaboration of European Commission's Joint Research Centre (JRC), the European Council for Automotive R&D (EUCAR) and Concawe
JRC	European Commission's Joint Research Centre
kWh	Kilo-Watt Hours
LCA	Life cycle assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LMC	Land management change
LNG / e-LNG	Liquified Natural Gas / synthetic LNG from renewable electricity
Low Carbon GIA	Global Industry Alliance to Support Low Carbon Shipping
LPG	Liquefied Petroleum Gas
LUC	Land use change
MJ	Mega Joule (measure of energy)
MRV	Monitoring, Reporting and Verification (EU)
N_2O	Nitrous Oxide
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NOx	Nitrogen Oxides (NO and NO_2)
ODP	Ozone Depletion Potential
PM, PN	Particulate Matter, Particulate Number

PMFP	Particulate Matter Formation Potential
POFP	Photochemical Ozone Formation Potential
PV	Photo-Voltaic (solar panels)
RED II	Renewable Energy Directive
RFS	Renewable Fuel Standard (USA)
RSB	Roundtable on Sustainable Biofuels
RTFO	Renewable transport fuel obligations (UK)
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
TtW	Tank-to-Wake (or Tank-to-Wheel)
UK	United Kingdom
US / USA	United States / United States of America
WtW	Well-to-Wake (or Well-to-Wheel)

1. INTRODUCTION

The Global Industry Alliance to Support Low Carbon Shipping (Low Carbon GIA), is a public-private partnership established under the framework of the GEF-UNDP-IMO Global Maritime Energy Efficiency Partnerships Project (GloMEEP Project). The Low Carbon GIA was launched with the aim to identify and develop innovative solutions to address common barriers to the uptake and implementation of energy efficiency technologies and operational measures. Since January 2020, the Low Carbon GIA has been operating under the GreenVoyage2050 Project[1], a joint IMO-Norway initiative to support implementation of the Initial IMO greenhouse gas (GHG) Strategy (resolution MEPC.304(72)).

With this report, the Low Carbon GIA is seeking to increase understanding of existing sustainability criteria and life cycle GHG emission assessment/calculation methods that are of relevance to marine fuels and identifying areas where further work is required. This is with a view to promoting the production and uptake of low carbon fuels and supporting IMO Member States and the wider maritime sector in gaining a better understanding of the environmental impact of alternative fuel options for the maritime sector.

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1.1 BACKGROUND

The use of fossil fuels is almost universal across the shipping industry, although in recent years vessels with alternative energy sources have been introduced in small numbers. While a range of low-carbon and zero-carbon energy sources are potentially available for shipping, currently there is no clear decarbonisation path or paths. Each of the options has merits and practical challenges, with differing technical maturity and infrastructure availability. It is likely that in the future a range of solutions will be adopted according to different vessel and operational requirements.

However, understanding the actual lifecycle GHG emissions from each energy source is essential, including how the energy source is produced and distributed as well as at point of use. And hence, it is critical to have clarity on how GHG emissions from alternative fuels will be calculated and accounted for in order to be able to compare options.

While carbon dioxide (CO_2) emissions dominate GHG emission from shipping, the role of other well-mixed GHGs such as methane (CH_4), nitrous oxide (N_2O) and some halogenated species should also be considered (though halogenated species are not usually included in assessments of fuels for combustion).

Additionally, a distinction is to be made between non-biogenic and biogenic CO_2 emissions. The former derive from the combustion of fossil fuels and represent a net addition of CO_2 to the atmosphere. Conversely, the latter derive from the combustion of the carbon contained in fuels which have been produced by processing biomass substrates (i.e., biofuels). In principle, since the same amount of carbon (on a molar basis) was previously absorbed from the atmosphere through photosynthesis during the biomass growth phase, the biogenic CO_2 emissions result in a net-zero addition of CO_2 to the atmosphere over the full life cycle of the fuel. However, there are other non-net-zero emissions associated with their combustion, such as agriculture, production, and refining. Therefore, this type of net carbon accounting only holds fully if it can be proven that the totality of the biomass was in fact grown sustainably (e.g., from well-managed short-rotation plantations that lead to net zero standing biomass change over time); otherwise, a partial (non-zero) net addition of CO_2 to the atmosphere would still ensue.

There are also wider concerns related to biofuels' GHGs which need to be considered before concluding on whether any one particular biofuel should be considered 'net zero' or 'carbon neutral'. These are discussed further in a dedicated Text Box in Section 5.1.

Beyond CO_2, short-term climate forcers such as NOx, SOx, organic and black carbon, ammonia, CO and NMVOC can also increase or decrease global warming, either as GHGs or via changes in anthropogenic

[1] https://greenvoyage2050.imo.org

aerosols. Their influence is less well understood as the location and timing of the emissions will significantly change their impact, and thus they are not usually considered.

To combine GHG emissions with different lifetimes and infrared absorption spectra, their quantities are multiplied by their specific global warming potentials (GWP) relative to that of CO_2, over a given time frame; one hundred years and twenty years (GWP100[2] and GWP20[3] respectively) are commonly used. The Intergovernmental Panel on Climate Change (IPCC) has aligned on using GWP100 as the default option for reporting.

When it comes to fossil fuels, GHG emissions arising from on-vessel fuel combustion (referred to as "Tank-to-Wake" or TtW) typically contribute the majority of the total GHG emissions along the entire fuel life cycle (which is referred to as "Well-to-Wake" or WtW). While fuels containing no carbon entail zero TtW CO_2 emissions, they may produce N_2O during combustion. Importantly, the GHG emissions over their supply chains (i.e., from "Well-to-Tank" or WtT) may vary from zero to significant, depending on the method of production. Indeed, WtT emissions of a fuel are largely determined by the production pathways and important factors including whether renewable electricity is used, whether fugitive emissions are captured, and the process efficiency (e.g., see (Pavlenko N, 2020)).

Furthermore, the sustainability of fuels is about more than their GHG emissions alone. Other environmental considerations for each energy source need to be understood, such as air and water pollution (both in use and in production and distribution), and disruption and damage to ecosystems with associated loss of biodiversity; the use of scarce resources including land, water, feedstock, and energy; and societal concerns for food competition, human rights. However, while a concise high-level overview of a range of additional environmental impact categories as currently addressed by life cycle assessment is provided hereinafter in Section 3, it should be recognised that there can be impacts that are difficult to quantify, while societal and economic sustainability considerations fall outside of the intended scope of this document.

1.2 PURPOSE OF THE STUDY AND ITS CONTENTS

Ricardo have been contracted by the Low Carbon GIA to carry out a study to identify relevant sustainability criteria and life cycle GHG emission assessment / calculation methods for the production and use of alternative marine fuels.

The study aims to map out relevant existing and upcoming standards and regulations applying such criteria and methods and assemble relevant sustainability criteria for alternative marine fuels that provide for the broader considerations needed for sustainability than just GHG emissions. To complement the sustainability criteria, this study reviews the standards and regulations relevant to fuels and from other transport modes to identify the GHG emission calculation methods that would be appropriate for marine fuels, covering WtT and TtW components (see Figure 1-1). Many existing fuel standards and regulations of varying scopes have been designed for specific use cases, and thus have limits in their applicability to the global marine sector. In this study such gaps have been identified, and the options to close those gaps and to tailor the methods for the maritime sector are explored. To exemplify the methods, the study includes examples ("case studies") that work through both the sustainability criteria and the calculations of GHG emissions for a selected number of fuel pathways.

[2] GWP100 refers to GWP calculated using characterisation factors with a 100-year time horizon. This is a better indicator of long-term climate change potential, thereby assuming reduced average characterisation factors for those meta-stable GHGs that gradually degrade/oxidise to form other chemical species which are characterised by a lower GWP.

[3] GWP20 refers to GWP calculated using characterisation factors with a 20-year time horizon. This better captures the short-term climate forcing potential of those GHGs, like CH_4, which initially have a high GWP but gradually degrade/oxidise to form other chemical species which are characterised by a lower GWP (e.g., in the case of CH_4, CO_2 is the end-point oxidation product).

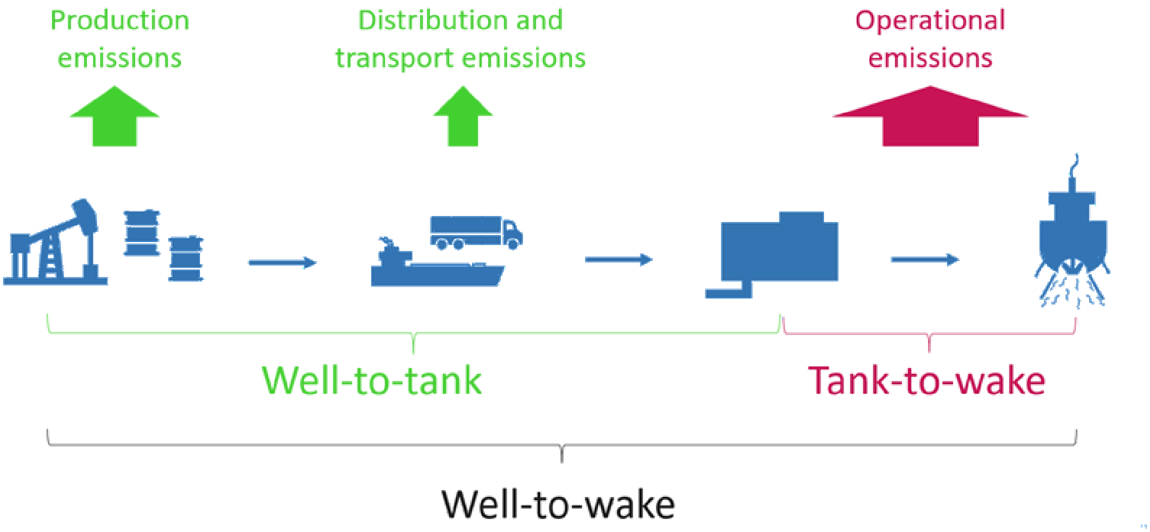

Figure 1-1: Well-to-wake (WtW) accounting encompasses the sum of well-to-tank (WtT) and tank-to-wake (TtW) emissions (Source: IMO)

1.3 FUTURE USES OF THIS STUDY AND INTERACTION WITH EXISTING EFFICIENCY REGULATIONS

Currently, the emissions from shipping are calculated by applying the appropriate fuel CO_2 factor by the amount of fuel used. This CO_2 factor is a measure of the amount of CO_2 released per unit of fuel used and does not consider other pollutants or upstream emissions.

Under the IMO approach for existing ships using fossil fuels, ship efficiency will be evaluated (from 2023) using the Carbon Intensity indicator (CII). CII is a measure of how efficiently a ship transports its cargo in terms of CO_2 emissions, and is calculated with the following formula:

$$\text{CII} = \frac{\text{Annual fuel used} \times \text{Fuel CO}_2\text{ factor}}{\text{Annual distance travelled} \times \text{Capacity}} \times \text{Correction factors}$$

In the case of CII, the *Fuel CO_2 factor* simply reflects the amount of CO_2 released when the fuel is completely combusted. This factor does not consider any WtT emissions or other non-CO_2 TtW emissions, such as methane slip or N_2O. For traditional marine fossil fuel oils, these simplifications miss only a small proportion of the total WtW GHG emissions. However, for non-traditional fossil fuels and future non-fossil fuels, the simplification may no longer be sufficient, since in some cases it results in significant omissions, as will be shown in this study. Therefore, WtW carbon dioxide equivalent factors calculated using the methods identified in this study could be used as a replacement of the existing CO_2 factor in future versions of CII.

The Energy Efficiency Design Index (EEDI) is an efficiency standard for new shipbuilding and is normally the responsibility of the shipyard. As the calculations are complex, they will not be repeated here. However, as with the operational CII, the fuel CO_2 factor is included, to enable the conversion between specific fuel consumption and emissions.

1.4 REPORT STRUCTURE

To achieve these objectives, this final report from the study has been structured as follows:

- This **Section 1** has outlined the background to the study, its purpose, and contents

- **Section 2** introduces life cycle assessment principles and considers how they are to be applied to marine fuels, including the selection of appropriate boundaries for this study
- **Section 3** explores the sustainability criteria for assessing the impact of alternative marine fuels and assesses their likely importance
- **Section 4** reviews regulations, standards, and guidelines, concerning the environmental impact of fuels across all transport sectors, and their relevance for the maritime sector. From this, established methods and tools for calculating GHG emissions from the use of alternative fuels are investigated, and a shortlist of methods and tools to apply to the case studies are selected
- **Section 5** considers three case studies covering different fuel types and production pathway scenarios. The selection of the case study scenarios and the details of their pathways is described, showing how they were selected to demonstrate a range of fuel types and production methods. Each case study is evaluated through the methods and tools shortlisted in Section 4, and the differences between and the significance of gaps/omissions in the methods reported
- **Section 6** discusses the findings from Sections 2 to 5 with application to alternative marine fuels. In particular, the application of standards and methods for evaluating GHG emissions of international shipping is considered, ensuring they would apply to all relevant marine fuels globally and that they would address the appropriate sustainability criteria and emissions scope, highlighting lessons learned from the evaluation of case studies, and discussing what an ideal method might look like.
- Finally, **Section 7** summarises the recommendations from this study including where further work is needed or is already ongoing.

The study has been carried out in close consultation with the Low Carbon GIA to ensure the coverage remains aligned to their aims, particularly in selecting appropriate and relevant case study fuel pathway scenarios as discussed in Section 5.1. Ricardo have engaged internal experts covering alternative (low-carbon and bio) fuels, life-cycle analysis, marine sector, powertrains and emissions, and other specialists as required.

2. LIFE CYCLE ASSESSMENT APPLIED TO THE MARITIME SECTOR

While the scope of this study covers WtW emissions for fuels, elements of the TtW emissions also depend on the vessel design, voyage, weather, and other factors that unrelated to the fuel.. For this study to establish an analysis method for comparing fuels it was decided to exclude these factors, and so, as explained in Section 2.2, the shaft work output of the propulsion system was selected as the output (functional unit) of the fuels analysis. The TtW stage therefore includes powertrain fuel efficiency and exhaust emissions while excluding vessel-specific factors, which can be considered *a vessel-independent harmonised WtW*.

2.1 LIFE CYCLE ASSESSMENT PRINCIPLES

Life cycle assessment (LCA) as an instrument of environmental analysis has been established since the 1980s. The LCA approach represents an important method for the characterisation and identification of environmental burdens of systems. ISO14040 (2006) and ISO14044 (2006) standards provide the common basis for LCA studies and include general requirements for all aspects of a product or system's lifecycle. However, due to the broad scopes of LCA studies today the ISO norms still leave many methodological aspects to be further defined by the LCA practitioner.

In practice LCA is a fit-for-purpose procedure to record and evaluate environmentally relevant processes. Originally developed primarily to evaluate products, it is now also used for processes, services, and behaviour. The results of LCAs can be used to optimise processes for sustainable production, but also for policy development. Depending on the time horizon (current or future situation) different modelling approaches can be taken. The key strength of an LCA lies in the fact that all stages of the product or process life cycle are taken into consideration. If the analysis focused on a single process stage or a subsection of the product life cycle (e.g., only the use phase of a fuel), grave misinterpretation of environmental impacts may occur.

The main guiding principles of an LCA are therefore: (1) all material flows associated with the system under consideration (raw material inputs and emissions from supply and disposal processes, energy generation, transport and other processes) must be taken into account; and (2) a wide and diverse range of potential harmful effects on the environment, in terms of emissions to soil, air and water, as well as depletion of resources, may in principle be taken into account, thereby enabling the analyst to highlight any potential trade-offs or impact shifting that may be taking place between different types of impact.

2.2 CONSIDERATION OF FUNCTIONAL UNITS AND BOUNDARIES

Before evaluating the calculations for GHG emissions and other sustainability metrics for a range of marine fuels / energy carriers, an assessment of appropriate Functional Units and Boundaries was carried out. The Functional Unit (FU) represents the reference product or service to which the input and output flows from the life cycle inventory are related. The Boundaries (or Scope) determine which processes are included in the assessment and need to be in accordance with the goal of the study. This assessment is required to ensure a consistent framework for the comparison of the fuel alternatives, including their suitability for application to the marine sector, and to avoid potentially drawing misleading conclusions.

2.2.1 Consideration of appropriate Functional Units for this study

For the WtT section of the analysis, the fuels can be fairly analysed and compared on a basis of *per MJ of delivered energy*. When considering Tank to Wake, however, an appropriate Functional Unit must be chosen. Much of the published literature and standards have focussed on road vehicles, and the functional unit often used is "transport work" – emissions per unit of cargo x distance (CO_2 per tonne-km) often for a specified vehicle. This unit is chosen as it enables a fair comparison of the utility of the fuel, considering all effects of the fuel on the vehicle, and its analogue for marine is CO_2 per tonne-nautical mile, abbreviated as t-nm.

Listed below are some examples of why this approach is challenging when considering marine fuels rather than a specific vessel:

- In comparison to road transport, marine vessels have much greater variation in physical and operational characteristics, from a few metres long, to in excess of four football pitches, from tankers to container ships to offshore service vessels.

- For some vessel types, a low energy density fuel would have a significant effect on cargo capacity, whereas for others, the effect might be minimal.
- There are potential energy saving devices (e.g. wind assistance) which may have a significant effect on the amount of fuel used to transport a cargo a certain distance. These could be implemented on some vessels but be impractical for others.
- The relevant cargo "unit" associated with the transport work above differs depending on vessel categories, such as deadweight tonnage, cubic metres or twenty-foot equivalent unit, or indeed passengers carried.

For these (and other) reasons, it is not considered appropriate for this study to use a single TtW functional unit including transport work that is appropriate for all vessel types. Instead, it is proposed to apply a functional unit considering energy conversion from tank to propeller-shaft, including conversion losses, exhaust emissions and fugitive emissions – that is, emissions per unit of powetrain system output work (CO_2e/MJ). For the purposes of the case studies in this project, Ricardo has proposed typical thermal efficiencies of large marine engines using the three fuels. For different powertrain types, such as fuel cells or smaller engines, the TtW efficiency and emissions will vary, necessitating different factors. Vessel type and specific design elements will need to be considered outside of the "shaft energy" approach, as is done now with CII & EEDI, and described in Section 1.3.

The relative boundaries of these functional units are illustrated in Figure 2-1, showing how using shaft work excludes the characteristics specific to a vessel, its payload or cargo, and voyage, but includes the powertrain efficiency and emissions. Auxiliaries driven by the main powertrain are also included in this definition, although if separate generators are used it should be noted their efficiency will differ, and this case is ignored for the purposes of this study (that is, any auxiliary uses of the fuel are assumed to have the same efficiency as the main engine). Also, the use of shore-power is ignored as it would not impact shaft work and is not a factor in considering the emissions of the fuel pathway. The powertrain efficiency is defined as the work output divided by the energy content of the fuel used; for the case studies in this report fuels are considered in isolation, but for dual-fuel vessels the two fuel pathways should be considered in parallel by calculating an appropriate powertrain efficiency for each fuel, attributing the work done according to the proportions of the fuels used and their calorific value, and totalling the GHG impacts for the vessel.

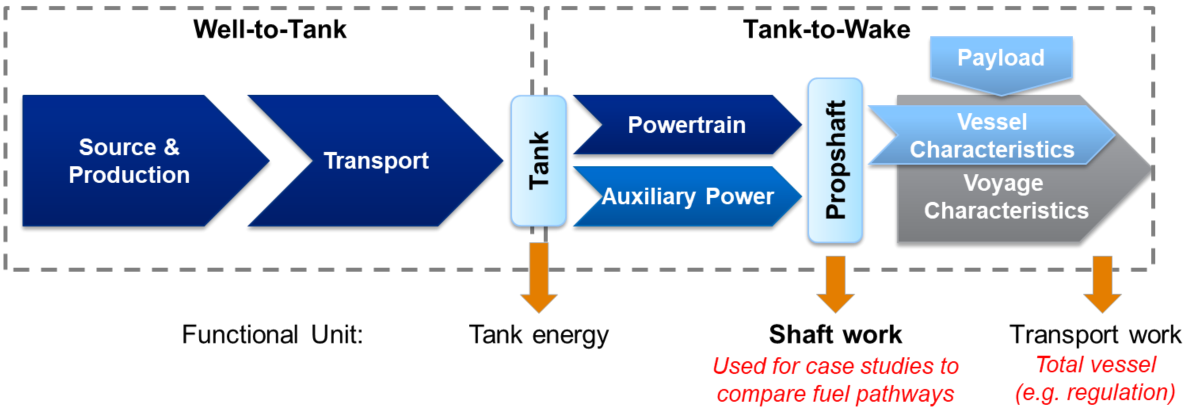

Figure 2-1: Functional units for fuel life cycle calculations from well to wake

By excluding the vessel and voyage characteristics from the case studies it could be argued that they do not represent a *true* WtW, since they stop at the propeller shaft. However, since the scope is to cover the fuel pathway in isolation of the vessel-specific considerations, the use of shaft work is chosen for the case-studies as a vessel-independent "normalised" WtW measure of the fuel pathway.

2.2.2 **Consideration of boundaries**

The definition of the system boundary is a key preliminary step in any life cycle/WtW study, as it essentially determines which life cycle/supply chain stages and processes are included, and often even seemingly small differences in system boundaries may result in significant changes to the results. Ideally, the boundary should be as broad as possible, thereby including all the processes that directly and indirectly contribute to the system under study, from the extraction of all the raw resources, to the intended point of use of the delivered product.

In principle, this all-inclusive approach would ensure that no potentially significant contributions to the overall environmental impacts are overlooked, irrespective of whether they occur in the "foreground" of the system (i.e., those parts of the system that are under the direct control of the operator), or in the "background" (i.e., in those sub-systems whose role is to provide the technical material and energy inputs to the foreground operations, including, e.g., the generation of electricity used as an energy input to the system, and the manufacturing of the various assets required along the supply chain of the product, such as transport vehicles, storage vessels, roads, etc.). Depending on the goal of the study, the system boundary may also be extended in time to cover the future operations related to the end-of-life management of the product(s) and all the assets involved. From a practical standpoint, however, there are always a range of time and resource considerations that limit the extent to which the system boundary can be extended. The choice of what to include in the analysis and what to instead leave out must then be informed by pre-existing knowledge, or – in the absence thereof – best educated inferences on the likely relevance of the relative contributions of the various foreground and background processes towards the overall impact assessment results.

In the specific case of the marine fuel supply chains being considered here, it is our recommendation that the system boundary should include[4]:

- Fuel/electricity production (including feedstock cultivation and harvesting, extraction, and fugitive emissions, allowing for waste streams and by-products)
- Fuel conversion processes such as compression and liquefaction (where applicable)
- Fuel transport and dispensing
- Fuel conversion at point of use (e.g., for hydrogen carrier fuels)
- Vessel operation phase (propulsion and ancillaries)

The impacts associated with the construction of ports and fuel/electricity infrastructure are expected to be minimal when expressed per functional unit, given (i) their long service lives and (ii) that their use is shared by many other systems. As a result, they are excluded from the boundary of this study. Impacts associated with land use change related to biomass and renewable power installation on the other hand have been considered.

[4] Given the focus is on a Well-to-Wake analysis, the production and end-of-life of the vessel are not included.

3. ENVIRONMENTAL SUSTAINABILITY CRITERIA FOR MARINE FUELS

The assessment of the ways in which a product or service may impact on the environment should go beyond GHGs and GWP. In this section the range of sustainability criteria applicable to alternative marine fuels are considered. Strictly speaking, the term **sustainability criteria** refers to often partly subjective value judgements and choices, and they entail thresholds. These are formed based on an assessment of **impact categories** against **impact indicators**. For example, for a fuel to be considered sustainable against a particular impact category, the impact indicator must meet a stated target.

Impact categories are used in LCA to investigate a diverse range of potential environmental impacts caused by a product or a service. Many such environmental impact categories have been defined, each addressing a different *type of impact* (JRC, 2010) (Althaus et al. , 2010), and LCA can calculate corresponding quantitative **impact indicators** (also referred to as "impact metrics") for each of these impact categories, which are *numerical values*, expressed in category-specific units (cf. Table 3-1). Other types of environmental and ecosystem impacts are so far not quantifiable by LCA, and as such – important though they may be – they are not included in the brief high-level overview provided in this Section. Additionally, as already mentioned in Section 1.1, societal and economic sustainability considerations fall outside of the intended scope of this document, and they are therefore not discussed in here either.

Table 3-1 lists the specific impact categories and associated impact indicators that have been selected for consideration here; this shortlisting was done of the on the basis of their prominence in the LCA literature, the recommendations given by the UNEP-SETAC Life Cycle Initiative[5], the European Commission JRC guidelines for Product Environmental Footprints[6], and Ricardo expert knowledge.

Table 3-1: Selected LCA impact indicators, with brief description thereof

Impact Indicator	Units	Brief description of type of impact category
Global Warming Potential (GWP)	kg(CO_2-eq)	The enhanced trapping of heat in the atmosphere (i.e., the "greenhouse effect") by those gaseous emissions whose electromagnetic spectra present absorption bands in the infrared region.
Ozone Depletion Potential (ODP)	kg(CFC11-eq)	The destruction of the protective ozone layer in the polar regions of the Earth's stratosphere brought about by the interaction of certain gaseous emissions (e.g., CFCs) with NOx and UV radiation.
Acidification Potential (AP)	kg(SO_2-eq)	The potentially damaging effects of acidic atmospheric depositions (i.e., rain, sleet, snow) which ensue from the natural hydration of acidic gaseous emissions (e.g., SOx, NOx) in the presence of atmospheric humidity.
Particulate Matter Formation Potential (PMFP)	kg(PM_{10}-eq)	The release of fine particulates into the lower troposphere, with potentially adverse effects on the human respiratory system.
Photochemical Ozone Formation Potential (POFP)	kg(NMVOC-eq)	The release of meta-stable volatile organic compounds which, in the presence of UV radiation and NOx, give rise to a series of photochemical reactions that ultimately lead to the formation of ozone and other secondary pollutants and respiratory irritants (such as peroxy-acyl nitrates) in the lower troposphere.

[5] https://www.lifecycleinitiative.org/reaching-consensus-on-recommended-environmental-indicators-and-characterisation-factors-for-life-cycle-impact-assessment-lcia/
[6] https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html

Impact Indicator	Units	Brief description of type of impact category
Human Toxicity Potential (HTP)	Comparative toxic units (for humans) CTUh	The cumulative potential human toxicity of a range of gaseous, liquid and solid emissions; characterization factors depend on estimates of environmental fate (i.e., how each emission ends up being distributed among different environmental compartments) and human exposure (i.e., the extent to which each emission is bio-available to humans). HTP may be further split into cancer and non-cancer HTP.
Eco-Toxicity Potential (ETP)	Comparative toxic units (for ecosystems) CTUe	The cumulative potential ecosystemic toxicity of a range of gaseous, liquid and solid emissions; characterization factors depend on estimates of environmental fate (i.e., how each emission ends up being distributed among different environmental compartments) and ecosystem exposure (i.e., the extent to which each emission is bio-available to a range of key organisms in the ecosystem). ETP may be further split into Freshwater, Marine water, Freshwater sediment, Marine water sediment, and Soil ETP.
Eutrophication Potential (EP)	kg(PO_4^{3-}-eq)	The cumulative "fertilization" effect of a range of emissions that can act as phytonutrients (i.e., emissions containing bio-available forms of N, P and K). The release of such emissions may ultimately cause excessive algal blooms and ensuing die-offs, which in turn leads to oxygen starvation and loss of aquatic biomass across all food chain levels.
Ionizing Radiation Potential (IRP)	kg(U^{235}-eq)	All emissions of radioactive elements, which have potentially carcinogenic effects.
Cumulative Energy Demand (CED)	MJ(oil-eq)	This is not, rigorously speaking, an LCA impact category, but rather an impact metric that accounts for the total harvesting of renewable (i.e., solar, wind, water geopotential, tidal, and biomass energy) and non-renewable (i.e., fossil and fissile fuels) primary energy resources from the geo-biosphere.
Non-renewable Cumulative Energy Demand (nr-CED)	MJ(oil-eq)	This is a sub-set of CED, which accounts for the total harvesting of non-renewable (i.e., fossil and fissile fuels) primary energy resources only, from the geosphere.
Abiotic Depletion Potential (ADP), elements	kg(Sb-eq)	The demand for mineral resources (excluding energy resources such as fossil and fissile fuels), relative to their scarcity (estimated on the basis of the respective total crustal content).
Abiotic Depletion Potential (ADP), fossil	MJ(oil-eq)	The demand for energy resources (i.e., fossil and fissile fuels); it largely (albeit not exactly) duplicates the indication provided by nr-CED.
Water use	m^3	The total water withdrawal-to-availability ratio, where "withdrawal" refers to all off-stream water use (i.e., excluding the water that is extracted and then returned to the environment unpolluted, like e.g., cooling water), and "availability" is estimated using a regionalized characterization model that takes into account competition with other users of freshwater.
Land use	m^2*a	This relates to all degradative land use, and also takes into account the length of time over which such use is sustained, and the degree to which the land can be restored to its original condition after the use has ceased.

It is important to point out that a degree of conceptual simplification is adopted in LCA, whereby all impact categories are assumed to be independent of one another; i.e., an increase (or decrease) of impact in any one category is assumed not to induce (neither directly nor indirectly) any change in impact in any other category. While the various impact categories are defined in such a way that this simplifying assumption does hold true in first approximation, it may however not fully capture potential synergistic effects between some of the different types of impact. For instance, an increase in the acidity of atmospheric depositions (e.g., acid rain) may in fact lead to increased bio-availability of some metal emissions, which in turn would lead to increased human and ecological toxicity potentials.

A second consideration related to the various impact categories is to do with interpretation of the associated impact results. When comparing alternative products, the indications provided by different impact categories may point to opposite rankings / orders of preference, whereby for instance product A may be characterized by a higher impact in category 1 (e.g., GWP) *vs*. product B, whereas conversely product B may have a lower impact than product A in category 2 (e.g., HTP). While accurate, such results may be difficult to translate into a clear policy recommendation. Individual impact results may be combined into a single indicator of "overall" environmental impact through the optional LCA steps of normalisation and weighting, which however entail subjective value judgements, since the weighting factors for the individual category-specific impact indicators cannot be based on scientific considerations alone. As a result, while potentially useful from the point of view of facilitating the interpretation and communication of the LCA results, normalisation and weighting (and any ensuing aggregated indicators of "overall" environmental impact) are formally recommended against by ISO 14044 for all "comparative assertions intended for public disclosure".

One first way in which the various LCA impact categories (and associated indicators) may be grouped is to do with whether the impact itself is caused by the demand for resources ("upstream" impact), or by the release of emissions ("downstream" impact). Emission-related impact categories can further be classified according to the geographical scale affected by the impact: "global" impacts are those that affect the whole planet, irrespective of where the emissions are generated, whereas "regional" impacts are those that only affect the specific geographical areas where the emissions are released[7].

The following three tables Table 3-2, Table 3-3 and **Table 3-4** present a high-level identification of the comparative performance of a range of potential alternative marine fuels/energy carriers with respect to each of the considered impact categories.

For concision and simplicity, and because the indications provided in these tables are not intended as rigorous quantitative results for any one specific fuel pathway, but rather as high-level semi-qualitative indications of "likely relevance", the alternative marine fuels/energy carriers were broadly categorised into the following groups:

- "Green" fuels – synthetic fuels produced from non-fossil fuel substrates and using renewable electricity (e.g., e-H_2, e-NH_3, e-methane, e-methanol)
- "Blue" fuels – synthetic fuels produced from fossil fuel substrates with carbon capture and sequestration (CCS) technologies (e.g., H_2, NH_3)
- Hydrogen from plastic waste
- Biofuels from organic waste, including from agricultural residues (biodiesel, biomethane, bioethanol)
- 1st generation biofuels from non-waste substrates (biodiesel, bio-fatty acids, bio-fatty acid methyl esters, biodiesel from hydrogenated vegetable oils, bio-methanol, and bioethanol)
- Electricity (produced from a range of possible technologies and technology mixes, and intended to be used in electric power trains)

The three tables respectively focus on impact categories and indicators for:

- global emissions, including Global Warming Potential (GWP) (Table 3-2);
- regional emission-related impacts (Table 3-3);
- resource use and depletion (Table 3-4).

In each table, each fuel group is ranked from "low" (L) to "high" (H) in terms of its likely relative mid-point[8] impact indicator per unit of energy delivered. This ranking was arrived at based on Ricardo expert knowledge and literature, also drawing from previous work by Ricardo on LCA of road transport fuels/power trains (Ricardo-DG CLIMA, 2020). It bears reiterating, though, that the relative "low" to "high" ratings provided for the various fuel groups within each impact category are to be interpreted as indicative, as only a set of fully fledged

[7] However, it should be acknowledged that LCA is typically incapable of accurately tracking the exact geographic distribution of these "regional" types of impacts as they occur along the supply chain of a product (e.g., along the WtT chain in the case of marine fuels). This is essentially because the life cycle inventory stage of an LCA moves from the local foreground inventory level to the global life-cycle inventory level (which includes all background processes too) in a single step, resulting in a long list of inputs and outputs at the global scale, which are then all classified and characterised together to arrive at the category-specific mid-point indicators.

[8] Mid-point impact indicators are measured in equivalent units of a category-specific reference resource or emission (e.g., CO_2-eq in the case of Global Warming Potential) and eschew the subsequent normalization and weighting steps of life cycle impact assessment, which aim at combining various category-specific impact indicators into a single a-dimensional metric of overall "environmental impact". According to (ISO 14044, 2006), normalization and weighting are optional steps, and, since they always entail subjective value judgements, their use is explicitly prohibited in all "comparative assertions intended for public disclosure".

LCAs would allow their rigorous final ranking (and clearly, the latter falls outside of the intended scope of this document).

A range of environmental sustainability criteria may then be set. Each criterion usually entails a quantitative threshold for a specific LCA impact indicator (which in turn measures the impact in a corresponding impact category). A given fuel may thus be deemed “sufficiently sustainable” if its impact indicator is lower than that pre-set threshold.

Based on the analysis of the information presented in Table 3-2, Table 3-3 and Table 3-4, the following environmental impact categories were identified as being of high relevance, and therefore of importance when considering sustainability criteria for alternative marine fuels:

- Large Global Warming Potential (GWP) and Cumulative Energy Demand (CED) impacts for 1st generation biofuels from non-waste substrates, the former primarily due to land use change (LUC) carbon emissions. These emission flows are often not reported in many commonly employed life cycle databases, and they must be carefully accounted for separately. A range of sources of quantitative information for these LUC carbon emissions exist, as discussed in Section 4.3.2, among which for instance the GLOBIOM report (Ecofys-IIASA-E4tech, 2015). GWP may also be significant for hydrogen, ammonia, and other “blue” and “green” fuels, depending on a range of factors, including: the source of electricity used, any fugitive methane emissions from Steam Methane Reforming (SMR) and from methane combustion, any N_2O emissions from ammonia combustion, and the effectiveness of Carbon Capture and Storage (CCS).
- Large Eutrophication Potential[9] (EP), also from land use as well as water use impacts for 1st generation biofuels from non-waste substrates.
- Large Particulate Matter Formation Potential (PMFP) for biodiesel (both from waste and non-waste substrates), from the use phase[10]
- Potentially large Ecological and Human Toxicity (ETP and HTP) and Abiotic Depletion[11] (ADP, elements) impacts of material demand associated to (i) electricity as an energy carrier and (ii) “green” hydrogen and hydrogen precursor fuels. These are due to the increased demand for metals for renewable electricity generation. Also, when assessed including the use phase, ETP and HTP are further increased due to the metal demand for electric motors, batteries and fuel cells (if used).
- Large land and water use for 1st generation biofuels from non-waste substrates.

[9] Eutrophication Potential is the impact of over-fertilisation or excess supply of nutrients on land or aquatic environments, in particular nitrogen and phosphorous, leading to increased plant/algae growth and bacterial use of oxygen

[10] Particulate matter emissions from combustion of biodiesel are typically lower than fossil diesel

[11] Abiotic Depletion Potential (elements) measures the cumulative use of a range of non-fuel and non-living natural resources, such as metals and minerals, each weighted according to its relative scarcity.

Table 3-2: Global emission-related impact categories and indicators, with indication of likely relevance

Impact indicator	Fuels/energy carriers and associated supply chains					
	"Green" fuels (H_2, NH_3, CH_4, CH_3OH)	"Blue" fuels (H_2, NH_3)	H_2 from plastic waste	Biofuels (bio-CH_4, bio-ethanol, bio-diesel) from organic waste	1st generation bio-fuels (bio-ethanol, bio-diesel) from non-waste resources	Electricity (for use in battery electric power trains)
Global Warming Potential (GWP)	L / M [a]	M [b]	L [c] / M [d]	L [c]	H [e]	L [f]
Ozone Depletion Potential (ODP)	L	L	L	L	L	L

Indication of likely relevance: L(ow)/M(edium)/H(igh)

[a] Potentially med for CH_4 / CH_3OH and NH_3 due to, respectively, fugitive CH_4 and N_2O emissions.
[b] Potentially low GWP for H_2 if using CCS.
[c] Assuming cut-off rule assigning zero upstream impact to waste substrate.
[d] If carbon emissions from plastic waste are simply vented (instead of captured).
[e] High impact due to LUC emissions.
[f] Depends on mix of technologies used for electricity generation (low impact for renewables and nuclear); impact per tonne-km[12] is favourably influenced by comparatively higher power train efficiency.

[12] (tonne*km) is the default unit used in virtually all LCAs for all transport-related impacts; it is however acknowledged that in marine shipping, distance is more usually measured in units of nautical miles (nm).

Table 3-3: Regional emission-related impact categories and indicators, with indication of likely relevance

Impact indicator	Fuels/energy carriers					
	"Green" fuels (H_2, NH_3, CH_4, CH_3OH)	"Blue" fuels (H_2, NH_3)	H_2 from plastic waste	Biofuels (bio-CH_4, bio-ethanol, bio-diesel) from organic waste	1st generation bio-fuels (bio-ethanol, bio-diesel) from non-waste resources	Electricity (for use in battery electric power trains)
Acidification Potential (AP)	L / M [a]	L / M [a]	L	M	M	L [b]
Particulate Matter Formation Potential (PMFP)	L	L	L	low / H [c]	H [c]	L
Photochemical Ozone Formation Potential (POFP)	L	L	L	M	M	L
Human Toxicity Potential (HTP) [d]	H [f,g]	L / H [g]	L / H [g]	M	M	H [h]
Eco-Toxicity Potential (ETP) [e]	H [f,g]	L / H [g]	L / H [g]	M	M	H [h]
Eutrophication Potential (EP)	L	L	L	M	H	L
Ionizing Radiation	L / M [i]	L	L	L	L	L / M [i]

Indication of likely relevance: L(ow)/M(edium)/H(igh)

[a] Potentially higher for NH_3 if significant boil-off occurs.
[b] Depends on mix of technologies used for electricity generation (low impact for renewables and nuclear).
[c] For bio-diesel when assessed per tonne-km (i.e., including use phase emissions).
[d] Cancer and non-cancer HTP may be calculated separately, if using the USETox LCIA method (recommended by ILCD for Environmental Footprints (JRC, 2010)).
[e] Marine water ETP may also be calculated separately. Additionally, it may be informative to also calculate marine water ETP impacts for the operational phase (i.e., WtT) emissions only, to assess the direct impact during the operation of the vessel.
[f] Primarily due to metal demand for renewable electricity. Note that NH_3 itself is toxic in the event of leakage.
[g] When assessed per tonne-km, also due to copper and other technology-specific metals demand for power trains (if using Fuel Cells and electric motor).
[h] Primarily due to copper and other technology-specific metals demand for renewable electricity; when assessed per tonne-km, also due to copper and other technology-specific metals demand for powertrain (motor and batteries).
[i] If nuclear is used to generate low carbon electricity.

Table 3-4: Global resource-related impact categories and indicators, with indication of likely relevance

Impact indicator	Fuels/energy carriers and associated supply chains					
	"Green" fuels (H_2, NH_3, CH_4, CH_3OH)	"Blue" fuels (H_2, NH_3)	H_2 from plastic waste	Biofuels (bio-CH_4, bio-ethanol, bio-diesel) from organic waste	1st generation bio-fuels (bio-ethanol, bio-diesel) from non-waste resources	Electricity (for use in battery electric power trains)
Cumulative Energy Demand (CED)	M [a] / H	M	L [b]	L [b]	H	L [c]
Non-renewable Cumulative Energy Demand (nr-CED)	M	M	L [b]	L [b]	M	L [c]
Abiotic Depletion Potential (ADP), elements	H [d,e]	L / H [e]	L / H [e]	L	L	H [f]
Abiotic Depletion Potential (ADP), fossil	L	H	L	L	M	L
Water use	L	L	L	M	H	L
Land use	L	L	L	L	H	L

Indication of likely relevance: L(ow)/M(edium)/H(igh)

[a] Renewable electricity generation is generally efficient in terms of MJ(el)/MJ(primary energy). Also, if assessed on WtW basis, results in this category are favourably affected if fuels are used in higher-efficiency power trains (e.g., fuel cells).
[b] Assuming cut-off rule assigning zero impact to waste substrate.
[c] Depends on mix of technologies used for electricity generation (low impact for renewables and nuclear); impact per tonne.km is favourably influenced by comparatively higher power train efficiency.
[d] Primarily due to metal demand for renewable electricity.
[e] When assessed per tonne.km, also due to copper and other technology-specific metals demand for power trains (if using Fuel Cells and electric motor).
[f] Primarily due to copper and other technology-specific metals demand for renewable electricity; when assessed per tonne.km, also due to copper and other technology-specific metal demand for power train (motor and batteries).

4. LIFE CYCLE GHG EMISSION ASSESSMENT METHODS AND STANDARDS FOR ALTERNATIVE MARINE FUELS

4.1 RELEVANT EXISTING STANDARDS AND REGULATIONS

In order to inform the possible methods for estimating GHG emissions from the marine sector, existing and upcoming standards and regulations covering a range of transport sectors and pollutants were reviewed for the broadest possible understanding of approaches to controlling emissions and to assess their potential applicability to the maritime sector.

4.1.1 Evaluation and index of standards, regulations, and guidelines

The identified regulations, standards, and guidelines mapped and evaluated are listed Table 4-1. Further details are found in Appendix 1 which lists the full range of criteria used for the evaluation and provides a summary for each entry, including the key attributes, a brief synopsis of coverage, and comments on observations against the criteria used, for each of the listed entries. The following discussions reference the regulations, standards, and guidelines using *italics*, please refer to the index for full descriptions and details.

This mapping of the regulatory and standards landscape covers a broad range of transport sectors and regions to understand how sustainability impacts are controlled, especially GHG and pollutant emissions. The following discussion considers where approaches used for other sectors are different to the maritime sector, or have coverage where the maritime sector does not, and whether lessons can be learned, or principles transferred. The applicability over the well-to-tank-to-wake/wheel lifecycle of the fuel, and whether other sustainability considerations are included, is assessed. Methods and guidelines for calculating the GHG emissions impacts from alternative fuels are identified, whether from regulations or other sources, to be considered in Section 4.2 for evaluation against the case studies.

Table 4-1: List of evaluated standards, regulations, and guidelines

Regulations and policies evaluated	
IMO MARPOL / NOx Technical Code	IMO Energy Efficiency Design Index (EEDI)
IMO Ship Energy Efficiency Management Plan (SEEMP)	IMO Data collection system for fuel oil consumption of ships
IMO Energy Efficiency Existing Ship Index (EEXI)	US EPA Emissions standards for marine engines
European Union Monitoring, Reporting and Verification (MRV) of carbon dioxide emissions from maritime transport	International Shipping Commission Lake Constance Shipping Regulations
European Union Euro 6 Emissions from light duty road vehicles	US EPA Emissions standards for heavy duty vehicles
European Union Euro VI Emissions from heavy duty vehicles and non-road sources	US EPA Emissions standards for non-road engines
European Union EU Stage V Emissions from non-road mobile machinery (NRMM)	US EPA CAFE & SAFE
European Union Fuel Economy & CO2 emissions for light duty road vehicles	US EPA (NAAQS) National Ambient Air Quality Standards
European Union Heavy Duty Vehicles - CO2 emissions standards	California Air Resources Board (CARB) California Global Warming Solutions Act (AB32)
European Union On board fuel consumption monitoring	California Air Resources Board (CARB) 13 CCR, section 2299.2
European Union EU Emissions Trading System (EU ETS)	United Nations ICAO CORSIA
European Union FuelEU Maritime	UK Government Transport Decarbonisation Plan
European Union Fuel Quality Directive (FQD)	US EPA Renewable Fuel Standard Programme (RFS)
European Union EU Renewable Energy Directive (REDII)	UK Government Renewable transport fuel obligations (RTFO)
US EPA Regulation Of Fuels And Fuel Additives - Subpart I of 40 CFR Part 80	European Union Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)
Standards, guidelines, methods, and tools evaluated	
EU standards EN 14214, EN 228, EN 590, EN 589, EN 14214, EN 15940	ISO standards ISO 8217, ISO 23306, ISO 14687
Zemo Partnership Renewable Fuels Assurance Scheme (RFAS)	RSB (Roundtable on Sustainable Biomaterials) RSB-STD-01-001 RSB Principles & Criteria
European Union International Sustainability Carbon Certification (ISCC)	ISO 14040/14044 Life cycle assessment
European Union and Intelligent Energy Europe BioGrace	U.S Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy GREET
JRC, EUCAR, and Concawe: JEC WtW Report (Prussi, et al., 2020)	Ecoinvent database
GHGenius LCA model	IFEU GHG calculator

4.1.2 Control of pollutant emissions

Regulations to control transport pollutant emissions are well established, such as *IMO MARPOL Annex VI NOx Technical Code, US Environmental Protection Agency* (EPA) *Emissions standards for marine engines, Euro Stage V* for non-road machinery (including inland waterways), and *Euro 6/Euro VI, US EPA and California Air Resources Board* (CARB) regulations for road vehicles. Many other countries choose to adopt either the EU or US regulations, although some such as Japan have their own. These all share the principle of measuring engine emissions over standard test cycles (either within the vehicle or on a test stand) with limits for pollutants, including Nitrogen Oxides (NOx), Hydrocarbons (HC), Particulates by Number (PN) and Mass (PM), and Carbon Monoxide (CO), although the pollutants included, and measurement methods vary. Since they consider fuel use, they do not cover WtT emissions. Their aim is to protect human health including reducing smog, and do not cover GHG or other sustainability impacts. The approaches do not usually measure actual emissions in-use, although on-board measurements for validation and in-service conformity, along with on-board diagnostic sensors are increasingly used for road vehicles.

Fuel standards from the International Standards Organisation (identified as ISO…) or national equivalents, or the European Committee for Standardisation (identified as EN…), are used to control fuel composition and properties. As well as ensuring the fuel is safe to use and gives the expected performance, limitations on the content of polluting elements such as sulphur, lead, hydrogen sulphide, and carbon residue, serve to reduce emissions of these harmful substances in use. However, these do not cover GHG emissions or other sustainability impacts, and only consider in-use (TtW) emissions.

Control of emissions related to the contents of the fuel is implemented by regulations which mandate the use of fuels that meet specified standards, or a maximum concentration of specific elements, and so reduce the emissions of pollutants linked to the fuel composition. In the marine sector the IMO limits sulphur content in fuel to reduce sulphur oxide emissions through MARPOL Annex VI, with most recently a global limit reduction in 2020, following stricter limits in designated emission control areas covering certain regions.

4.1.3 Reduction of GHG emissions

Regulations for reducing GHG emissions from transport have been introduced in recent years and vary according to sector, focusing on the in-use TtW emissions.

For cars and vans the CO_2 emissions are measured at certification/homologation over a defined cycle in an emissions lab. While manufacturers are incentivised to produce vehicles with low emissions through customer demand influenced by CO_2-emission related taxes, the legislative driver is a target set for the average CO_2 emissions of all the vehicles sold by each manufacturer (or group/alliance of manufacturers) in a year, which demands decreasing emissions and has led to increasing shares of hybrid and electric vehicle sales, as established by the EU regulation *Fuel Economy & CO_2 emissions for light duty road vehicles*, and in the US by the Environmental Protection Agency (EPA) *Corporate Average Fuel Economy* (CAFE), and *Safer Affordable Fuel Efficient* (SAFE). These schemes allow for emissions to be "traded" between under and over performing manufacturers. Similar schemes apply to heavy duty vehicles set out in EU *Heavy Duty Vehicles - CO_2 emissions standards*, and US EPA *Emissions standards for heavy duty vehicles*; and manufacturers face heavy fines for each g/km of CO_2 per vehicle sold over the limit. There is no in-use GHG emissions measurement for road vehicles (although in some cases CO_2 emissions from on-road tests have been published) and homologation tests are considered to provide a poor indication of real-world in-use emissions. The EU is introducing on-board monitoring of fuel consumption, but it is not yet clear how this will be used. However, in many countries a policy of road fuel taxation is used to encourage fuel efficiency and so GHG emissions reduction.

The regulation of GHG emissions from road vehicles is primarily focused on CO_2 except for heavy duty vehicles in the EU, for which emissions of CH_4 are limited in the certification test (as with pollutant emissions), although total HC emissions (so including CH_4) are limited, and future Euro 7 standards for both light and heavy-duty vehicles are expected to include limits for CH_4 and N_2O. US regulations exclude methane from pollutant emissions limits. Soot and/or particulates are limited through vehicle certification tests, but not considered for greenhouse effects as black carbon.

For international aviation, the International Civil Aviation Organisation (ICAO) *Carbon Offsetting and Reduction Scheme for International Aviation* (CORSIA) focuses on offsetting carbon emissions, although it is not currently mandatory (until 2027). However, flights within the EEA are covered by the EU *Emissions Trading System* (ETS) along with power generation and large industries; this provides allowances (carbon credits) for GHG emissions which reduce year-on-year, with fines for exceedance although carbon credits can be traded, and covers 40% of EU GHG emissions. Many EU Member States have taken additional measures, although it is being further strengthened (now in 4th revision) and targets reduced. Similar schemes apply in other regions including the UK, California, and some associated US states.

For the maritime sector, the IMO adopted an initial strategy on the reduction of GHG emissions from ships in 2018, which set out an ambition for at least a 50% reduction in GHG emissions by 2050 compared to 2008, with an objective of phasing them out entirely as soon as possible. Measures adopted include the *IMO Energy Efficiency Design Index* (EEDI) which requires continually improving efficiency and reducing CO_2 emissions per tonne mile from new ships (and similarly the *Energy Efficiency Existing Ship Index* (EEXI) will monitor existing vessels), while the fuel consumption of vessels in-use is monitored through the IMO *Data Collection System* (DCS), and in Europe through the parallel EU *Monitoring, Reporting and Verification* (MRV) regulation.

Additionally, new mandatory measures to cut the carbon intensity of international shipping were adopted by the IMO in 2021 and the proposals presented by the European Commission in the EU *Fit for 55* package seek to expand ETS coverage to include the maritime sector for intra-EU journeys as well as half of journeys into or out of the EU. While DCS and MRV are based on TtW emissions, the EU *Fit for 55* package includes a broader WtW approach in the *FuelEU Maritime* initiative, which aims to increase the use of renewable and low-carbon fuels as described below.

The use of residual fuel oils in the marine sector contributes to emissions of black carbon, identified as a significant cause of global warming, especially when emitted in the Arctic, with 100- and 20-year CO_2e GWP of 900 and 3200 respectively (Comer, Olmer, Mao, Roy, & and Rutherford, 2017). The IMO is looking at how to measure and report on black carbon emissions with a view to considering regulatory options for controlling them[13].

As with the regulations covering pollutant emissions, and with the exception of the *FuelEU Maritime* initiative as discussed below, these GHG regulations consider the emissions from vehicles/vessels in-use (that is, TtW), and do not account for emissions in the production or distribution of fuels. Their focus is on CO_2 emissions although increasingly other GHG emissions including CH_4, N_2O, and black carbon are being considered where relevant, albeit limited to the use-phase of the fuel. Since the regulations are largely based around traditional fossil fuels the GHG emissions and other environmental impacts are not considered over the life cycle of the fuel, omitting emissions from production and distribution, such as fugitive releases (e.g., of methane) which may be significant for some fuels. However, renewable and biofuels are covered by additional regulation.

4.1.4 **Renewable fuels and sustainability**

The use of biofuels to displace a proportion of fossil fuels is encouraged through the EU *Fuel Quality Directive* (FQD) in conjunction with the *Renewable Energy Directive* (RED II), the similar UK *Renewable transport fuel obligations* (RTFO), and the US EPA *Renewable Fuel Standard* (RFS) *Programme*, which set minimum targets for the fuel suppliers to meet a proportion of fuel to come from renewable sources, along with methods for calculating their GHG emissions. Voluntary certification schemes such as *Roundtable on Sustainable Biofuels* (RSB) *standard*) and *Zemo Partnership Renewable Fuels Assurance Scheme* (RFAS) are based on RED II and RTFO methods respectively. Work on developing guarantees of origin certification for low-carbon hydrogen for the EU (CertifHy[14]) and the United Kingdom (currently undergoing consultation by UK government[15]) are also based on these methods. These affect a range of transport sectors including (in a limited way) maritime where alternative and renewable fuels are used.

These regulations take a broader life-cycle approach to considering the GHG emissions for fuel pathways from WtW, including regulating the source of energy used in fuel production, and have stipulations about feedstock sources, their impact on LUC and other sustainability concerns.

The recent EU *Fit for 55* package proposed changes to increase the adoption of renewable fuels in transport, and RED II will be revised to increase the use of energy from renewable sources, improve energy system integration (with other regulations), and increase protection for biodiversity. *FuelEU Maritime* will effectively apply the RED II approach to fuels sold to the maritime sector within the EU, but with the vessel owner as the obligated party rather than the supplier. Similarly, *RefuelEU Aviation* will boost the supply and demand of sustainable aviation fuels (low-carbon fuels for aviation) in the EU, while a review of the *Energy Taxation Directive* will aim incentivise low carbon and renewable fuels.

4.1.5 **Relevance for alternative zero and low carbon marine fuels**

The existing maritime regulations for GHG reduction focus on TtW reduction (and specifically CO_2 emissions) since they are designed in the context of fossil fuel use, with default emissions factors for the limited range of fuels used, although the impact of black carbon and how it may be reduced is now being considered. Other potential GHG emissions including CH_4 and N_2O are not quantified or controlled, nor are the fuel production and distribution emissions (including potentially significant fugitive emissions), or other environmental impacts

[13] IMO Sub-Committee on Pollution Prevention and Response (PPR 8), 22-26 March 2021. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/PPR-8.aspx

[14] CertifHy project: https://www.certifhy.eu/

[15] Low Carbon Hydrogen Standard Consultation (UK): https://www.gov.uk/government/consultations/designing-a-uk-low-carbon-hydrogen-standard

over the life cycle of the fuel. However, biofuels and low carbon fuels are covered by cross-sector regulations that do cover WtT emissions and sustainability concerns.

In the EU the proposed extension of the ETS (already applied to power generation, industry, and aviation) to include part of the maritime sector along with the measures proposed in *FuelEU Maritime* will incentivise operational and technical efficiency measures, increase the use of shore power in some sectors and *FuelEU Maritime* is specifically designed to encourage uptake of alternative fuels. Other transport sectors have regulations that encourage the use of alternative fuels in place, notably for road transport where a proportion of fuel must be renewable, and the uptake of zero-emission vehicles is heavily incentivised. Both the EU ETS and ICAO CORSIA schemes have received criticism for being too weak, while road vehicle CO_2 measures have been reported as not reflecting real world emissions since they are established in laboratory homologation tests, and actual fuel consumption measures are not yet available.

The regulations and standards around the use of alternative sustainable fuels include EU REDII (and the similar UK RTFO, and the voluntary *Roundtable on Sustainable Biofuels* (RSB) *standard*); US EPA RFS (and similar from CARB); and ICAO CORSIA. These all include WtT analysis methods and some considerations of wider sustainability impacts, and so have relevance to considering alternative fuels for the maritime sector regardless of their actual scope. While neither a regulation nor a standard, the JRC Well-to-wheels report (Prussi, et al., 2020) also serves as a guideline on WtT analysis and sustainability. These are discussed in more detail considering how they are applied to GHG emissions and sustainability measures in Section 4.2, and in the application of the case studies in Section 5.

4.2 SYNOPTIC OVERVIEW OF EXISTING STANDARDS, REGULATIONS, METHODS AND INVENTORIES FOR CALCULATING OR MEASURING GHG EMISSIONS AND SUSTAINABILITY IMPACTS OF MARINE FUELS

Using the existing knowledge of the Ricardo experts and the findings of Task 2 indexing standards and regulations, a list of established methods/tools and inventories applicable to fuel pathways was compiled. These methods and tools were evaluated against the following key criteria:

- Overview:
    - Type (i.e. guideline/method *vs*. standard *vs*. regulation *vs*. certification *vs*. inventory)
    - Energy vectors covered
    - Relevant date
- Well to Tank:
    - Impact categories considered
    - Production pathways considered
    - Geographic distribution
- Tank to Wake:
    - Energy conversion
    - System efficiency
    - Lifetime
    - Sector of application

The full list of attributes evaluated for each method/tool and their groupings is summarised in Table 4-2 These attributes were then reviewed for each method to assess what would be included within the case studies.

In total twelve standards, methods, tools, and inventories for GHG and sustainability evaluation have been reviewed and are listed in Appendix 2 with a short synopsis of each, and a comment on their relevance to this study. This includes their coverage of the impact categories discussed in Section 3. These standards, methods, tools, and inventories were selected due to their relevance to the project and recognition within the industry. This indicates that they are not all independent, and their relationships are highlighted.

Table 4-2: Attributes for evaluation of reviewed standards, methods, and inventories

			RSB - stds & certification	CARB/LCFS	RTFO	REDII	CORSIA	US RFS	JEC WTW	GHGenius	BioGrace	GREET	ecoinvent	IFEU GHG calculator
Overview	Type	Guideline/methodology	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y
		Standard	Y	N	N	N	N	Y	N	N	N	N	N	N
		Regulation	Y	Y	Y	Y	N	N	N	N	N	N	N	N
		Certification scheme	Y	Y	Y	N	Y	Y	N	N	Y	N	N	N
		Default values/inventory	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N
		Blue H2	N	N	Y	N	N	N	Y	Y	N	Y	N	N
		Green H2	N	N	Y	N	N	N	Y	Y	N	Y	N	N
		Ammonia (green/blue)	N	N	N	N	N	N	N	N	N	Y	Y	N
		Synthetic hydrocarbons	N	N	Y	N	Y	N	Y	Y	N	Y	Y	N
		Biofuels	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
		Electricity	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y
Well to Tank	Impact categories	CO_2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
		GWP	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
		Air Quality (AP, PMFR)	N	N	N	N	N	N	N	Y	N	Y	N	Y
		Toxicity (HTP, ETP)	N	N	N	N	N	N	N	N	N	N	N	Y
		Energy Use (CED, ADP)	N	Y	N	N	Y	N	Y	Y	N	Y	N	Y
		Land use	N	N	N	N	Y	N	N	Y	N	Y	N	Y
		Resource depletion	N	N	N	N	N	N	N	Y	N	Y	N	Y
	Production	Carbon source	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
		Carbon capture	Y	N	Y	Y	N	N	Y	Y	Y	Y	N	N
		Carbon storage	Y	N	Y	N	N	N	Y	Y	Y	Y	N	N
		Energy use	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
		Counterfactual	N	N	Y	Y	N	N	N	Y	N	N	N	Y
		Energy source	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
		Fugitive emissions	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Distribution	Included Y/N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
		Transport/pipeline	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
		EV Grid/charging efficiency	Y	N	N	N	N	N	Y	Y	N	Y	Y	Y
		Recharge/discharge	N	N	N	N	N	N	N	N	N	N	N	Y
		Compression/liquefaction	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y
Tank to X		Energy conversion	N	N	N	N	Y	N	Y	N	N	Y	Y	Y
		System Efficiency	N	N	N	N	N	Y	Y	N	N	Y	Y	Y
		Lifetime/degradation	N	N	N	N	N	Y	N	N	N	Y	Y	Y
	Sector	Road	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y
		Marine	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	Y
		Air	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y
		Other	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	Y

4.3 SHORTLIST OF METHODS AND TOOLS TO BE APPLIED TO THE CASE STUDIES FOR CALCULATING OR MEASURING GHG EMISSIONS

Following the evaluation of all reviewed standards, methods, tools, and inventories as described above, four were shortlisted to be applied to the case studies. As detailed in Appendix 2 these were found to be of high relevance since they were independent of each other, include a range of sector and geographical perspectives, and provided a method with sufficient coverage and specific guidance for application to marine fuels, albeit with some choices to be made around methodology selection and assumptions as described below. General LCA standards and guidelines without specific guidance for fuels pathways, e.g., ISO 14040/14044, were excluded from the review, as were tools (such as GHGenius) or databases (such as Ecoinvent) that do not strictly define a method of calculation, and standards that follow or are broadly similar in approach to those selected. The selected methods and tools are:

- Renewable energy directive (RED II)
- JEC (JRC-EUCAR-Concawe) Well to Wheels study
- Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET)
- ICAO CORSIA carbon certification

These four standards and tools were found to be the only major relevant ones suitable for the purposes of this study, and they have been reviewed in detail through their application to the case studies with a view to identifying any loopholes or omissions.

4.3.1 Renewable energy directive (RED II)

The Renewable Energy Directive (RED II, Directive (EU) 2018/2001)[16] sets binding targets for all EU Member States to increase the use of energy from renewable sources, including a specific target for the transport sector. It establishes strict sustainability and GHG emission saving criteria (see Text Box 4-1) which biofuels, bioliquids and biomass fuels[17] must comply with to be counted towards the renewable energy target.

RED II also establishes the calculation method for deriving the GHG emission savings from biofuels, bioliquids and biomass fuels and provides a set of typical and default values for a range of pathways. These should be used unless the economic operator decides to use actual values (or a combination of default and actual values) for their fuel pathway. The methodology covers GHG emissions from the production and use of biofuels, bioliquids and biomass fuels, including:

- Emissions from the extraction or cultivation of raw materials
- Annualised emissions from carbon stock changes caused by land-use change
- Emissions from processing
- Emissions from transport and distribution
- Emissions from the fuel in use;
- Emission savings from soil carbon accumulation via improved agricultural management
- Emission savings from CO_2 capture and geological storage; and
- Emission savings from CO_2 capture and replacement.

However, emissions of the fuel during combustion are assumed to be zero for biofuels. The methodology also specifies that the impacts of co-products from the production and use of fuels should be considered in the calculations and allocated based on the energy allocation method (further details are found in Appendix 4).

The European Commission is also preparing the method to determine the share of biofuel, and biogas for transport, resulting from biomass being processed with fossil fuels in a common process, and the method for assessing GHG savings from renewable liquid and gaseous renewable fuels of non-biological origin (RFNBOs) and from recycled carbon fuels (RCFs). The revision to RED II proposed as part of the Fit for 55 package in July 2021 includes consideration of RFNBOs, but currently while it states a minimum GHG saving they must achieve there is no methodology for them.

To qualify for RED II targets, biofuels need to demonstrate compliance with the sustainability and GHG emission saving criteria through national verification systems or European Commission-approved voluntary schemes. Tools such as BioGrace[18] have been used help verify the GHG emission saving calculations in the auditing process. However, BioGrace I has not been recently updated and therefore is not in line with the sustainability criteria of the RED II and cannot be used to demonstrate compliance.

A use of RED II within the maritime sector is already established. The Roundtable on Sustainable Biofuels (RSB) voluntary certification scheme covers shipping and uses RED II as its basis, while RED II will also form the basis of the method used in certifying fuels for WtT GHG intensity in the FuelEU maritime regulations recently proposed by the European Commission (which includes all zero-carbon fuels and propulsion methods).

[16] Repealed the previous Directive (Directive 2009/28/EC – RED I). In July 2021, the European Commission proposed a revision of RED II as part of the Fit for 55 package to deliver on the European Green Deal.

[17] *Biofuels* are defined as liquid fuels made from biomass and consumed in transport. *Bioliquids* are defined as liquid fuels made from biomass and used to produce electricity, heating or cooling. *Biomass fuels* are defined as solid or gaseous fuels made from biomass.

[18] The BioGrace is an EU-funded project which developed GHG calculation tools: BioGrace I calculates the GHG emissions for the 22 biofuel production pathways in line with the RED method. BioGrace II calculates the GHG emissions for electricity, heating and cooling from biomass in line with the RED II method.

Text Box 4-1: Sustainability and greenhouse gas emissions saving criteria in RED II (Article 29)

Biomass production

- RED II establishes that biofuels must not be produced from raw materials originating from protected areas, high biodiversity lands and high carbon stock lands, including wetlands, peatlands, forests.
- In addition, RED II sets additional criteria to minimise the risk of using forest biomass derived from unsustainable production and to ensure the legality of harvesting operations, the regeneration of harvested areas and the maintenance of soil and long-term forest productivity.
- Also, RED II sets out that biofuels and bioenergy from forest materials must comply with requirements on LULUCF (land-use, land-use change and forestry).

Biomass end-use performance

GHG emission reductions[19] to be achieved by biofuels used in transport are at least:

- 50% for installations starting operations before 5 October 2015,
- 60% for installations starting operations after 6 October 2015 and before 31 December 2020,
- 65% for installations starting operations from 1 January 2021

In addition, it establishes that GHG emissions savings from renewable liquid and gaseous transport fuels of non-biological origin (such as electro-fuels) need to be at least 70% from 1 January 2020 – if they are used to comply towards RED II targets.

1.1.1 JEC (JRC-EUCAR-Concawe) Well to Wheels study

JEC (JRC-Eucar-Concawe) is a collaboration between three entities, the European Commission's Joint Research Centre (JRC), the European Council for Automotive R&D (EUCAR) and Concawe. The JEC's ultimate goal is to support the sustainability of European vehicle and oil industry and provide the EU with policy-neutral scientific facts.

A core objective is to evaluate energy use and emissions related to engine and vehicle technologies, fuel qualities, and the interaction between them. This is demonstrated through the JEC WtW study that provides data on over 250 resource to fuel pathways and over 60 powertrain combinations resulting in over 1,500 possible combinations. The study is regularly updated to keep pace with technological development and innovation and version 5 has recently been published.

The study presents energy use and GHG balances for the different combinations of fuel and powertrain in road transport. It does not consider the maritime sector, but the method for estimating emissions can be applied in the same way, particularly the WtT. The scope of the analysis covers WtT and TtW including fuel production, transport and distribution, and use within the vehicle.

The study uses a consequential LCA methodology for calculating the impact of co-products on final emissions. It draws attention to the validity of this methodology and has a section comparing consequential and attributional LCA methods. However, they caveat their work by stating that the values in the report remain focused on a product-basis comparison and do not include detailed modelling of possible scale-driven consequences or market-mediated effects on other sectors of the economy. Therefore, the results can provide a useful guide but should not be used for large-scale, strategic policy decisions.

4.3.2 Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET)

GREET is a USA-centric, self-enclosed and largely self-sufficient simplified LCA modelling tool which has been developed by Argonne National Laboratory since 1999 (Argonne National Laboratory, 2021) for the analysis of non-conventional vehicles – including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) – and transport fuels. Based on the description given by Argonne National Laboratory on their website, GREET is a specific integrated tool for a quick and pragmatic

[19] The fossil fuel comparator is set at 94 g CO_2/MJ

assessment, intended to be used "*to perform life cycle analysis simulations of alternative transportation fuels and vehicle technologies in a matter of a few clicks*". Consistently with its primary aim, GREET contains general information about emissions from all fuel supply stages (Well-to-Tank) as well as from vehicle operation, including for marine vessels (Tank-to-Wake), which are appropriate for calculating GHG emissions in terms of carbon dioxide equivalents (CO_2e), as well as primary energy use and a limited set of regulated emissions to air. However, it does not contain enough information for the assessment of emissions to water and soil.

Overall, GREET is agile, user-friendly, and relatively powerful as a stand-alone method, and covers the majority of the attributes identified for the purposes of this study. Specifically, as of May 2021, the latest release of GREET (Argonne National Laboratory, 2021) includes, among other things:

- an expanded marine module to include six methanol pathways for its production from natural gas, flare gas, biomass, renewable natural gas, coal, and black liquor
- electro-fuels (e-fuels) pathways using high-purity CO_2 from ethanol production with renewable electricity and low-carbon hydrogen
- low-carbon ammonia (i.e., green ammonia) production pathways using N_2 from air separation technologies and H_2 from renewable and industrial by-product sources
- four pathways for performance-enhancing, drop-in biofuel blends that improve engine efficiency for spark ignited engines and reduce engine out emissions for compression ignition engines
- waste-to-energy, waste-to-product and palm fatty acid distillate pathways for renewable diesel production
- renewable natural gas production via anaerobic digestion
- land management change (LMC)-driven soil carbon emission factors
- a Feedstock Carbon Intensity Calculator for farm-level carbon intensity calculation of corn produced as bioethanol feedstock
- pathways for animal feed (co)production including formulations of soybean meal, corn, distiller-dried grains with solubles and synthetic amino acids.

However, it is also acknowledged that GREET is otherwise severely limited in terms of its ability to be used as a more general LCA tool for applications outside of its originally designated primary scope.

GREET allows for different approaches to account for multi-output processes, allowing system expansion, or allocation between the co-products on the basis of mass, energy or market value (i.e., economic) (cf. Appendix 4 for a full discussion of these alternative approaches). This is because it is a model that is designed to be flexible and allow implementation of different methodological approaches. This puts it in stark contrast to RED II, which instead is intended as a regulatory standard, and as such it specifies all aspects of the method to be applied, including the allocation method.

Use of GREET in the case studies

For the purpose of comparing the methods and tools certain assumptions were made in the application of GREET to the selected fuel pathways. This is because GREET is flexible and allows for multiple approaches to be undertaken, and as such a defined approach is needed.

For the purpose of the comparison the system expansion approach (cf. Appendix 4) was selected for use in GREET.

Other specific assumptions depend on the individual fuel pathways and are discussed in detail when introducing the case studies themselves (Section 5.1). A full list of data and assumptions can also be found in Appendix.

4.3.3 ICAO CORSIA carbon certification

ICAO established CORSIA in 2016.

CORSIA eligible fuels include Sustainable Aviation Fuels (SAF) and Lower Carbon Aviation Fuels (LCF). So far, though, detailed guidelines (ICAO, 2021) and default life cycle emission factors (ICAO, 2021) have only been provided for a set of SAF pathways, which do not include renewable fuels of non-biological origin (RFNBO). However, for the purposes of being able to compare methods, Ricardo followed the CORSIA approach for biofuels, applied to RFNBOs. It is expected that as RFNBOs become available, CORSIA will be expanded to include RFNBOs. These covered pathways are:

1. Fischer-Tropsch (FT) pathways from agriculture/forestry residues and woody/lignocellulosic crops, and from MSW
2. Hydroprocessed esters and fatty acids (HEFA) pathways from oil crops and used cooking oils
3. Synthesised iso-paraffins (SIP) pathways from sugarcane/sugarbeet
4. Alcohol pathways from agricultural/forestry residues and corn/sugarcane/herbaceous crops

The basic guiding principles of the CORSIA method are:

1. Including GHG emissions beyond just CO_2. However, it is noteworthy that non-CO_2 emissions from the aircraft tailpipe are excluded due to concerns on measurement accuracy and on their effects (partly due to the comparative importance of contrails). The latter sources of uncertainty do not apply to marine vessel emissions, and so it is our recommendation that all direct operational GHG emissions should be included for the purposes of the study.
2. Taking a full life-cycle perspective. Specifically, the CORSIA framework makes it clear that it that does not automatically allow all biofuels to claim zero CO_2 emissions on the life-cycle scale, and it includes default indirect land use change emission factors for various crops, based on GTAP-BIO (Taheripour, Hertel, Tyner, Beckman, & Birur, 2008) and GLOBIOM (Ecofys-IIASA-E4tech, 2015) (cf. Section 5.3.2).

Another key aspect of the CORSIA method is that multi-output processes are modelled by using energy content allocation (cf. Appendix 4) for all co-product (except for waste flows, which are assigned zero impact).

5. CASE STUDIES APPLYING GHG EMISSION ASSESSMENT METHODS AND TOOLS

Three case study fuels are used to demonstrate how the methods and tools for evaluating GHG emissions and other sustainability criteria (as explored in Section 3) could work in practice. The four methods and tools identified in Section 4.3 have been applied to each case study fuel to identify their gaps, weaknesses, and key sensitivities.

There were two approaches taken where gaps were identified. Firstly, where the gap could be considered a conscious part of the process, for example including direct land use change, but not indirect, the case study was assessed leaving the gap as intended. Secondly, where there were gaps in fuels or pathways considered by the method, such as RED II not including blue fuels or ammonia, reasonable assumptions were made based on other included pathways.

The case studies are used to understand and compare the methods and tools as applied to maritime fuel pathways. They are not definitive final assessments of the GHG intensity of the fuels evaluated.

5.1 CASE STUDY SELECTION

The selection of appropriate fuels for case studies was not straightforward as there are a wide range of potential fuel types or energy vectors that have potential for application to the marine sector. Also, most have multiple production pathways that could be adopted, with many differing views for their suitability and potential.

Therefore, in consultation with the Low Carbon GIA, the following key criteria were applied for the selection of case studies:

- The aim for the case studies was to showcase the methods and tools and their divergence, rather than explore the fuels themselves. Ideally, the three case studies should act as a tool to study the main processes and emissions of future marine fuels rather than necessarily reflecting the most likely fuels themselves (though the fuels chosen should be relevant to the maritime sector).
- However, the chosen fuel types should be relevant and appropriate for marine use in the short or long term.
- While an existing fossil fuel such as HFO would have provided an interesting baseline, the associated WtT phase was considered unlikely to be a good test of methods, and it was considered that there would be more value in focusing on future fuels since they have more complex and varied production pathways.
- LNG was of interest to evaluate how, for example, liquefaction, fugitive emissions and methane slip are considered in the methods and tools, and because replacement low-carbon fuels such as e-LNG could be an attractive drop-in option for LNG.
- Electricity was seen as relevant for shore power as well as batteries; also, although less interesting as a fuel/energy pathway in itself, it is a significant requirement for "green" electro-fuel production.
- The three key fuel pathways to be covered were:
    - "Green" synthetic fuels capturing the significance of renewable power/ electricity mix and carbon source;
    - "Blue" fuels based on fossil fuel production with integrated carbon-capture technologies in the WtT stage; and
    - "Bio" with considerations of land-use changes and/or waste streams.

Based on these criteria, the fuel types and production pathways of green synthetic methane (e-LNG), blue ammonia and renewable diesel fuel from Hydrogenated Vegetable Oil (HVO) discussed below were agreed for the case studies.

As well as meeting the criteria established above, these fuels were chosen for realistic production scenarios where reasonable data are available, although data for low maturity processes (such as Direct Air Capture) may still have some uncertainty.

Each of the case studies is introduced in turn, describing the assumed realistic production pathway. Associated emissions are included for all process components discussed in the case study process descriptions. The quantitative inputs into each case study are detailed in Appendix 3.

There is ongoing debate, particularly within Europe, about the principle of additionality of electrolysis based fuels. Therefore, in order to demonstrate the effect of a realistic carbon intensity of e-fuels, where a renewable electricity supply is included for a specific pathway, a carbon intensity has been applied to that electricity based on Fthenakis (2021). To understand the effect of electricity carbon intensity, the case study for e-LNG has been performed with the carbon intensity set to zero to reflect the case where the electricity is assumed to be “fully renewable”, for a baseline of 20 gCO_2e/kWh (realistic for the case study scenario) and a high case of 40 gCO_2e/kWh.

The selection of the case study fuels does not imply that these are expected nor recommended to be significant future marine fuels, merely that they represent potential fuel pathway scenarios that cover the range of criteria as described above. The potential penetration of different fuel types depends on many other factors, including their cost and competition from other sectors, that are not within the scope of this study.

Case Study 1: Liquified synthetic green methane (e-LNG) from renewable powered electrolysis and the Sabatier process (Methanation)

The first case study is based on a conceptual future scenario where synthetic methane is created at a fuel production facility in Chile and liquefied and exported to the port of Callao in Peru by ship. Chile has considerable renewable energy resource that provides low-cost power to the electrolysis process, consequently providing a commercially competitive synthetic methane. Synthetic methane is handled in the same way as fossil fuel methane and is compatible with available internal combustion engine technology. However, the production process is still under development, particularly when carbon dioxide is sourced from the atmosphere through direct air capture technology. Although the processes are similar, methane was chosen over other synthetic hydrocarbon fuels for the case study, due to its gaseous form that is more difficult to handle than liquid fuels. Its risk of releasing fugitive emissions adds to the case study’s complexity and its relevance in the methods and tools.

Process description

Hydrogen is produced by electrolysis of desalinated sea water and the carbon dioxide is sourced from the atmosphere using fully electrified direct air capture technology. The carbon dioxide is piped a short distance to the plant where it is compressed to the pressure required by the Sabatier process.

The plant is assumed to be vertically integrated, and purpose built to maximise efficiency. Hydrogen is combined with carbon dioxide in a plant utilising the Sabatier process to create synthetic methane. Heat is produced as a co-product of the Sabatier process. It is assumed to be utilised at a neighbouring industrial business that would otherwise burn natural gas for their heat requirements.

The synthetic green methane is also liquified to increase its volumetric energy density for storage and transport. Since this is equivalent to the main constituent of Liquified Natural Gas (LNG) but made from renewable electricity, it may also be referred to as e-LNG and could be a drop-in fuel for vessels already using LNG. The e-LNG is loaded from the liquefaction plant onto large-scale e-LNG carrier that runs on the e-LNG being carried. Once at its destination it is unloaded into a bunkering terminal. The fuel is assumed to be used in a LNG Otto internal combustion engine (dual fuel medium speed) with assumed thermal efficiency of 50% (50% of chemical energy from the fuel is converted to mechanical energy at the shaft, Source: Ricardo analysis) and methane slip of 3.1% (as per Annex II of the 2021 revision to Directive 2009/16/EC). The efficiency of the ship is not considered as it varies considerably from vessel to vessel.

All processes in the supply chain are powered by dedicated solar renewable energy with an assumed lifecycle carbon intensity of 20 gCO_2e/kWh (assuming production to take place in high solar irradiation locations (Fthenakis, 2021)). Losses of electricity distribution are assumed at 2.6%.

GREET-specific assumptions

For the green methane pathway, the production steps were the same as used in the other methods and tools (JEC WtW, REDII and CORSIA), and the emission factors were taken from JEC WtW. There is the additional factor of fugitive emissions in the form of methane leakage from LNG station included in GREET, which is not included in the other three methods/tools. This value was taken as 0.051 g CH_4/MJ (Babak Manouchehrinia, 2020). The system expansion factors for electricity and natural gas were taken from standard UK values provided by the UK Government (Department for Business, 2021).

Case Study 2: Ammonia from Steam Methane Reforming (SMR) with Carbon Capture and Storage (CCS) and the Haber-Bosch process

This case study is based on a conceptual future scenario where ammonia is created beside the Port of Hull in the UK in a Haber-Bosch plant fed with hydrogen feedstock piped from a SMR plant located at the planned nearby decarbonised industrial cluster, potentially located in Immingham. The UK has indicated its support for hydrogen made from North Sea gas through the SMR with CCS process and it is anticipated that decarbonised industrial clusters will benefit from direct pipelines to depleted North Sea gas fields for carbon sequestration. The production of ammonia is a well-developed process used by the fertiliser industry. The use of ammonia as a fuel is currently the subject of research and development, with the first commercial ammonia-fuelled vessels not due to set sail until 2024.

Process description

Natural gas is used as a feedstock for the SMR process to create hydrogen. The gas is assumed to be sourced and conditioned at a gas well in the North Sea. It is then compressed with electricity used by a local gas generator and delivered to the plant by subsea pipeline.

The SMR plant features carbon capture technology to prevent 84% (Prussi, et al., 2020) of the emitted carbon dioxide from being released into the atmosphere. The captured carbon dioxide is transported by subsea pipeline to depleted North Sea gas fields for permanent sequestration.

The hydrogen is piped a short distance to a port where a Haber-Bosch plant reacts it with nitrogen sourced from on-site air separation units. The waste heat from the Haber-Bosch plant powers a steam generator that produces enough electricity for the plant's needs. Finding a purpose for the remaining waste heat could allow it to be treated as a co-product. In this case study, no additional off-taker of the heat is assumed and so the heat is released into the atmosphere. The product ammonia is liquified and stored portside ready for bunkering. The fuel is used in an internal combustion engine with assumed thermal efficiency of 48% (Source: Ricardo analysis and GIA feedback) with N_2O slip of 20g CO_2e per kWh (N_2O figure provided by a GIA member as data for ammonia is "to be measured" in Directive 2009/16/EC).

Electricity for these processes is assumed to come from offshore wind energy with an assumed lifecycle carbon intensity of 15gCO_2e/kWh (Bouman, 2020).

GREET-specific assumptions

The process steps for blue ammonia under GREET were taken to be the same as the process steps under the other methods/tools, using the values form JEC WtW where available and supplemented with Haber-Bosch process data to convert the hydrogen into ammonia (Pfromm, 2017).

Case Study 3: Biodiesel from HVO

This case study is based on the Midwest-US production of biodiesel from soybeans, delivered to the Port of Virginia by truck. HVO is a well-developed production process and biodiesel is compatible with existing internal combustion engine technology. This case study therefore represents a near-term decarbonisation option for the maritime industry. Marine engines would be capable of combusting lower-quality, lower cost fuels such as FAME, which could have been an alternative case study. The JEC WtT report shows that the WtT of FAME and HVO are similar, and as the HVO pathway has more features, this was chosen to test the methodologies. The environmental impacts of biodiesel from first generation crops can be highly variable and are difficult to capture accurately, due to complexities in calculating associated emissions and their impacts on land use and food supply. These complexities (discussed in Box 5-1) cause HVO biodiesel to be an interesting case study for assessing sustainability calculation methods and tools.

Box 5-1: On the carbon neutrality of biofuels

Biofuels should not be considered as *de facto* carbon neutral. Even when the associated *biogenic* carbon emissions result in a net-zero addition of CO_2 to the atmosphere, the upstream *non-biogenic* carbon emissions from biofuel production can be significant – for example:

- Biofuel supply chains (from crop harvesting to processing, to delivery) almost invariably entail use of fossil fuels (and hence fossil GHG emissions), both directly and indirectly for the provision of fertilizers, herbicides, etc., per unit of delivered biofuel. In principle, if renewable energy (RE) were used in the supply chain instead of fossil fuels, these emissions could be lower (albeit still not zero, since even RE generators require some fossil fuels in their own supply chains); however, fully replacing fossil fuels with RE in all stages of the supply chain is not yet realistic.

Specifically for energy crop biofuels (e.g., 1st generation bioethanol and biodiesel):

- Any irreversible topsoil erosion and oxidation contribute further to the positive GHG emission budget per unit of delivered biofuel.
- Any uncontrolled on-site anaerobic degradation of agricultural residues from biofuel crops leads to CH4 emissions, which has a much larger global warming potential than CO2.
- Biomass displacement (referred to as land use change - LUC) is often a further source of significant additional GHG emissions. Furthermore, simple tabulated values may fail to take this into account accurately, especially when the goal of the study is to estimate the prospective future consequences of large-scale biofuel deployment, since future LUC emissions will then depend on which further biomass will be displaced (Fargione J., 2008).

Additional methodological issues:

- Whereas 2nd generation biofuels (derived from waste substrates) do not incur the GHG emissions mentioned above for energy crop biofuels, if/when answers are sought on whether (or the extent to which) 2nd generation biofuels may represent a viable “carbon neutral” (or even “low-carbon”) strategy on the large scale, careful attention should be paid to the issue of waste substrate availability, and whether (or the extent to which) it may be expected to meet the demand for biofuel production in quantities significant enough to displace conventional fuels.
- Whenever a biofuel is accompanied by a marketable co-product (e.g., biodiesel + glycerol), life cycle assessment and “carbon footprint” methodologies assign variable shares of the overall life-cycle GHG emission budget for the whole supply chain to the two co-products, on the basis that both share “responsibility” for the emissions (the specific quantitative shares vary depending on whether system expansion, or mass or economic or energy allocation is employed, as discussed in Appendix 4). However, while this is a tenable methodological approach in the short term and when approaching the analysis from a simple “attributional” standpoint, once again there is a risk of inadvertently failing to acknowledge an implicit shift in goal and scope definition when the results of a study are instead intended to be used to support long-term policy decisions on whether (or the extent to which) biofuels represent a viable “carbon neutral” (or even “low-carbon”) strategy on the large scale. In fact, if/when the market for a co-product becomes saturated, then such co-product should be treated as a waste flow, and as such: (a) it should no longer be assigned any share of the GHG emission budget (i.e., the entirety of the GHG emission budget should be assigned to the biofuel), and (b) the further GHG emissions caused by its necessary treatment should be estimated and also assigned entirely to the biofuel (which is the only remaining marketable product).

Process description

Soybeans are the raw feedstock for the HVO process and are grown through modern agricultural processes at a large scale. The cultivation of the soybeans includes associated emissions from seeding material, fertilisers, pesticides, soil neutralisation, field emissions and on-farm vehicles.

The soybeans are transported from the farm to a processing facility where they are dried, crushed and distilled to produce a crude soybean oil. Hydrogen from unabated steam methane reforming (SMR) of grid natural gas is used to remove oxygen resulting in an oil that is then refined into fuel products with similar properties to fossil fuels. During the HVO process by-product electricity and heat are produced that is assumed to be utilised by a nearby industry that would have otherwise used grid electricity and gas respectively. A soya meal animal feed is produced by the HVO process as a by-product and is sold onto animal feed markets. The fuel is used in an internal combustion engine with assumed thermal efficiency of 52% (Source: Ricardo analysis) and emissions as per the HVO pathway in Annex II of the 2021 revision to Directive 2009/16/EC.

Electricity for processes is assumed to come from onshore wind energy with an assumed lifecycle carbon intensity of 12.5 gCO_2e/kWh (Bouman, 2020).

GREET-specific assumptions

Under the Hydrogenated Vegetable Oil (HVO) pathway the application of GREET has used the Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) land use change model (discussed further in Section 5.3.2). This accounts for domestic, direct and indirect land use change. The selected land use change fields used for the HVO fuel pathway are shown in Table 5-1 below.

Table 5-1 Selected land use change fields for GREET

Field	Setting
Soy Biodiesel Case	Soy Biodiesel_CARB case 8
Domestic Emissions Modelling Scenario	Century
International Emissions Modelling Scenario	Winrock
Harvested Wood Product (HWP) Scenario	0 HWP
Tillage Practice for Corn and Corn Stover Production	Conventional Till
Forest Prorating Factor	No

The assumption on the animal feed substitution within the HVO pathway was derived from JEC WtW under the Biodiesel section. The soya meal animal feed produced from the HVO pathway substitutes dry corn.

5.2 CASE STUDY EVALUATION OF GHG CALCULATION METHODS/TOOLS

An important output of this study is to review and compare the WtW methods and tools. Due to the complexity of both the methods/tools and the details of the fuel pathways chosen, these have been summarised in the form of tables, one for each fuel pathway. These Tables 5-2, 5-3 and 5-4 provide an indication of whether each fuel production stage is considered by each method (if included, shown as green; if excluded shown as yellow), and show where there are differences (shown as grey). Where differences are identified, these are discussed in further detail in Section 5.3.

Table 5-2: Comparison of methods/tools for green methane

Key	
Included	(green)
Excluded	(yellow)
Different	(blue)

Green methane

Emission source	Description	REDII	JEC	GREET	CORSIA
Hydrogen production					
Solar power	Lifecycle carbon factor of 20 gCO_2e/kWh	Included	Included	Included	Included
Distribution	Losses in distribution	Included	Included	Included	Included
Desalination & Electrolysis	Electricity usage at 20 gCO_2e/kWh	Included	Included	Included	Included
Methanation (Sabatier process)					
CO_2 absorption through Direct Air Capture	Electricity usage at 20 gCO_2e/kWh	Included	Included	Included	Included
CO_2 compression	Electricity usage at 20 gCO_2e/kWh	Included	Included	Included	Included
Synthetic natural gas synthesis	CO_2 feedstock for Sabatier process	Included	Included	Included	Included
	H_2 feedstock for Sabatier process	Included	Included	Included	Included
	Heat surplus	Different	Different	Different	Different
Ship distribution (LNG)					
Natural gas liquefaction	Electricity usage at 20 gCO_2e/kWh	Included	Included	Included	Included
	Flared natural gas	Included	Included	Included	Included
	Fugitive CH_4 emissions	Included	Included	Included	Included
Liquified natural gas (LNG) loading terminal	Electricity usage at 20 gCO_2e/kWh	Included	Included	Included	Included
	Gas for loading terminal	Included	Included	Included	Included
LNG sea transport	Distance	Included	Included	Included	Included
	Natural gas evapouration	Included	Included	Included	Included
	Heavy fuel oil for propulsion	Included	Included	Included	Included
	Fugitive CH_4 emissions	Included	Included	Included	Included
	N_20 emissions	Included	Included	Included	Included
LNG unloading terminal	Electricity usage at 20 gCO_2e/kWh	Included	Included	Included	Included
	Gas for unloading terminal	Included	Included	Included	Included
LNG bunkering	LNG delivery, manual vent, boil-off gas from the tank, continous station, fuel tank, fuel nozzle	Included	Included	Included	Excluded
Propulsion					
Powertrain efficiency	50% thermal efficiency fuel to shaft	Excluded	Included	Included	Included
TTW emission from engine	Combustion emissions: CO_2, CH_4, N_20	Excluded	Included	Included	Included

For the majority of the green methane production pathway, the methods/tools are identical (Table 5-2). RED II and CORSIA use an attributional approach and opt for energy-based allocation for the heat surplus, while JEC and GREET use a consequential approach and forego allocation, in favour of system expansion instead. This is discussed in more detail in Section Appendix 4. Finally, unlike all other methods, by design RED II does not include TtW emissions.

Table 5-3: Comparison of methods/tools for blue ammonia

Key
- Included (green)
- Excluded (yellow)
- Different (blue)

Blue Ammonia

Emission source	Description	REDII	JEC WtW	GREET	CORSIA
Hydrogen production					
Natural gas extraction	Energy as natural gas	Included	Included	Included	Included
	CO_2 venting	Included	Included	Included	Included
	Fugitive CH_4	Included	Included	Included	Included
Natural gas pipeline transport inside EU	Compressors powered by gas turbine with natural gas fuel	Included	Included	Included	Included
	Fugitive CH_4 emissions from compression	Included	Included	Included	Included
	N_20 emissions from compression	Included	Included	Included	Included
	Compression specific energy	Included	Included	Included	Included
	Distance	Included	Included	Included	Included
	Fugitive CH_4 emissions from pipeline	Included	Included	Included	Included
Steam Methane Reforming + Carbon Capture & Sequestration	Natural gas feedstock	Excluded	Included	Included	Excluded
	CO_2 emissions from capture slip	Excluded	Included	Included	Excluded
	Fugitive CH_4 emissions	Excluded	Included	Included	Excluded
Haber-Bosch process					
H_2 pipeline	Short distance pipeline from SMR plant	Included	Included	Included	Included
Syngas compression	Steam from Haber-Bosch cooling runs generator to power compression.	Included	Included	Included	Included
Haber-Bosch process	Exothermic reaction, negligible start up emissions. Steam generator runs power requirements.	Included	Included	Included	Included
Air separation unit	Electricity usage at 15 gCO_2e/kWh	Included	Included	Included	Included
NH_3 condensation	Electricity usage at 15 gCO_2e/kWh	Included	Included	Included	Included
Pipeline distribution					
Ammonia storage	Electricity usage at 15 gCO_2e/kWh	Included	Included	Included	Included
Ammonia bunkering	Electricity usage at 15 gCO_2e/kWh	Included	Included	Included	Included
Propulsion					
Powertrain efficiency	48% thermal efficiency fuel to shaft	Excluded	Included	Included	Included
TTW emission from engine	Combustion emissions: CO_2, CH_4, N_20	Excluded	Included	Included	Included

As with the green methane pathway, for the majority of the stages, all the methods/tools are identical for blue ammonia (Table 5-3). As with green methane, RED II by design does not account for TtW. RED II and CORSIA do not currently include methods for taking into account the impact of CCS, which is clearly relevant for Blue fuels. However, it is expected that were a fuel utilising CCS to be submitted under either method, CCS values could be readily incorporated. While these fuels are not included in RED II, it is felt to still be useful to make sensible extensions to RED II so it can be used – this will allow learnings from other sections of the pathway that are included within RED II.

Table 5-4: Comparison of methods/tools for HVO

Key

Key	
Included	Green
Excluded	Yellow
Different	Blue

HVO

Emission source	Description	REDII	JEC WtW	GREET	CORSIA
Cultivation					
Cultivation	Embedded emissions of fertilsers: nitrogen, phosphorus, potassium and calcium	Included	Included	Included	Included
	Embedded emissions of pesticides	Included	Included	Included	Included
	Embedded emissions of seeding material	Included	Included	Included	Included
	Diesel	Included	Included	Included	Included
	CH_4 emissions	Included	Included	Included	Included
	CO_2 from soil neutralisation	Included	Included	Included	Included
	N_2O field emissions	Included	Included	Included	Included
Local transport of soybeans	Diesel	Included	Included	Included	Included
	CH_4 emissions	Included	Included	Included	Included
	N_2O emissions	Included	Included	Included	Included
Oilseed drying 13%	Beans to local oil mill: Soy beans drying (13%), storage and handling, diesel	Included	Included	Included	Included
	Natural gas	Included	Included	Included	Included
	Liquefied petroleum gas	Included	Included	Included	Included
Oilseed drying 11%	Natural gas	Included	Included	Included	Included
Land Use Change (LUC) Domestic (Based on Century; sa/100cm)	Soy Biodiesel Case	Excluded	Excluded	Different	Different
LUC Direct (Based on Winrock)	Domestic Emissions Modeling Scenario	Different	Excluded	Different	Different
LUC Indirect (Based on Winrock)	International Emissions Modeling Scenario	Excluded	Excluded	Different	Different
Hydrogen production					
Natural gas extraction	Energy as natural gas	Included	Included	Included	Included
	CO_2 venting	Included	Included	Included	Included
	Fugitive CH_4	Included	Included	Included	Included
Hydrogen SMR	Natural gas feedstock	Included	Included	Included	Included
	CO_2 emissions	Included	Included	Included	Included
	Fugitive CH_4 emissions	Included	Included	Included	Included
HVO process					
Raw oil production w/ meal export	Raw oil yield	Included	Included	Included	Included
	Soya meal	Included	Included	Included	Included
	Heat to process	Included	Included	Included	Included
	Electricity usage at 12.5 gCO_2e/kWh	Included	Included	Included	Included
	n-Hexane	Included	Included	Included	Included
	CO_2 emissions (from n-hexane)	Included	Included	Included	Included
	Emissions credit for meal animal feed sub. Meal substituttes: dry corn	Different	Different	Different	Different
Hydrogenation of oil	HVO yield	Included	Included	Included	Included
	Hydrogen	Included	Included	Included	Included
	Phosphoric acid - H_3PO_4	Included	Included	Included	Included
	Sodium hydroxide - NaOH	Included	Included	Included	Included
	Emissions credit for electricity surplus, grid-mix	Different	Different	Different	Different
	Emissions credit for heat surplus based on alternative generation with natural gas combustion with 90% efficiency	Different	Different	Different	Different
Truck distribution					
Local transport	Diesel	Included	Included	Included	Included
	CH_4 emissions	Included	Included	Included	Included
	N_2O emissions	Included	Included	Included	Included
Propulsion					
Powertrain efficiency	52% thermal efficiency fuel to shaft	Excluded	Included	Included	Included
TTW emission from engine	Combustion emissions: CO_2, CH_4, N_20	Excluded	Included	Included	Included

Table 5-4 shows that again, the methods/tools treat many of the process steps in the same manner for HVO. The main differences being that JEC does not consider land use change, and RED II only considers direct land use change. Land use change is discussed in more detail in Section 5.3.2. As seen in the green methane process, JEC and GREET use system expansion when dealing with co-products (e.g., animal feed, electricity and heat), while the other methods use energy-based allocation. In many cases, the different methods use different numerical assumptions and input data. Where possible, common numbers have been used in the case study calculations, to ensure that any differences in methodology are not masked by differences in input data.

5.3 DISCUSSION OF DIFFERENCES BETWEEN METHODS/TOOLS

5.3.1 Handling of multi-output processes and co-products

One of the key differences among the four selected methods and tools is to do with the way in which they handle multi-output processes and co-products. In general terms, the first methodological distinction that needs to be made is between the 'system expansion' and 'allocation' approaches. This is a complex topic that is the subject of many studies and can only be covered at a high level here, although a more detailed discussion of the system expansion and allocation approaches with illustrative examples are included in Appendix 4.

System expansion is the preferred LCA approach according to the recommendations given by ISO (ISO 14044, 2006), and it is often adopted in "consequential" LCAs (where the emphasis is on system-level change rather than on individual product units). However, its implementation is not straightforward, as it entails a degree of subjectivity in determining which alternative products may be deemed functionally equivalent to each co-product. The system expansion approach is used in the JEC method, and it is also one of the available options in GREET.

The alternative approach to co-product assessment is allocation, whereby the attempt is made to assign (i.e., allocate) different shares of the input and output flows, and hence of the overall environmental impact, of the operation of a multi-output process to the various co-products. The shares can be allocated by different measures; mass, energy, and economic allocation are all used depending on the object of the study and the intended goal and scope of the assessment. While mass and energy are well defined physical quantities, economic allocation depends on the respective market values of the co-product streams, which may and often do fluctuate over time. Energy-based allocation is used in the REDII and CORSIA methods, while both energy and economic allocation are available options in GREET.

For most marine fuels and their co-products, physical (and in particular, energy-based) allocation could be the most appropriate approach in those cases where the co-products are also energy vectors. An exception to this may be for biofuel supply chains entailing the co-production of both fuel and non-fuel co-products (in the case of the soy HVO case study, the products are the HVO fuel and animal feed): the adoption of economic allocation may be preferable to better reflect the difference between what may be a high-value main energy product on one hand, and a lower-value co-product or vice versa.

5.3.2 Land use change

Land use change may be categorised as direct (DLUC) or indirect (ILUC) land use change. DLUC occurs when biofuel feedstock cultivation results in land use change on the land where it is grown i.e., when the feedstock cultivation displaces a different former land use. ILUC, instead, comprises a change in land use outside of a feedstock cultivation area that is induced by changes in use or the production quantity of the feedstock. Therefore, crops which were previously produced in a given area are now required to be grown elsewhere to meet demand, resulting in indirect land conversion. "Indirect" LUC is thus often referred to as "induced" LUC (Scarlat & Dallemand, 2019).

RED II

RED II introduced limits on high ILUC biofuels, bioliquids and biomass fuels. In addition, RED-II outlines GHG accounting methods for calculating the GHG impact of biofuels and bioliquids, and biomass fuels, and their fossil fuel comparators, respectively (European Commission, 2018).

In order for economic actors to show compliance with RED II, the Excel-based GHG calculation tool BioGrace-II has been developed, specifically for the calculation of GHG emissions for electricity, heat and cooling from biomass. BioGrace-II follows BioGrace-I which is in line with sustainability criteria of the Renewable Energy Directive (2009/28/EC, RED) but is not consistent with RED-II as its default and standard values are now outdated. In spite of this, as outlined in RED-II paragraph 115, the calculation of GHG impact of land conversion which are detailed in guidelines published in the European Commission decision on 10 June 2010, are yet to be revised (BioGrace, 2021).

Annualised emissions from LUC are calculated as a change in carbon stocks from the reference land use, which refers to the land use in January 2008 or 20 years before the feedstock was obtained, compared to the actual land use. The guidelines provide methods for calculating such carbon stocks which are aligned with IPCC Guidelines for National Greenhouse Gas Inventories, as well as standard values for probable combinations of climate and soil type. The difference in carbon stocks, measured in tonnes of carbon per unit area, is then multiplied by the productivity of the crop to give grams of CO_2-equivalent per unit of biofuel energy (megajoules) (BioGrace, 2021).

In addition, a significant bonus of 29 g CO_2e/MJ in emissions savings is attributed if evidence is provided that the land was not in use for agriculture prior to January 2008, or that such land is severely degraded (BioGrace, 2021). It is also important to note that RED-II Annex VIII provides provisional estimated ILUC emissions for cereals and other starch-rich crops, sugars, and oil crops. However, this is assumed to be zero for feedstocks which have led to direct land-use change, namely, a change from "one of the following IPCC land cover categories: forest land, grassland, wetlands, settlements, or other land, to cropland or perennial cropland. In such a case a direct land-use change emission value should have been calculated in accordance with point 7 of part C of Annex V", as outlined above (European Commission, 2018).

GREET – Carbon Calculator for Land Use Change from Biofuels Production (CCLUB)

CCLUB represents an integral part of the GREET model, calculating carbon emissions from land use change (LUC) and land management change (LMC) for a number of fuel pathways including soy biodiesel. As such, the CCLUB part of GREET relies upon a number of data sources which feed into the calculation of GHG emissions.

CCLUB is reliant upon biofuel production scenarios, LUC and LMC scenarios and emission factors to calculate GHG emissions in grams of carbon dioxide equivalent (CO_2e) per MJ of fuel produced. The Global Trade Analysis Project (GTAP) provides estimates of domestic United States and international area of land which is converted from one of four land use types to another, namely, forest, grassland, cropland pasture, and feedstock lands. CCLUB includes GTAP results from nine biofuel scenarios, with each scenario reflecting fluctuations in the economy as a result of increase in demand for a particular biofuel.

The area changed as a result of land transition is then multiplied by corresponding emissions factors, which are aggregated or disaggregated as appropriate from a range of spatial coverages. For domestic LUC emissions, soil carbon emission factors are generated using a parameterized CENTURY model and aboveground carbon content data are sourced from the Carbon Online Estimator. CENTURY is solved within a non-linear regression model, and is well developed for cropland, grassland and forest, making it able to simulate land transitions incorporated within the GTAP modelling framework. Meanwhile, international emission factors are calculated primarily from the Winrock dataset, as well as the Woods Hole dataset. Each dataset provides country-level emission factors developed using satellite imagery amongst other sources, and provide different estimates arising from some variations in definitions and scope (Harris, Brown, Hagen, Baccini, & Houghton, 2012).

CORSIA

The CORSIA method breaks down the emissions inventory into two main components: "core" life cycle emissions (corresponding to the full supply chain of fuel production and use), and induced land use change emissions.

For the "core" calculations, an attributional life cycle assessment (A-LCA) approach is adopted, including:

- feedstock cultivation;
- feedstock harvesting, collection and recovery;
- feedstock processing and extraction;
- feedstock transportation to processing and fuel production facilities;
- feedstock-to-fuel conversion processes;
- fuel transportation and distribution; and fuel combustion in an aircraft engine.

Instead, for the ILUC calculations, a consequential LCA (C-LCA) approach is recommended, whereby the expected crop displacement / land use change is taken into account. Specifically, as explained by Rehmatulla et al. (2020), in CORSIA, "*to estimate a fuel's ILUC emissions, two models were used - GTAP-BIO* (Taheripour, Hertel, Tyner, Beckman, & Birur, 2008) *and GLOBIOM* (Ecofys-IIASA-E4tech, 2015)*. These two models have different structures, land categories, data sets, parameters and emission factors that therefore lead to different results. To determine default ILUC emission standard values, when the difference between the two analyses falls within the tolerance level after harmonisation of the data and assumptions, the mid-point between the two results is taken as the default value. When this is not the case, the lower of the two model values plus an adjustment factor of 4.45 gCO_2e/MJ is taken (which corresponds to half of the tolerance level)*" (Rehmatulla, et al., 2020).

JEC

Land use change is not considered within the JEC approach. While the importance of LUC in accounting for climate change effects of biofuels, and the potential impact this may have on final figures, is acknowledged, LUC has not been considered within the JEC approach due to the high uncertainties in the method for estimation.

As such, several key areas of uncertainty are identified. Firstly, a wide variation in possible direct LUC (DLUC) emissions can be obtained depending on the particular land that is converted, across different methods. In addition, a complicating feature of land use change emissions, is that they occur over a period of time after the land conversion process has begun. Regarding ILUC, emissions are inherently difficult to account for, even in retrospect, as it is impossible to determine what would have happened if biofuels were not introduced (Prussi, et al., 2020).

Summary of land use change approaches

Land use change emissions are a determining parameter in calculating lifecycle emissions for fuel pathways, despite the considerable uncertainties associated with estimating them, and the variability in results across different methods. In spite of introducing uncertainty and thus making results less precise, including LUC estimations may make results more accurate and representative of the system studied (Brandao, Azzi, Novaes, & Cowie, 2021) (Prussi, et al., 2020). Indeed, as outlined in section 5.4.3, there are considerable variations in results for the WtT stage of the HVO pathway across the different methods due to their differing approaches to LUC emissions.

Of the four methods and tools reviewed here, JEC is clearly the one that stands out for neglecting all GHG emissions ensuing from land use change. Consequently, extra caution is to be exercised when interpreting the results produced when adhering to this method, since significant contributions to the overall carbon budget of the fuel may be missed. It is concerning that different fuels pathways are affected to varying degrees by this omission, and as a result the relative ranking of competing fuels may end up being inaccurate and potentially misleading.

All three remaining methods/tools do include land use change emissions in principle, but they still differ with respect to the specific models and databases used for their estimation.

- RED II is the least up-to-date method in terms of LUC data, and it also makes some simplifying assumptions, which are likely to result in an underestimate of the associated emissions.
- GREET and CORSIA appear to be the most thorough and likely accurate in their assessment of LUC emissions, and they both make use of the US-developed and generally well-regarded GTAP model.
- CORSIA also uses a second model (GLOBIOM), and then takes the approach of picking the lower ILUC value between the two models (plus a conservative adjustment factor) when these are in disagreement by more than 8.9 gCO_2e/MJ. This latter approach has been questioned, on the basis that the lower value may just be the result of unduly optimistic estimations of ILUC values in one of the models (Rehmatulla, et al., 2020).

Overall, in light of the inevitable uncertainty that such estimates entail, arguably the best strategy might be to use the mid-point values between those provided by GTAP and GLOBIOM, instead.

5.4 CASE STUDY RESULTS

The TtW (or in this case tank to shaft as explained in Section 2.2.1) data were calculated for each fuel as described by the selected methods and tools. Note that in order to compare the methods/tools directly, a common set of emission factors per pathway stage were used wherever possible. These were largely based on the JEC WtW factors, with the addition of land use change factors from Biograce. **This removes any differences in the method or tool emission databases and enables focus on the differences in the components of the methods/tools rather than the default values and assumptions. Therefore, the results shown here may differ from pathways calculated for these methods using standard defaults.**

Figure 5-1 shows an overview of the results of the case studies, compared to a baseline of TtW emissions from a notional large 2-stroke marine engine running on HFO. Note that all plots include the effect of powertrain thermal efficiency – in other words, for a 50% efficient powertrain, the emissions per MJ of fuel would be doubled to give the emissions per MJ of work.

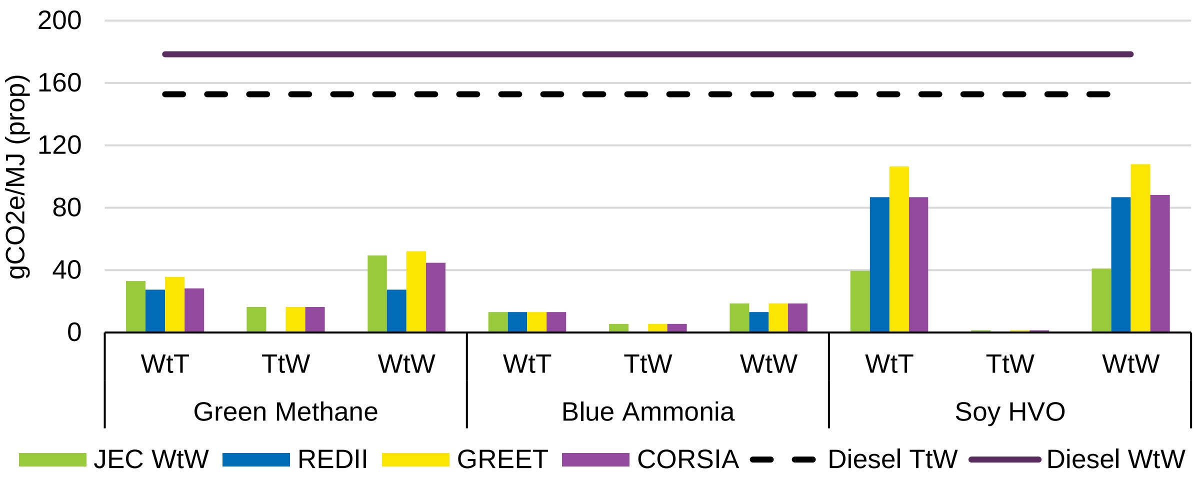

Figure 5-1: Comparison of Case Studies

While there are some significant differences in the case study results from method to method, all the WtW emissions for the fuels studied are shown to be lower than the WtW emissions (based on CO_2 factor and TtW emissions (Comer, Osipova, & ICCT, 2021) from a notional large marine 2-stroke engine running traditional fossil fuel at 52% thermal efficiency. Despite the similarities in the methods discussed in Section 4.2, in some cases the results are dramatically different – the reasons for which will be discussed in the following sections.

5.4.1 Green Methane

Detailed results for green methane are shown in Figure 5-2.

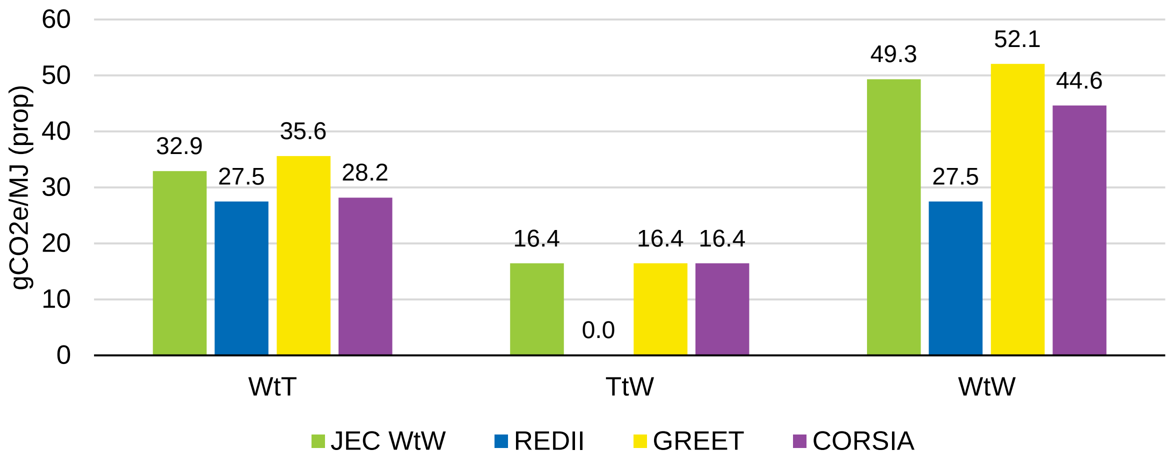

Figure 5-2: Detailed comparison of green methane results

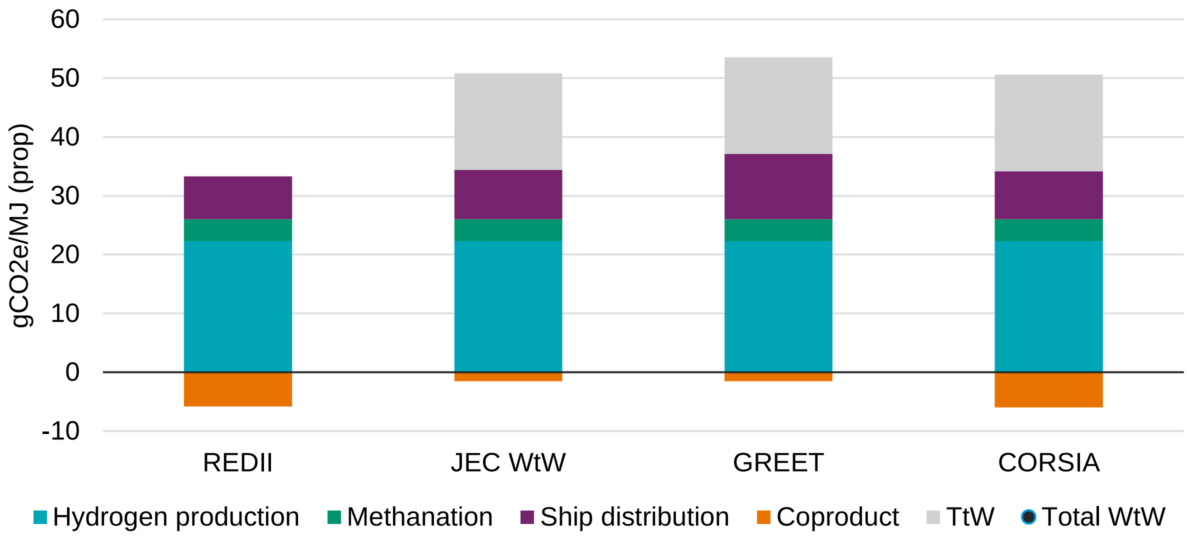

Figure 5-3: Breakdown of green methane WtW results by stage

Inspection of the results from the above figures reveals the following findings:

- WtT emissions are relatively low, partly due to the relatively low carbon intensity of the electricity used, reflecting the good solar potential for Chilean production. Additionally, the methods give credits for surplus heat in production. Heat credit is shown as a means of proving the method, rather than as a precise description of the scenario.
- For the WtT stage of green methane production, REDII and CORSIA arrive at the same result. This is because there is no land use change in the green methane pathway, and REDII and CORSIA have the same co-product allocation method (energy based). These two methods differ from JEC and GREET which use system expansion.
- The system expansion approach to co-product assessment (JEC and GREET) results in a smaller share of the pathway emissions being assigned to green methane compared to the energy-based allocation method. This means that JEC and GREET have higher WtT emissions for green methane compared to REDII and CORSIA.
- While all methods and tools include methane leakage along the production pathway, only GREET includes leakage from the LNG unloading terminal LNG delivery, manual vent, boil-off gas from the tank, continuous station, fuel tank, fuel nozzle.

- The CO_2 emissions during combustion are set to zero by the methods/tools, as they are assumed to be balanced by the carbon captured from the air to create the methane. Therefore, the only TtW emissions considered are from methane slip during combustion. Note that for a future fuel using captured industrial CO_2 emissions, there are challenges around allocation for the emitter of the CO_2, be it the original industrial emitter or the ship using the synthetic fuel. These challenges are wider than just the marine sector, including government and international policies around the responsibility for the final CO_2 emissions
- The methods and tools show the same TtW emissions, with the exception of REDII
    - RED II does not include TtW CO_2, CH_4 or N_2O emissions for biofuels for transport (RED II assumes CO2 emissions are net-zero). Note that RED II does include CH_4 and N_2O emissions for bioliquids only. Bioliquids are defined within RED as biofuels only used for electricity or heat, not for transport.

The carbon intensity of grid electricity has a significant impact on the overall WtW of the fuel, particularly for synthetic electrofuels where electricity usage is significant. There is ongoing debate, particularly in the EU around additionality of electricity supply for e-fuels. It is also likely that in future, many electrolysers will use electricity from a newly constructed dedicated solar or wind plant. Therefore, it is useful to investigate the effect of lifecycle emissions from the electricity to the fuel generated by it, particularly as these emissions could in fact be the largest contributor to the WtW emissions of the fuel (they would otherwise be near-zero, regardless of the methodology chosen).

In order to demonstrate the effect of grid intensity on WtW emissions, Figure 5-4 presents a brief **sensitivity analysis** for green methane (using the JEC WtW method), by varying the assumed grid carbon intensity as follows:

- Grid electricity appropriate for the EU at 200g CO_2e/kWh.
- (Central case) solar PV in areas of high irradiation (2,300 kWh/(m^2*yr)) – 20g CO_2e/kWh, corresponding to the example of Chile used for the case study (Fthenakis, 2021).
- “zero-emission” or “fully renewable” grid, i.e. 0g CO_2e/kWh.

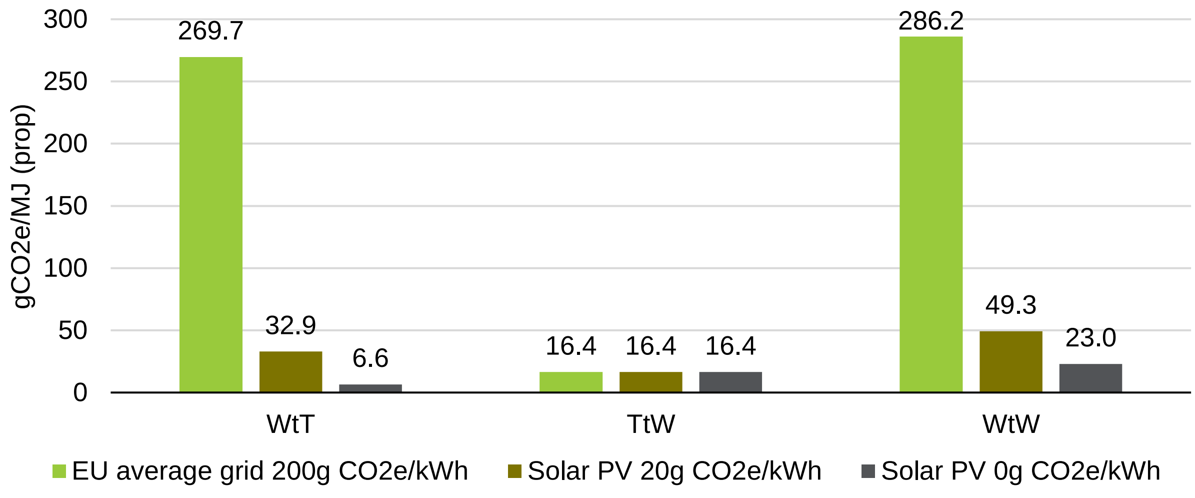

Figure 5-4: Sensitivity analysis of the green methane fuel pathway WtT, TtW and WtW calculations based on varying the assumed GHG intensity of grid electricity (using the JEC WtW method)

It is clear in this simple case that the choice of carbon intensity of electricity directly affects the WtW emissions. In fact, e-LNG made by grid electricity at 200g CO_2e/kWh has ~50% higher WtW emissions than the fossil fuel example. Therefore, if these methods are used in the future for regulatory or tax purposes, there will need to be careful decisions made as to the allocation of real-world emissions to any given fuel. This may be especially true in the case of electricity where the true source of the electricity used could be potentially complex to determine, and when considering whether "renewable", "grid average" or "marginal" (increased use) emissions factors are appropriate.

5.4.2 Blue Ammonia

Detailed results for blue ammonia are shown in Figure 5-5.

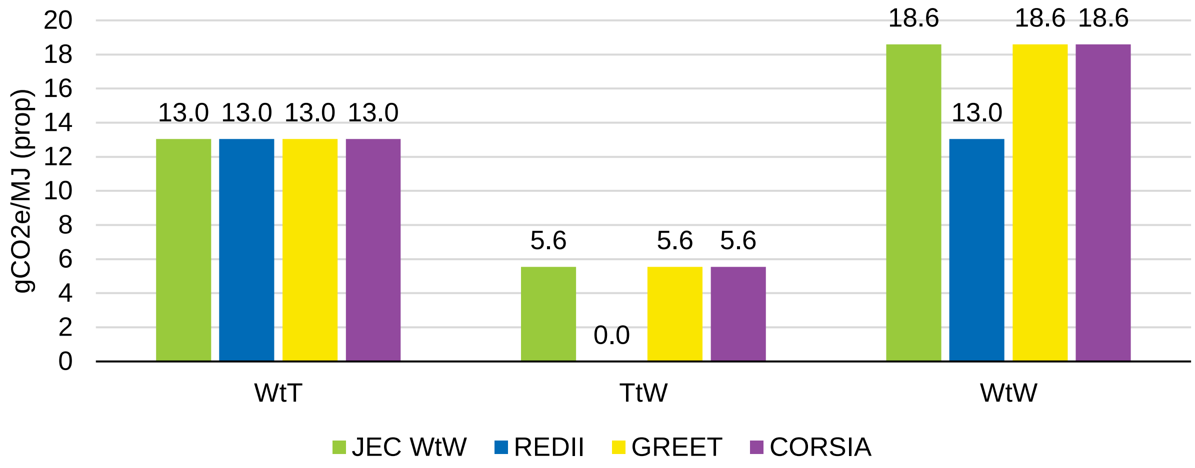

Figure 5-5: Detailed comparison of blue ammonia results

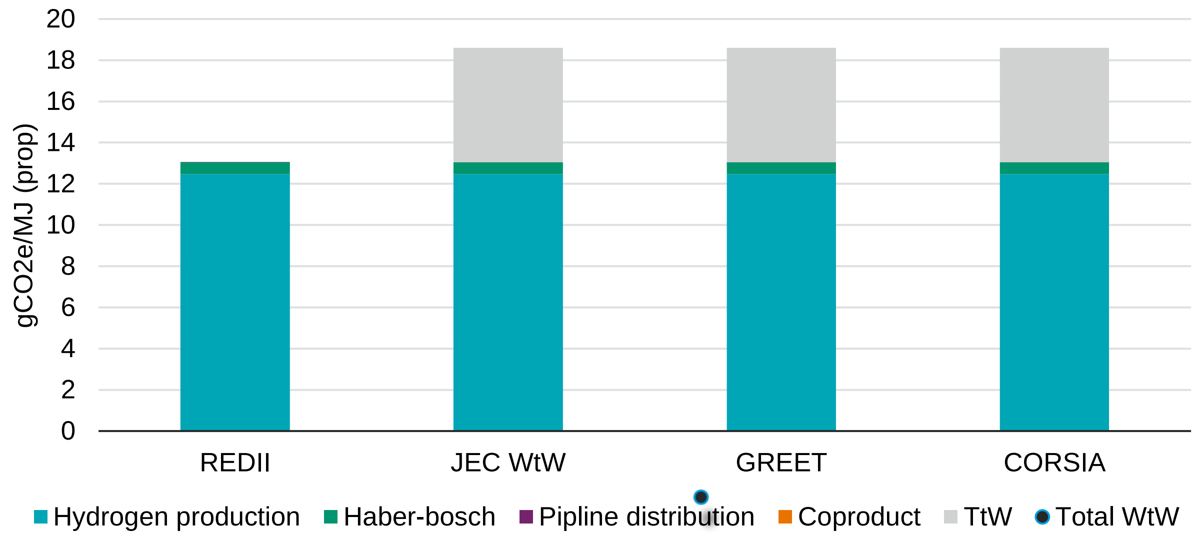

Figure 5-6: Breakdown of blue ammonia WtW results by stage

Inspection of the results from the above figures reveals the following findings:

- Ammonia has low WtT emissions due to the hydrogen being generated by SMR with CCS (with an assumed 73.3% efficiency, as per the JEC method). For stages requiring electricity, a renewable electricity carbon intensity of 15 gCO_2e/kWh (from offshore wind, which is reasonable for the UK scenario chosen) is assumed. The biggest contributor to the WtT emissions come from CO_2 slip during the CCS process (59%).

  For the pathway chosen (JEC GPCH2bC, see Appendix A3), the upstream emissions are not excessive. This may not be representative of blue ammonia produced in less regulated regions and may represent a "best case" for blue ammonia.

- For the ammonia pathway there is no land use change or co-product, and therefore all methods and tools result in the same value for WtT.
  - Should there be any co-products, such as heat from the Haber-Bosch process, then the results would differ, as seen in the green methane and Soy HVO case studies.
  - Note that at present, while JEC and GREET include CCS, RED II and CORSIA do not explicitly mention CCS. CCS has been included in the calculations for these methods/tools, as it is assumed that regulators would not reject carbon capture for methodological reasons, should a fuel supplier present a blue fuel for accreditation.
- Ammonia combustion engines are prone to ammonia slip on fuel combustion, which would be expected to then get treated by an ammonia slip catalyst, which in turn generates N_2O, a highly potent greenhouse gas. This is important to account for in the WtW approach; all the methods and tools tested are able to account for this. Based on the discussions with the IMO GIA, it was agreed to use a notional value of 20 gCO_2e of N_2O per kWh. There are no CO_2 or methane emissions associated with ammonia combustion.
  - The methods and tools have the same TtW emissions, with the exception of REDII which does not include TtW.
  - With N_2O having a global warming potential of 298, any deviations from the above assumed N_2O emissions may have a large effect on the total WtW emissions from an ammonia fuelled engine, so may need homologation and careful monitoring or legislating during service, especially as the engine and aftertreatment age.

5.4.3 HVO from soybean

Detailed results for HVO are shown in Figure 5-7:

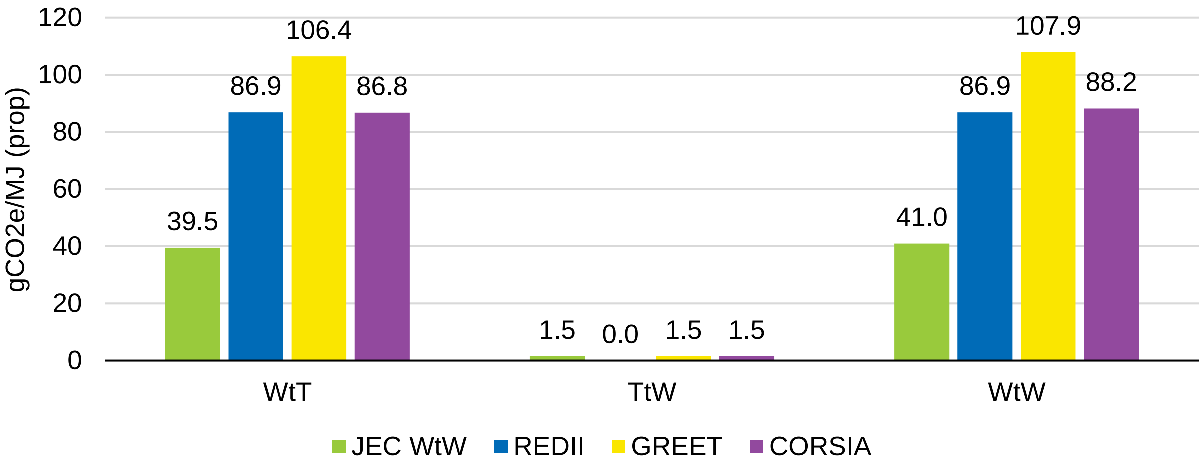

Figure 5-7: Detailed comparison of Hydrogenated Vegetable Oil results

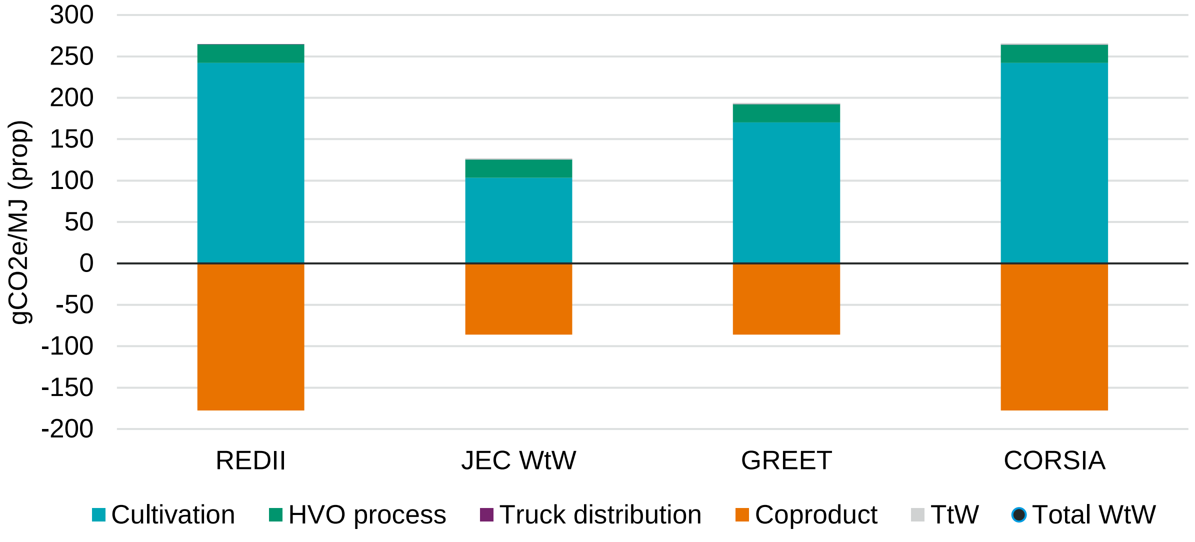

Figure 5-8: Breakdown of HVO WtW results by stage

Inspection of the results from the above figures reveals the following findings:

- The Soy HVO pathway chosen has generally the highest WtW emissions of the three fuels, which is clear from Figure 5-7: Detailed comparison of Hydrogenated Vegetable Oil results in Figure 5-7 shows that the majority of the WtW emissions occur during the WtT phase.
- HVO has high emissions associated with land use change, though the scenario (see Section 5.1) assumes gains from carbon credits for animal feed substitution as well as heat and electricity surplus during the hydrogenation phase are possible.
- HVO has significantly different WtT emissions from each of the methods/tools:
    - Note that due to the significant differences in the methods and tools, it was not possible to use a common input dataset, therefore each method uses the land use change associated with that method.
    - GREET shows the highest WtT emissions of the four. While both GREET and CORSIA considers both direct and indirect land use change, their methods for doing so are different (see Section 5.3.2). This necessitates different input values, leading to significantly different calculated WtT. There is no land use change within JEC, and therefore JEC has the lowest WtT emissions for HVO of the four methods. REDII only considers direct land use change.
    - GREET adopts the system expansion approach to co-product assessment. A co-product of the HVO pathway is animal feed from the crushing of seed to form oil. The energy content of the animal feed is high (around 2 MJ for 1 MJ HVO), and so the energy allocation co-product method results in a large proportion of emissions allocated to the animal feed co-product. This results in energy-based co-product allocation methods (such as in REDII and CORSIA) having lower emissions compared to GREET.
    - The ~2.5x difference between the highest and lowest WtW emissions highlights the sensitivity of biofuels to the land-use and co-product assumptions, and the challenges in choosing a “correct” method. Furthermore, the example fuel pathway chosen is for a well-developed and understood feedstock and geography. For innovative or “controversial” feedstocks, it may be challenging to agree a reasonable WtT emissions factor.
    - Note that electricity use is assumed to be from an onshore wind farm with a carbon intensity of 12.5gCO_2e/kWh, representing a future scenario in the US Midwest.
- The TtW CO_2 emissions from combustion are considered by the methods and tools to be wholly offset by the cultivation of the soybeans (as per the carbon capture for green methane). Therefore, the only TtW emissions considered are from N_2O and CH_4, which are relatively low for HVO (compared to methane or ammonia fuels). For the purposes of a future method applied to the maritime sector, it

may be beneficial at least for the purposes of presentation, to break out the negative emissions during feedstock cultivation (or carbon capture) and the positive emissions from combustion. The methods and tools have the same TtW approach and emissions, except for REDII which does not include TtW CO_2 emissions.

6. CONCLUSIONS ON APPLYING THE METHODS AND TOOLS TO INTERNATIONAL SHIPPING

The objective of this study is to identify sustainability criteria and criticalities, evaluate methodological differences from possible WtT and TtW calculation methods and tools through the use of case studies, without overly focussing on the actual numerical outcomes. The fuel pathway scenarios were chosen to ensure a good coverage of sources, production methods, distribution and use cases, and applying the methods and tools to them was intended to test how the methods/tools treat this range of cases. The methods/tools and fuel pathways tested were:

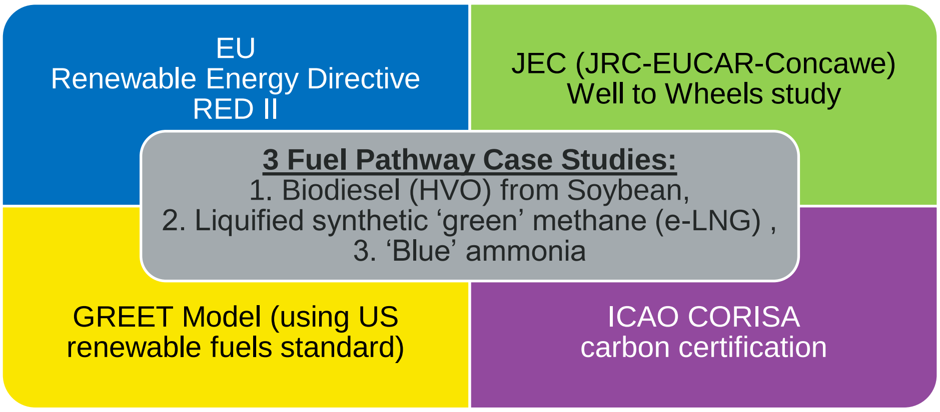

Figure 6-1: Methods and tools tested using three fuel pathway case studies

It should be borne in mind that the case study fuels are only representative of the specific pathways chosen, and other pathways may have different emissions. For example, methane production in a country with different legislation governing methane emissions may be expected to have higher or lower extraction and pipeline emissions, or a different feedstock for HVO may have different land use change impacts.

Both the European (RED II) and the US (EPA renewable fuels standard applied through GREET) regulatory methods for assessing the GHG and sustainability impacts of alternative fuels were assessed through the case studies for their applicability to marine fuels. Two further methods were also assessed: that used by the ICAO CORSIA scheme for aviation, and that set out in the JEC "Well to Wheels" report focused on road vehicles (Prussi, et al., 2020).

There is a distinction between tools which set or apply selected guidelines, but may have flexibilities for different applications or standards, and the standards or regulations which set the guidelines or rules to use. As discussed in Section 4.3.2, GREET allows different approaches which had to be selected, while GHGenius was omitted from the case study evaluation since it did not set a method in itself. Regulatory approaches such as RED II, RFS, and CORSIA must be clear and consistent in approach.

This section sets out a series of conclusions from the findings of this study, which cover:

- The evolving regulatory landscape, highlighting relevant ongoing work
- Boundaries for analysis of the methods and tools, exploring how LCA principles can be practically applied to the fuel pathway, and the potential implications
- Environmental sustainability criteria – considerations beyond GWP
- Applicability of existing methods and tools to alternative marine fuels, providing an overview of the methods/tools evaluated in the case studies
- Gaps and significant differences in methods and tools – conclusions from the detailed analysis of the methods/tools and their approaches
- Assumptions and input data needed in applying the methods and tools – conclusions from applying the methods/tools to the case studies and testing their sensitivity

Specific recommendations for applying GHG calculation methods to alternative marine fuels and for future work are extracted in Section 7.

6.1 EVOLVING REGULATORY LANDSCAPE

The review of regulations, standards, and guidelines revealed mixed approaches for different transport sectors and regions, with some overlapping requirements such as between the EU and IMO for maritime. The regulatory landscape is also evolving rapidly, for example the EU published its Fit for 55 package of measures to reduce GHG emissions while this study was underway, which has implications for all transport sectors including maritime. Developments that are ongoing at the current time relevant to GHG emissions from the maritime sector include:

- ✓ A revision of RED II to increase the use of energy from renewable sources, improve energy system integration (with other regulations), and increase protection for biodiversity
- ✓ Proposed FuelEU Maritime regulation which aims to increase the use of sustainable alternative fuels in European shipping, addressing market barriers and technical uncertainty
- ✓ EU ETS proposed extension to include maritime emissions
- ✓ Alternative Fuels Infrastructure Directive revision

6.2 BOUNDARIES FOR ANALYSIS OF THE METHODS AND TOOLS

To compare life cycle GHG emissions of marine fuel pathways in this study, it was considered appropriate to interpret well-to-wake as well-to-shaft (with emissions intensity expressed as e.g. g CO_2e / MJ), excluding vessel-related details

Whilst the terminologies for LCA that began for vehicles as ‘well to wheel’ are commonly translated to vessels as ‘well to wake’, it is not possible to create a single metric that covers all vessel types and considers all the on-ship technologies that can improve the efficiency of the ship or operational measures. The metric of grams of CO_2 equivalent emissions per tonne-mile (or similar) using work done was considered but rejected for this study as being too vessel dependent to allow objective comparison of the fuel pathways. Instead, the metric of shaft work output from the powertrain (i.e., grams of CO_2 equivalent emissions per MJ of shaft work) was chosen to include powertrain efficiency and exhaust emissions, while excluding vessel and voyage dependent variables. So, the case study evaluations consider WtW for the fuel pathway “harmonised” to exclude vessel-specific factors.

Boundaries for analysis should be appropriate to the evaluation required

The selection of this boundary for the evaluation of the methods and tools in this study does not imply it is an appropriate boundary for all WtW analysis, or for regulatory purposes. For example, evaluation of a vessel must include the vessel-specific factors and indeed its operations. Recommendations of appropriate boundaries for regulation are made in Section 0.

A well-to-wake analysis of GHG emissions of a fuel does not imply a full life cycle assessment of a vessel, although such an assessment could add value for new vessel design

The assessment of the life cycle of a fuel is not the same as that for a vessel, and so does not account for the CO_2 emissions inherent in the steel on the ship or the materials needed to build a battery, nor does it capture the impact on the cargo capacity of a vessel from the weight or space needed for the energy storage. To ensure the most efficient use of resources and minimum GHG impact of a particular vessel an LCA of that vessel should consider its construction, lifetime usage emissions, and end-of-life disposal, which can be evaluated for example against cargo carried and distance. This is important to consider in the design of a new vessel considering its application since the impacts of the materials used, propulsion system, and fuel/energy choices will depend on the size and type of vessel and its intended duty cycle; for example, the results for a bulk carrier would look very different to those for a short-distance ferry. However, the life cycle implications for vessels are outside the scope of this study.

The implication for the IMO’s energy efficiency measures is that standard factors (such as Fuel CO_2 Factor in CII) could be expanded in scope to WtW factors

Existing maritime legislation provides for the recording of fuel used by a vessel through the IMO DCS from which the CII is calculated using a Fuel CO_2 Factor (see Section 1.3). These regulations only consider the CO_2 emitted by the vessel and do not consider non-CO_2 emissions from use or emissions during fuel production.

The current regulations are reasonable for existing liquid fossil fuels (where the majority of emissions are in the form of CO_2 from combustion). For other (future) fuels, where emissions occur throughout the production chain, there is a growing understanding that all relevant GHG emissions should be taken into account on a WtW basis. It would be possible to apply life cycle principles for the fuel to a fuel GHG intensity factor covering WtW, calculated per unit of fuel. The factor should be representative of the fuel production pathway used, which may be specific to the region or production facility. The factor may also need to reflect the different emissions characteristics of different powertrains (such as 2/4 stroke, exhaust treatment), and so the factor may have two parts – calculated for WtT and TtW. However, the powertrain efficiency, ancillary systems, vessel efficiency and other characteristics, and the impact of operational and weather factors, are captured in the fuel use measurement via DCS. Similarly, multi-fuel vessels (whether used for alternative or pilot fuels in propulsion or for ancillaries) may be included through the measure of all fuels used, and application of an appropriate WtW GHG intensity factor for each fuel.

6.3 ENVIRONMENTAL SUSTAINABILITY CRITERIA

The environmental sustainability criteria for a fuel should consider more than just GWP

As well as the need to calculate emissions, this study identified the need to consider environmental sustainability criteria for several impact categories:

- Contribution to global warming potential (GWP) from fuel feedstock sourcing – especially through land use change (LUC) for non-waste biofuels.
- Contribution to GWP from fuel production – such as the effectiveness of carbon capture and storage (CCS), fugitive emissions, and the carbon intensity of electricity sources
- Eutrophication Potential – from land use for non-waste biofuels
- Particulate Matter Formation Potential for liquid hydrocarbon fuels (e.g., biodiesel), which may be similar to some existing fossil fuels
- Potentially large Ecological and Human Toxicity and Abiotic Depletion concerns from material demands associated with electricity as an energy carrier and input to green fuels, and the demand for electric motors, batteries, and fuel cells.

The evaluation of the existing methods and tools showed a focus on GWP aspects, and the coverage of feedstock sourcing and fuel production categories is described below. However, the criteria for a sustainable fuel should also include other high impact categories.

6.4 APPLICABILITY OF EXISTING METHODS AND TOOLS TO ALTERNATIVE MARINE FUELS

In this study four established methods and tools for calculating the total GHG emissions of fuels have been evaluated using three marine fuel case study scenarios.

The EU regulatory approach **RED II** is fundamental to various European legislation, where marine decarbonisation is arguably being pushed more strongly than in other regions. It does not provide complete WtW coverage since being based around biofuels it assumes tailpipe CO_2 emissions are net-zero, and it omits other GHG emissions. Therefore, it should not be applied to a WtW analysis without additional consideration of TtW emissions. RED II also omits fugitive emissions from distribution (which may have significant GHG impact for some fuels) and indirect and domestic LUC (being limited to direct), furthermore it does not currently cover CCS. However, the use of attributional allocation is less demanding of the user than consequential allocation.

- ➢ **RED II can only provide an incomplete method for alternative marine fuels in its current form**

The international aviation **CORSIA** scheme also omits fugitive emissions and does not cover CCS, supporting only limited fuel pathways at present.

- ➢ **While CORSIA provides an example of an international transport sector GHG calculation method, and can be applied to marine fuels, it is currently limited in the fuel types supported**

The method used in the **JEC** report (Prussi, et al., 2020) has no LUC coverage at all, as well as lacking CCS and fugitive emissions. Therefore, it cannot provide a complete assessment of the GHG impacts of all fuels.

- **The JEC method does not provide sufficient coverage to be used for the range of alternative marine fuels**

GREET was found to provide a flexible tool with broad coverage. Although there was a North American regional focus it provided a sound platform for the analysis of alternative marine fuels. However, the use of consequential allocation is demanding on the user

- **GREET would be suitable for marine fuel GHG assessment with appropriate standards, assumptions, and input data selected**

6.5 GAPS AND SIGNIFICANT DIFFERENCES IN METHODS/TOOLS

Some omissions in the methods and tools were identified through the comparison in Section 5.3, and the key characteristics of each are summarised above. Analysis of the gaps and significant differences provides the following conclusions:

WtW analysis should include all TtW emissions

Since RED II is intended for biofuels, it assumes that CO_2 emissions in use (the TtW phase) are net-zero. However, not all low-carbon fuels are net zero, and emissions with GWP other than CO_2 may be emitted from the use of the fuel, depending on the fuel and the propulsion system. As CO_2 emissions fall, CH_4 and N_2O releases will become relatively more significant.

Fugitive emissions of GHG (especially methane) from production, distribution, storage, and use of low-carbon alternative fuels has a significant impact on their total GWP

Fugitive methane emissions in production and distribution are an important GHG, and are covered to some degree by all methods/tools, but most thoroughly by GREET. RED II, JEC, and CORSIA did not include fugitive methane emissions from distribution. In principle, it is important that fugitive emissions are included for all stages of the fuel pathway, but it is acknowledged that by their very nature, they are hard to measure and quantify accurately.

Emissions from the use of fuels is not well understood for some fuels and technologies (such as ammonia ICE), while the powertrain technology and aftertreatment (exhaust catalysts) change the characteristics of such emissions.

Future 'blue' marine fuels will require a method able to account for the impacts of CCS; not all the methods and tools tested currently account for CCS

Some future fuel pathways may include the use of carbon capture and storage to provide a low carbon fuel that uses fossil fuels in its production. The example tested in this study was blue ammonia. Of the methods and tools tested, CORSIA and RED II do not (currently) explicitly include CCS, but CCS was included within the case studies as it would be reasonable to expect it to feature in the treatment of future marine fuel pathways. As the carbon capture efficiency of plant can vary during operation, some monitoring and approval may be required for any regulated blue fuels. It should also be noted that, at the time of writing, there are still relatively few established CCS facilities in the world, most of which are only operating at pilot plant scale (Global CCS Institute, 2021).

Biofuel pathways have additional sustainability considerations, particularly regarding land-use change accounting. The four methods and tools tested account for this differently.

Fuel pathways for biofuels have additional considerations, which can be controversial and complicated to resolve, particularly regarding land-use change accounting. Methods/tools able to fully or at least partially account for this include: REDII (direct LUC only), CORSIA and GREET (direct plus indirect LUC). Conversely, JEC is lacking in that it does not address LUC emissions at all.

A further, often fundamental, point about many biofuel supply chains is that of scalability. In essence, while almost any pathway may be feasible on a reduced scale, many thorny issues may soon start to crop up when attempting to upscale production to the degree that would be required if a significant portion of conventional fossil fuels were to be displaced. Examples of these issues include:

- Resource/feedstock availability; thereby including depletion of arable land, fertile topsoil, competition with food crops, etc.
- Land degradation which can lead to LUC emissions beyond what is currently considered and tabulated in the available methods and tools; if for instance a whole different type of naturally vegetated land has to be cleared to make space for the new plantations required to meet biofuel demand on a larger scale
- Market saturation for co-products; which can alter, potentially drastically, the impact allocation balance between the biofuel and its co-products, resulting in sharp increases in energy use and carbon emissions per MJ of biofuel (*cf*. for instance the example of bio-diesel and glycerol discussed in Appendix 4).

Partly because of these complexities at play, while there are differences in the methods, there is no universally accepted “right” approach to the WtT analysis of biofuels, which complicates the attribution of WtT emissions from biofuels for global regulatory purposes, especially as USA and EU regulatory systems differ. However, this study noted that the CORSIA approach to LUC has set a precedent for international emissions and has the most comprehensive coverage of all the methods and tools considered.

Significant variations in well-to-tank emissions can arise from the different methodological approaches to treating co-products, whether through energy or economic allocation, or ‘system expansion’

The system expansion method as recommended by ISO LCA standards is used by JEC and is an available option in GREET. Energy-based allocation is used in the REDII and CORSIA methods, while both energy and economic allocation are available options in GREET. Depending on the pathway significant differences in the treatment of co-products is found, which can in some cases have a dramatic effect on the WtT emissions. A trade-off exists for methods and tools between the arguably theoretically more appropriate method for consequential studies looking at system-level change (i.e., system expansion), and the often more practical and less complex/subjective alternative (i.e., energy allocation). The choice of approach to land use change and co-product allocation has been the subject of numerous studies, but this study noted that RED II and CORSIA are both international legislative measures and both use energy allocation of co-products.

6.6 ASSUMPTIONS AND INPUT DATA NEEDED IN APPLYING THE METHODS AND TOOLS

For the purpose of the comparison, common default values were used for all methods and tools, but in future applications, default values tailored to the specific fuel pathways will be needed

To fairly compare the methods and tools a common set of input data has been used for all case studies. There are default datasets available within the methods/tools chosen. The differences in default values between the methods and tools have not been fully considered by this project but would be expected to make a significant difference to the emissions associated with each fuel. These differences reflect the fuel pathways covered by and regional influences for each method. A possible method applicable to marine fuels globally should consider these factors, and assumptions would need to be based on the fuel pathway and region being considered in a fair and objective manner.

By extension, chemically identical fuels but from different pathways will need to be robustly differentiated and/or certificated

Unlike the current situation where CO_2 factors for a conventional fuel are universal, the WtT emissions for a fuel produced by one method, or in one geography may be significantly different to a chemically identical fuel produced elsewhere. This may require “certificates of origin” or equivalents if WtT approaches are used as part of the regulatory process. It is also likely that one plant can produce a range of products depending on input, for example an ammonia plant could supplement H_2 from LNG with green H_2 and therefore may want to allocate some product as green.

All GHG calculation methods and tools tested are sensitive to the input assumptions, particularly around land use change, upstream emissions, grid electricity intensity for green fuels, and N_2O and CH_4 emissions

While investigating the methods and tools and making the case study calculations, various input data were entered and later revised. Whilst doing this, it became very clear that the emissions values for each fuel were sensitive to the assumptions and input data used. Areas of particular risk centre around: land use change for biofuels; upstream emissions for blue fuels; grid electricity intensity for green fuels; and N_2O and CH_4 emissions from combustion. Therefore, should the findings in this report be used to support a regulatory procedure, careful setup and monitoring would be required to ensure fair results are generated. There is a significant risk of a user generating incorrect emissions values for a fuel, whether through error, insufficient data, or to deliberately show a fuel in more favourable light.

The calculation of GWP impact from some species such as methane and black carbon is particularly sensitive to the choice between 20-year or 100-year time horizon

Most methods recommend (or require) the use of a 100-year time horizon to establish the CO_2e characterisation factors for all GHG emission flows, and this is by far the most prevalent time horizon used in the scientific literature too. However, when considering some species such as methane where the GWP is significantly higher over a 20-year timeframe than a 100-year timeframe, the short-term climate effects could be much higher than the use of a 100-year GWP would suggest. Therefore, when considering shorter-term climate impacts, the use of a 20-year timeframe for GWP is more scientifically appropriate, whereas when considering longer term climate impacts, the use of a 100-year timeframe is more scientifically appropriate. Whether to prioritise shorter- or longer-term climate effects is ultimately a policy decision, which falls outside the scope of this report. However, it is noted that the choice between using 20-year or 100-year timeframes for GWPs will affect the WtW calculation of GHG emissions from different fuels differently – e.g., using 100-year GWPs will lead to comparatively higher calculated GHG emissions for a fuel with higher carbon but lower methane emissions, and using 20-year GWPs will lead to comparatively higher calculated GHG emissions for a fuel with higher methane but lower carbon emissions.

7. RECOMMENDATIONS AND FURTHER WORK

In this section, observations from this work and recommendations for further work on how to establish WtW GHG calculation methods to cover international shipping are presented, drawing on the findings of the previous sections. These are grouped by:

- The possible boundaries to be applied to the WtW evaluation of marine fuels, and where further work can increase understanding of the impact on the vessel life cycle
- The possible methodological approaches to calculating GHG emissions, and where further work may bring value
- The importance of accurate data, and how this may be established for fair WtW comparison
- A summary of possible approaches for a future WtW calculation method for marine fuels

The recommendations are highlighted in blue text.

7.1 BOUNDARIES FOR WTW EVALUATION OF MARINE FUELS

When applying LCA principles, consideration should be given to the boundaries to include all relevant factors and allow a fair comparison at the lowest possible complexity level of the calculation. This report considered the appropriate boundaries for assessing marine fuels in different contexts.

- ➢ When considering the WtW GHG emissions of marine fuels the system boundary may include:
  - Fuel/electricity production including sourcing of feedstock, production, and fugitive emissions.
  - Fuel distribution and storage, including losses and energy consumption from compression and liquefaction (where applicable), and fugitive emissions
  - Vessel operation phase including fuel conversion/combustion and exhaust and fugitive emissions, covering all fuel use (such as for auxiliary power and multi-fuel systems) and shore power electricity, and including non-CO_2 combustion emissions such as CH_4 and N_2O.

Recording of individual vessel fuel consumption and transport measures is already established through IMO DCS and for some vessels EU MRV regulations. To evaluate the WtW GHG impact of a vessel from its fuel consumption a GHG intensity factor can be applied.

- ➢ A WtW GHG intensity factor comprises the following elements:
  - A WtT factor for the fuel, established for each fuel type and production pathway, including the fuel distribution and bunkering processes.
  - A TtW emissions factor for the exhaust and fugitive emissions of the fuel in-use. While for today's engines and fuels, the GHG emissions are broadly proportional to the fuel used, in future, there may be marked differences in performance. An example would be for LNG engines, where some engines may have lower methane slip than others.

It is not unusual for vessels to use more than one type of fuel, whether alternatively or in combination (such as a pilot fuel), for propulsion or otherwise, and this is likely to become more common with the adoption of alternative fuels. Therefore:

- ➢ A WtW GHG methodology for the maritime sector should be able to fully accommodate dual-fuel systems for monitoring usage of all fuels used (whether for propulsion or otherwise) with their appropriate WtT and TtW emissions factors

The use of shore power to remove the need to run auxiliary engines in ports may in future be mandated through legislation as is proposed in the EU, and already in place in China and California, for various larger vessel types. While this means fuel is not consumed on the vessel, it may not mean there are no GHG emissions. Indeed, the evaluation of the GHG emissions of the electricity used may need to consider whether renewable, grid average or marginal factors are appropriate. Therefore:

- ➢ The GHG impact of electricity supplied for shore power or battery charging could be evaluated by measuring the energy provided and the use of an appropriate GHG factor for the electricity source.

With increasing uptake of lower/zero carbon fuels, the proportion of the lifecycle emissions associated with the vessel (construction, modification, and use) increase. This is particularly true for electrified and battery vessels, and not just for GHG as noted in the consideration of wider sustainability criteria. In addition, the effect of future lower density fuels on the “utility” of the vessel (more space used by fuel, less available for cargo) and so its sustainability may not be clear. This can only be assessed for a specific vessel design and usage.

- It is recommended to further study the relative emissions across lifecycle stages for a number of vessel types and energy vectors considering these factors. This would inform whether guidance or legislation may be required in future.

7.2 POSSIBLE METHODOLOGICAL APPROACHES TO CALCULATING GHG EMISSIONS

The case studies shared a common input dataset for each fuel scenario to evaluate the differences resulting from the methods and tools. That there were differences reflects differing assumptions in the methods and tools, and the fuels and regions they were designed to cover.

The scope of this project cannot compare the benefits or demerits to the various land use change options. However, the CORSIA approach to LUC is an existing example of a framework covering international emissions and has the most comprehensive coverage of LUC among the methods and tools assessed.

- CORSIA represents a relevant model for how a maritime WtW method could treat LUC, though a mid-point between GTAP and GLOBIOM ILUC models could be used.
- Further work could identify appropriate approaches to LUC that address the required sustainability criteria, and which apply to the range of potential alternative marine fuels available globally.

The most appropriate approach to co-product assessment is a subject of debate, since it relies on artificially defined boundaries and which sub-system is deemed responsible for which share of the total emissions. System expansion is the preferred LCA approach according to the recommendations given by ISO (ISO 14044, 2006), and it also recommended by the ILCD handbook (JRC, 2010) for “consequential” LCAs (where the emphasis is on system-level change rather than on individual product units). However, energy allocation is a less complex and subjective approach. It is noted that of the methods and tools studied, RED II and CORSIA are both international legislative measures and both adopt the simpler energy allocation approach.

- In principle, system expansion is the preferred approach to co-product allocation, but given the complexities associated with system expansion, and to a lesser extent also with economic allocation, an energy allocation approach as set by RED II and CORSIA could be used.

The GHG impact from fugitive emissions can be significant for certain fuels (such as those containing methane). These can occur e.g., from leaks or boil-off venting of storage vessels. While such emissions can be difficult to accurately quantify, there is no justification to disregard them.

- So far as is practicable, marine fuel GHG calculation methods should account for fugitive emissions at all stages of the fuel pathway.

Consideration should be given to the appropriate time horizon over which to establish the CO2e characterisation factors for all GHG emissions. The GWP of methane or black carbon emissions are much higher over a 20-year timeframe than the typically considered 100-year timeframe would indicate. The GHG emissions calculated for different types of fuels will be affected in different ways by the choice of timeframe.

- Further work could explore whether it is appropriate for GHG calculations for alternative marine fuels to capture short-term impacts as well as long-term ones, and how that may be achieved.

7.3 ESTABLISHING ACCURATE DATA

While the use of common datasets allowed comparison of the methodological differences, the methods and tools also differed in the default data inventories provided. Given the global nature of the marine industry and the future diversity of fuels, production methods and geographies, a wider set of input data and emissions factors may need to be developed to allow more accurate evaluation of variation in WtW emission calculations. In some cases, this may be a relatively simple task, but in others such as land use change and upstream fugitive emissions, establishing widely accepted data could be challenging. Some data are specific to the fuel pathway, location or vessel and the use of default assumptions may be inappropriate.

- It is recommended that a future study reviews the differences between pathways, production method or locales for specific fuels to determine the differences in WtT emissions for a single fuel. This could then be used to determine whether different WtT factors are needed per pathway or supplier.
- Ongoing monitoring of certain aspects of fuel production, is recommended due to differences in technology and process having a significant impact on the GHG intensity of the product.
- Further work could evaluate approaches to quantifying fugitive emissions (including fugitive) from alternative fuel production, storage, and distribution.

For future fuels, consideration of N_2O and CH_4 emissions from combustion or aftertreatment systems (including reagent consumption) will be critical, as these are expected to become a greater proportion of greenhouse gas emissions from shipping compared to today. This is likely to require some form of certification. It may also require monitoring of engine or ship, since emissions are likely to vary according to engine and exhaust emissions aftertreatment (catalytic converter) characteristics, use and indeed equipment health. On-board fugitive emissions should also be further evaluated.

- Further studies could evaluate approaches to establishing, certifying, and potentially monitoring non-CO_2 GHG emissions from vessels, including fugitive emission, as well as exhaust emissions from primary and any auxiliary powertrains.

7.4 CONSIDERATIONS FOR GHG EMISSION ASSESSMENT METHODS AND STANDARDS FOR ALTERNATIVE MARINE FUELS

From the analysis of existing GHG emission assessment methods and tools, Ricardo recommend that any WtW methodology applied to alternative marine fuels considers the following:

- Inclusion of in-use emissions of CO_2, CH_4 and N_2O, plus potentially black carbon.
- Inclusion of upstream emissions, particularly regarding methane leakage, energy used for production and carbon capture and storage rate.
- CORSIA represents a relevant model for the consideration of land use change, and RED II for considering co-product allocation.
- Any default data, assumptions, or emission factors provided should be conservative and the burden of proof for better values should be on the fuel producer or powertrain supplier.

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APPENDICES

Appendix 1 Mapping of Standards, Regulations, and Guidelines

Summary of standards, regulations, and guidelines, which have been mapped and evaluated as discussed in Section 4.1. The full evaluation was carried out against the criteria:

- Description/Synopsis - Aim, application, overview
- Type - Standard, Regulation, Policy
- Scope: Political - Government, organisation
- Scope: Geographical - Countries or territories covered
- Scope: sector - Marine, road, aviation…
- Responsible bodies - Organisations that certify, verify, or enforce
- Boundaries - WtT, TtW, Scope, and notes on coverage
- Emissions covered - CO_2/GHG, pollutants, etc.
- Measurement methods - How emissions are assessed
- Other sustainability impacts - Land/water use or other concerns
- Market volume - Scale of impact assessment
- Administrative burden - Effort to apply and enforce
- Commercial sensitivities and impacts
- Weaknesses, unintended consequences, loopholes
- Applicability to marine - Is marine covered? Are there lessons?
- Source – Note of references to sources
- Comments - maturity, future developments expected

These were recorded in an index, with a field for each of the criteria. Due to limited space in this report only the key attributes are listed, along with a brief synopsis of coverage, and comments on observations of interest for the other criteria, are shown here.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
IMO NOx Technical Code	Regulation	Marine	Pollution;	TtW	Requirement for marine diesel engines to ensure compliance with Nitrogen Oxide emissions limits prescribed by the IMO through testing and certification.	Certified on engine dyno. Only covers NOx emissions. Cost and potential cargo space implications.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
IMO Energy Efficiency Design Index (EEDI)	Regulation	Marine	GHG; Sustainability;	TtW	The EEDI promotes the use of more energy efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per tonne nautical mile for different ship type and size segments, to be tightened incrementally every five years, driving improved fuel efficiency of a ship from its design phase. EEDI adopted in 2011 with phase 1 (2015) for 20% reduction of carbon intensity of new ships, phase 2 (2020) for 20% reduction, phase 3 50% reduction for new large container ships (2022) and 30% for all new ships (2025).	
IMO Ship Energy Efficiency Management Plan (SEEMP)	Regulation	Marine	GHG; Sustainability;	TtW	The regulation quires an operational Ship Energy Efficiency Management Plan (SEEMP) measures for the energy efficiency of ships. Adopted in 2011 and in force from 2013 The Energy Efficiency Operational Indicator (EEOI) is a monitoring tool to drive increased operating efficiency	
IMO Data collection system (DCS) for fuel oil consumption of ships	Regulation	Marine	GHG;	TtW	Data collection system for fuel oil consumption of ships. Ships are required to collect consumption data for each type of fuel oil they use, as well as other specified data including proxies for "transport work". DCS reporting is mandatory from 2019, with first results published for MPEC 76 in March 2021	Small admin burden per ship. Limited to conventional propulsion fuels at present.
IMO Energy Efficiency Existing Ship Index (EEXI)	Proposed Reg/Std	Marine	Sustainability;	TtW	Requirement for all ships to calculate their Energy Efficiency Existing Ship Index (EEXI) to indicate the energy efficiency of the ship compared to a baseline and improve their energy efficiency, and to establish their annual operational carbon intensity indicator (CII) and CII rating (A-E). Carbon intensity links the GHG emissions to the amount of cargo carried over distance travelled, and corrective action is required for ships rated E, or not improving from D. Administrations, port authorities and other stakeholders as appropriate, are encouraged to provide	Slower steaming speeds and reduced engine powers likely. Some energy efficiency technologies e.g. wind assistance not fully described

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
					incentives to ships rated as A or B also sending out a strong signal to the market and financial sector. The 2021 guidelines set a GHG reduction rate of 11% by 2026 relative to 2019. The measure was adopted in 2021 with EEXI survey requirements taking effect in November 2022, and CII data collection starting from 2023.	
European Union Monitoring, Reporting and Verification (MRV) of carbon dioxide emissions from maritime transport	Regulation	Marine	GHG;	TtW	Requires vessels/companies to monitor CO2 emissions through the measurement of fuels consumed, along with data about voyage, cargo, distances, so as to gather annual data into an emissions report submitted to an accredited MRV shipping verifier. The report is then submitted to the EC, and a document of compliance is issued that all vessels should carry. Applies to ships arriving at, within or departing from ports under the jurisdiction of a Member State, in order to promote the reduction of CO2 emissions from maritime transport in a cost-effective manner.	Similar principle to IMO DCS system, but sufficiently different to require separate monitoring and reporting by vessels/companies. Adopted in 2016 and implemented from 2018, ahead of IMO DCS. EC proposed changes will align some measures to DCS but keeps some key differences. Requires voyage and cargo details to be reported.
US EPA Emissions standards for marine engines	Regulation	Marine	Pollution;	TtW	Emission standards and certification requirements for marine diesel engines - contains provisions which affect both engine manufacturers and others. Separate standards for commercial and recreational engines, outboards, etc.	Certified on engine dyno. Covers PM, NOx, HC, CO; and including leisure and outboard. Averaging, banking, and trading (ABT) can be used.
European Union EU Stage V Emissions from non-road mobile machinery (NRMM)	Regulation	Non-road engines (off highway, rail, tools, power generation, inland waterway	Pollution;	TtW	Limits of exhaust pollutants and measurement procedures applied to non-road engines in EU and many other countries. Similar to those for heavy duty engines. Various categories of engine applications and power ratings.	Certified on engine dyno, and ISV with PEMS. Covers HC, CO, Nox, PM, PN. Inland waterway vessels.
California Air Resources Board (CARB) 13 CCR, section 2299.2	Regulation	Marine	Pollution; Fuels;	TtW	Fuels and pollution standard to control PM, NOx, SOx on ocean-going vessels within “Regulated California Waters”.	Certified on engine dyno, covers PM, NOx, and SOx. Moderate admin burden for vessel operators.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
International Shipping Commission Lake Constance Shipping Regulations	Regulation	Marine	Pollution;	TtW	Limits pollutant emissions for boats using Lake Constance.	Certified on engine dyno, covers CO, HC, NOx. Limited geography.
European Union FuelEU Marine	Proposed Reg/Std	Marine	GHG; Pollution; Sustainability;	WtW	Proposed regulation as part of "Fit for 55" package, of the use of renewable and low-carbon fuels in maritime transport, including sailing into or out of EU ports. Use of shore power. Links to REDII and limits use of crop-based biofuels. EU database registering performance of each ship, penalties for non-compliance.	Applies REDII for WtT impacts, no feed and food based fuels promoted.
European Union Fuel Quality Directive (FQD)	Regulation	Road transport, non-road mobile machinery and inland waterway	GHG; Fuels; Sustainability;	WtW	Applies to petrol, diesel and biofuels used in road transport, and gasoil used in non-road-mobile machinery. Requires a reduction of the GHG intensity of transport fuels by a minimum of 6% by 2020. Together with the Renewable Energy Directive, it also regulates the sustainability of biofuels.	Should be considered alongside REDII
European Union EU Renewable Energy Directive (REDII)	Regulation	Transport (inc. inland waterway), energy, heat, and cooling. Will expand to cover marine	GHG; Pollution; Sustainability;	WtT	RED II sets the EU target for renewable energy sources consumption to 32%, with a transport sub target of 14%. RED II defines a series of sustainability and GHG emission criteria that bioliquids must comply with to be counted towards the 14% target. In addition, limits are placed on high ILUC-risk biofuels, and a dedicated target for advanced biofuels.	To be strengthened through EU "Fit for 55" package. High market impact. Limits use of crop-based biofuels or LUC impact.
US EPA Renewable Fuel Standard Programme (RFS)	Standard	Biofuels	GHG; Fuels; Sustainability;	WtT	The RFS programme requires certain volumes of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel. The Energy Independence and Security Act of 2007 (EISA) further amended the CAA by expanding the RFS programme.	Covers marine. Impacts of biofuels on: biodiversity and environment, economic and social, verification and auditing, indirect effects. Targets have not been met.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
UK Government Renewable transport fuel obligations (RTFO)	Regulation	Transport, NRMM, inland waterways. May expand to cover marine	GHG; Sustainability;	WtT	UK implementation / equivalent of EU RED. The RTFO encourages the use of biofuels that don't damage the environment, a proportion of fuel must come from renewable AND sustainable sources. Consultation in 2021 on increasing RTFO obligations, coverage of non-biological renewable fuels ("efuels") and changes for maritime, and updating sustainability criteria.	Includes electricity generation in WtT, checks for double-counting and additionality.
UK Government Transport Decarbonisation Plan	Policy	All transport sectors - Road, rail, marine, aviation	GHG; Sustainability;	WtW	UK policy statement ahead of COP26 and following Prime Minister's 10-point plan and CCC advice on carbon budgets, covering strategies to decarbonise transport to net-zero by 2050. Includes proposed ICE road vehicle and non-ZE marine vessel sales ban dates, increases in renewable fuel supply/use, technology and infrastructure investment, press the IMO for greater ambition, incorporate marine & aviation emissions in 6th carbon budget (CCC).	Policies - many of which are low maturity and will be subject to consultation. Political opposition unlikely to be strong but industry pressure could weaken some policies.
European Union International Sustainability Carbon Certification (ISCC)	Standard	Biomass and bioenergy	GHG;	WtT	ISCC promotes biomass, bio-energy and social sustainability among farmers and processors with the objective to respect climate and the environment. ISCC standards cover the entire biomass supply chain from the farm and plantation towards warehouses or logistics points to conversion unions, and to final users.	Voluntary certification initiatives have received criticism for limited effectiveness. Commercial benefits - environmental credibility.
European Union EU Emissions Trading System (EU ETS)	Regulation	Power, industries, civil aviation (in EEA-EFTA). Expansion for maritime, buildings and transport proposed.	GHG;	TtW	Objective to reduce GHG from power stations and other energy intensive industries (iron, aluminium, cement, glass, cardboard, acids, etc.) against target timeline. Companies hold allowances for emissions, capped by EU, but can trade them to be more efficient. EU Fit for 55 package considerably strengthens ETS increasing target reductions and scope changes, plus inclusion of marine.	Now in 4th revision to increase target reductions. Similar systems apply in UK and USA. Commercial opportunities for trading credits.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
US EPA REGULATION OF FUELS AND FUEL ADDITIVES - Subpart I of 40 CFR Part 80	Standard	Off-highway, power, rail, marine.	Pollution; Fuels;	TtW	Specifies diesel fuel standards for refiners to be used for motor vehicle diesel fuel; this includes nonroad, Locomotive and Marine Diesel Fuel as well as ECA marine fuel (i.e. used within the ECA waters). The North America ECA covers waters adjacent to the Pacific coast, Atlantic/Gulf coast and eight Hawaiian Islands. It extends up to 200 miles from the coast of United States, Canada and the French territories.	Marine coverage limited to ECA waters only.
United Nations ICAO CORSIA	Proposed Reg/Std	Aviation fuels	GHG;	TtW	CORSIA is a carbon offset and carbon reduction scheme to lower CO2 emissions for international flights, to curb the aviation impact on climate change. Aim to achieve carbon-neutral growth after 2020. Pilot scheme 2021-2023; voluntary 2024-2026, mandatory 2027-2035. The ICAO CO2 Estimation and Reporting Tool (CERT) is used for fulfilling monitoring and reporting requirements.	Limited ambition (carbon neutral growth). Domestic flights are not included, nor are small aircraft or operators. Requires potentially commercially sensitive information, data is anonymised. Delays due to COVID - EDF estimate 5 years, ICCT say 30% more CO2e.
European Union Euro 6 Emissions from light duty road vehicles	Regulation	Light duty road vehicles (up to 3.5t GVW)	Pollution;	TtW	Limits of exhaust pollutants and measurement procedures applied to light duty road vehicles in EU and many other countries. Covers Tailpipe emissions HC, CO, Nox, PM, PN. Evaporative emissions (HC) from gasoline vehicles. Direct measurement at tailpipe over prescribed (WLTP) test and not to exceed limits on road tests (CVS on dyno or PEMS on road).	Previous NEDC cycle often criticised for not being realistic enough. "Defeat device" risk e.g. VW "dieselgate". EU criticised for having less enforcement power than EPA. High cost of compliance (technical, hardware, and admin). EU7 limits expected to be more severe with additional pollutants.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
European Union Euro VI Emissions from heavy duty vehicles and non-road sources	Regulation	Heavy duty road vehicles (>3.5t GVW)	Pollution;	TtW	Limits of exhaust pollutants and measurement procedures applied to heavy duty road vehicles in EU and many other countries. Tailpipe emissions HC, CO, NOx, PM, PN. Basic limit on NH3. Measured at testbed test over WHSC, WHTC, plus NTE tests, ISC with PEMS.	Engine tested independently of vehicle, plus in-service tests using PEMS. Some applications e.g. high parasitic loads, cold starts, stop-start cycles may not be well covered. High cost of compliance (technical, hardware, and admin). EU7 limits expected more severe with additional pollutants.
European Union Fuel Economy & CO2 emissions for light duty road vehicles	Regulation	Light duty road vehicles (up to 3.5t GVW)	GHG;	TtW	Mandatory CO2 emissions limits for vehicles applied over "fleet average" by manufacturer, with fines. Targets for average of total fleet sold down to 130 g/km by 2015 and to 95 g/km by 2020, reducing 15% by 2025. Credits and super-credits for low emissions vehicles. Manufacturers can group for reporting averages, and bank/borrow/trade credits.	NEDC test seen as unrepresentative - gentle, low speed, low test mass. Potential to optimise technology. WLTP from 2020 more representative. Calculations for PHEV vehicles assume a high degree of EV use giving low CO2 figures. For premium/sports cars fine may not be a deterrent.
European Union Heavy Duty Vehicles - CO2 emissions standards	Regulation	Heavy duty road vehicles (>3.5t GVW)	GHG;	TtW	Mandatory CO2 emissions limits for vehicles applied over "fleet average" by manufacturer, similar to those for LDV. Emissions targets are specific to each manufacturer as linear reduction to 2025 target (15% reduction) and 2030 target (30% reduction TBC). Credits and super-credits for low emissions vehicles. Manufacturers can group for reporting averages, and bank/borrow/trade credits.	Relies on the extrapolation of engine dyno tests to vehicle emissions using a software tool and simplified usage assumptions. Targets likely to be reviewed in light of EU commitments to CO2 reduction by 2030/2050.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
European Union On board fuel consumption monitoring	Regulation	All road vehicles	GHG;	TtW	Requires vehicles to monitor fuel use over its life along with mileage, electrical energy use, etc. Intended to verify in-use CO2 impact. Data collection and reporting aspects incomplete.	No legislation yet for data collection or use, and significant hurdles e.g. payload monitoring, data transmission, security and validity of data.
US EPA Emissions standards for heavy duty vehicles	Regulation	Heavy duty road vehicles	Pollution;	TtW	Limits of exhaust pollutants and measurement procedures applied to heavy duty road vehicles in USA and adopted by many other countries. Tailpipe emissions HC, NMHC, CO, Nox, PM, Smoke. Evaporative HC in some cases. Direct measurement at tailpipe during engine testbed test over prescribed test cycles, and on-road using PEMS. OBD for monitoring emissions control systems.	California Air Resources Board (CARB) sets tougher emissions limits and standards than EPA. This suggests standards could be tighter. Averaging, banking, and trading (ABT) can be used.
US EPA Emissions standards for non-road engines	Regulation	Non-road engines (construction, agricultural, industrial)	Pollution;	TtW	Limits of exhaust pollutants and measurement procedures applied to non-road engines in USA and many other countries. Various categories of engine applications and power ratings. HC, NMHC, Nox, PM, CO, Smoke, Evaporative (HC) emissions. Measured at engine testbed test over prescribed test cycles.	Does not directly cover marine.
US EPA CAFE & SAFE	Regulation	All road vehicles	GHG;	TtW	Corporate Average Fuel Economy (CAFE), and Safer Affordable Fuel Efficient (SAFE) Vehicles sets fleet-average target fuel economy for manufacturers - similar to EU system but based on MPG rather than CO2. N2O and CH4 limits in place. Targets reduce over time and depend on vehicle size (area) or truck class. Multipliers for electric and FC vehicles, PHEV and gas fuelled vehicles.	Averaging, banking, and trading (ABT) can be used, as can early credits, technology credits. California Air Resources Board (CARB) limits are currently in close alignment to EPA, and EPA intention is to be "generally harmonised" with California and Canada.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
European Union Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)	Regulation	All sectors	Pollution; Sustainability;	N/A	REACH is adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals. REACH establishes procedures for collecting and assessing information on the properties and hazards of substances. In principle, applies to all chemical substances.	Not fuel-specific, doesn't consider use emissions. Relevant for consideration of new alternative fuels - for impacts to humans and environment of the fuel itself.
US EPA (NAAQS) National Ambient Air Quality Standards	Standard	Air Quality	Pollution;	N/A	The EPA has set National Ambient Air Quality Standards for six principal pollutants considered harmful to public health and the environment, which are called "criteria" pollutants. The standards are regularly reviewed, with primary standards aiming at protecting public health. Covers CO, Lead, NO2, O3, PM, SO2, with secondary standards aimed at limiting damage to animals, crops, vegetation and buildings.	The impact of marine vessels may be significant in port areas
ISO 14040/14044 Life cycle assessment	Standard	All sectors	GHG; Sustainability;	WtW	Standards for applying life cycle assessment from cradle to grave, widely used to compare the impact of different products and processes and used as the basis for impact assessment methods. Potentially applicable to any product or process.	Guidelines within which boundaries and assumptions must be decided. Different LCA's unlikely to be directly comparable - results are not absolute, but relative. Criteria can be difficult to meet for complex systems.
European Union EN 14214	Standard	Biofuels, fossil fuels	Pollution; Fuels; Sustainability;	TtW	Current EU standard for biodiesel Fatty acid methyl esters (FAME), that describes requirements and test methods	Covers Sulphur, Group I and II metals, Ash
European Union EN 228	Standard	Petrol engine vehicles	Pollution; Fuels;	TtW	Requirements and test methods for unleaded petrol.	Covers lead and sulphur content for gasoline, Benzene content, Oxygenates
European Union EN 590	Standard	Diesel engine vehicles	Pollution; Fuels;	TtW	Requirements and test methods for diesel fuel.	Covers Sulphur, carbon residue, Ash, Water

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
European Union EN 589	Standard	LPG engine vehicles	Pollution; Fuels;	TtW	Requirements and test methods for automotive liquefied petroleum gas (LPG), with LPG defined as low pressure liquefied gas composed mainly of propane, propane, butane, butane isomers, butenes with traces of other hydrocarbon gases.	Covers Sulphur
European Union EN 14214	Standard	FAME for use in compression ignition (diesel) engines	GHG; Pollution; Fuels; Sustainability;	TtW	Requirements and test methods for marketed and delivered FAME, including their verification and auditing schemes for biomass for energy applications.	Covers Sulphur and all fuel-dependent emissions associated with biofuels: Ash, Water, 'Acid value'. Impacts of biofuels on: biodiversity and environment, economic and social, indirect effects
ISO 8217	Standard	Marine and stationary engines	Pollution; Fuels;	TtW	Petroleum products — Fuels (class F) — Specifications of marine fuels. specifies the requirements for fuels for use in marine diesel engines and boilers. Specifies seven categories of distillate fuels and six categories of residual fuels including biofuel blends, synthetic and renewable	Covers Sulphur, hydrogen sulphide, carbon residue, other elements - Ash, Water, 'Acid value'
ISO 23306	Standard	Marine engines	Pollution; Fuels;	TtW	Specification of liquefied natural gas as a fuel for marine applications. Applies to LNG from any source, e.g. gas from conventional reservoirs, shale gas, coalbed methane, biomethane, synthetic methane.	Covers Sulphur
ISO 14687	Standard	PEM fuel cell road vehicles	Fuels;	TtW	Specifies the minimum quality characteristics of hydrogen fuel for vehicles and stationary applications, for PEM fuel cell technologies	
European Union EN 15940	Standard	Paraffinic diesel fuel	Pollution; Fuels;	TtW	Standards for hydrotreated paraffinic renewable diesel fuel and synthetic Fischer-Tropsch products GTL, BTL and Coal-to-Liquid (CTL). In the future e-fuels might also be covered with this standard. EN 15940 covers paraffinic diesel fuel used as such in vehicles.	Covers Sulphur

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
European Union and Intelligent Energy Europe BioGrace	Guideline	Biofuels, and biomass for electricity, heating and cooling	GHG;	WtW	BioGrace greenhouse gas (GHG) calculation tool has been recognised as a voluntary scheme by the European Commission. It is in line with the sustainability criteria of the Renewable Energy Directive (2009/28/EC, RED) as well as RED-II for biofuels and bioliquids. The BioGrace II GHG calculation tool is developed for companies that want to demonstrate compliance to RED-II sustainability criteria, for electricity, heating and cooling from biomass, for 22 biofuel pathways while BioGrace I is for transport fuels	Relevant for marine where under RED/REDII. Excel-based tool designed to be user friendly Includes emissions from land-use change, as well as savings from improving degraded land, carbon capture, excess electricity from cogeneration
JRC, EUCAR, and Concawe: JEC WtW Report (Prussi, et al., 2020)	Guideline	Road transport - v5 expanded to heavy duty vehicles adding to focus on passenger cars	GHG;	WtW	The JEC WtW study concentrates on fuel production and vehicle use stages, and while it is based on Life Cycle Assessment methods, it does not aim to be a full LCA. The aim of JEC WtW has been to evaluate the impact of fuel and/or powertrain substitution in Europe, on global energy usage and GHG emissions balance. WtW energy and GHG figures combine the WtT expended energy per unit of energy of fuel and TtW energy consumed by vehicles per unit distance.	Tool is for evaluation of fuels - low volume, high admin burden. Focused on road transport.
U.S Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy GREET	Guideline	Road, air, marine and rail	GHG; Sustainability;	WtW	The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) is an analytical tool that simulates energy use and emissions output of various vehicle and fuel combinations. Includes over 100 fuel production pathways from various energy feedstocks, includes electricity generation, and over 80 vehicle/fuel systems. Covers VOC, CO, NOx, PM10, PM2.5, SOx, and soil carbon changes, as well as GHG.	Non-mandatory method but used for compliance with US biofuel regulation. Relevant for marine where under US biofuel regulation. Datasets are limited to US applications.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
RSB (Roundtable on Sustainable Biomaterials) RSB-STD-01-001 RSB Principles & Criteria	Standard	Biomass fuel supply chain	GHG; Sustainability;	WtT	The Roundtable on Sustainable Biomaterials (RSB) is an independent and global multistakeholder coalition which works to promote the sustainability of biomaterials, including biomass and biofuels. As well as GHG covers Resource consumption, Sustainable development, Rural economic growth	Relevant to marine - the Sustainable Shipping Initiative has recently joined the RSB. Voluntary certification initiatives can have limited penetration. Commercial benefits - environmental credibility.
GHGenius LCA model	Guideline	All transportation fuels	GHG;	WtW	GHGenius is a free to download lifecycle analysis (LCA) model with a primary focus on transportation fuels in Canada. It includes data for activities ranging from crop production, to power generation, to tailpipe emissions in many regions spanning the globe. Development of new feedstocks, fuels, and regions is still ongoing. Covers GHG (CO2, CH4, N2O, CFC-12, HFC-134a), pollutants (CO, NOx, NMOCs, SO2, PM).	Potentially applicable to marine. Covers vast number of fuels. Detailed model with lots of components - complex to use. Factors come from various sources which need regularly updating, focus on Canada but can be applied globally.
IFEU GHG calculator	Guideline	All sectors	GHG; Sustainability;	WtW	The Institute provides a variety of methods and tools, including calculation tools, evaluations, models, sustainability assessments, and LCA and material flow analysis. Covers GWP, Ozone depletion, air pollutants, acidification, eutrophication, land use, raw materials	Voluntary methodology. Free, open-access excel-based tool. Can be used for marine. Seems to have more of a focus on 'midpoint' LCA, rather than 'endpoint' LCA. Has used default emission factors from Directive 2009/28/EC and JRC.

Regulation, standard	Type	Sector	Coverage of..	Over…	Description/Synopsis	Observations
California Air Resources Board (CARB) California Global Warming Solutions Act (AB32)	Regulation	Electricity generation; Cement, Lime, Nitric acid production; Petroleum refineries;	GHG;	WtW	GHG legislation and accompanying regulatory program implemented CARB. Two primary pathways for reporting/reducing GHG emissions: A Mandatory Reporting Program (MRP) and the Cap and Trade (C&T) Program for the California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms. Measured by the company/facility submitting the report but independently verified by a third party	Can be used for marine transport technologies/ fuel pathways. Potential conflict between consumer and verifier
Ecoinvent	Inventory database	All sectors	GHG; Pollution; Sustainability;	WtW	Ecoinvent is not itself a standard or regulation, but is arguably the most comprehensive and reputable LCI database. It is very thorough in terms of including inputs and emissions. It is limited to inventories of inputs and outputs of materials and energy (i.e., any aggregated impact metrics need to be calculated separately). Processes inventories are available both at "foreground" level (i.e., including inputs from Technosphere and local emissions only), and at the full life cycle level (i.e., accounting for all inputs from the geobiosphere, including all background processes, and total direct+indirect emissions).	Most widely-used LCI database, reliant on industry-vetted averages; combination of direct measurements and estimates. Does not include land use change GHG emissions
Zemo Partnership Renewable Fuels Assurance Scheme (RFAS)	Standard	Road (especially HD), off-highway, NRMM	GHG; Sustainability;	WtT	An initiative designed and managed by Zemo Partnership. The Scheme aims to verify claims made by companies supplying renewable fuels to heavy-duty vehicle and equipment operators regarding their product's GHG emission savings and provenance of raw material feedstocks. Provides assurance of compliance with RTFO, and covers same boundaries and emissions as RTFO.	Limited scope - UK only, just 9 fuels suppliers signed up. Provides assurance and credibility - voluntary but potential commercial benefit to suppliers.

Appendix 2 GHG Calculation Methods

Reviewed standards, methods, and inventories for GHG and sustainability evaluation reviewed in Section 4.2 for evaluating GHG and sustainability impacts, with a short synopsis and comment on their relevance to this study or interrelationships.

Name	Type	Synopsis	Relevance
EU REDII (2021 revision)	Standard	The Renewable Energy Directive (RED II, Directive (EU) 2018/2001) sets binding targets for all EU Member States to increase the use of energy from renewable sources, including a specific target for the transport sector.	**High**
UK RTFO	Standard	Renewable Transport Fuel Obligation (RTFO) is a UK implementation / equivalent of EU RED - largely similar. Applies to Transport, NRMM, and inland waterways in the UK. Consultation in 2021 considering extensions (including marine) and changes to sustainability criteria. Online GHG calculator tool provided (by I4tech) and spreadsheet.	See RED
RSB - stds & certification	Standard	The Roundtable on Sustainable Biomaterials (RSB) method is as RED except it considers forgone sequestration, slash and burn, N2O emissions from loss of soil organic carbon.	See RED
IFEU	Standard	Institute which provides methods on integrated LCA, GWP reporting, and other environmental impact reporting. IFEU developed BioGrace, so is aligned to RED.	See RED
BioGrace	Method, tool	BioGrace I and II are GHG calculation tools in line with RED and RED-II for biofuels. BioGrace II is developed for companies wishing to demonstrate compliance to RED-II sustainability criteria for electricity, heating and cooling from biomass for 22 biofuel pathways, while BioGrace I is for transport biofuels	See RED
US Renewable Fuel Standard (RFS)	Standard	Standards in US for biofuels.Based on EISA Lifecycle method. GHG, regulated emissions, and energy use calculated with GREET.	High, but see GREET
CARB	Standard	GHG reporting for the GHG regulatory program implemented by the California Air Resources Board (CARB) (covers ~12 US states as well as California). Applies to electricity production and some industries as well as fuels. GHG, regulated emissions, and energy use calculated with GREET.	See RFS
GREET	Method, tool	The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) is an analytical tool that simulates energy use and emissions output of various vehicle and fuel combinations. Includes over 100 fuel production pathways from various energy feedstocks, includes electricity generation, and over 80 vehicle/fuel systems. Used to evaluate US Renewable Fuel Standard and CARB standards.	**High**
JEC WtW	Method	The JEC WtW study concentrates on fuel production and vehicle use stages, and while it is based on Life Cycle Assessment methods, it does not aim to be a full LCA. The aim of JEC WtW has been to evaluate the impact of fuel and/or powertrain substitution in Europe, on global energy usage and GHG emissions balance.	**High**

Name	Type	Synopsis	Relevance
ISCC carbon certification (ICAO CORSIA)	Method	CORSIA 205 outlines the method, rules and guidelines for calculating, reporting and verifying emissions reductions. This is based on the ICAO CORSIA LCA method.	**Medium-high**
GHGenius	Method	GHGenius focuses on the life cycle assessment (LCA) of current and future fuels for transportation applications and uses historical data or correlations for changes in energy and process parameters with time or government forecasts that are stored in the model. Can be used for specific regions (east, central or west) of Canada, and the United States. The model can also be run for Mexico, India, and four regions of the European Union. For Canada, it is also possible to model many of the processes by province. It is also possible to model regions of North America.	Medium
Ecoinvent	Inventory	Ecoinvent is arguably the most comprehensive and reputable LCI database, but it is not a method in itself.	N/A

Appendix 3 Case Study Assumptions

Details of assumptions and input data used in the case study evaluations – see Section 5.2

Green methane

Electricity generation		
Emission source	*Assumption*	*Source ID*
Solar voltaic	20 g of CO_2e per kWh	A
Hydrogen production		
Emission source	*Assumption*	*Source ID*
Distribution HV	Losses of 2.6% in distribution	B
Electrolysis	1.538 MJ electricity per MJ of hydrogen produced	B
Methanation (Sabatier process)		
Emission source	*Assumption*	*Source ID*
CO_2 absorption (from electrified DAC)	5.526 MJ electricity per kg CO_2	C
CO_2 compression	0.1454 MJ electricty needed to compress kg CO_2	D
SNG synthesis	0.055 kg CO_2 required per MJ of CH_4	D
	1.1998 MJ H_2 required per MJ of CH_4	D
	-0.1998 MJ of heat surplus per MJ of CH4	D
Ship distribution (LNG)		
Emission source	*Assumption*	*Source ID*
NG liquefaction	0.0246 MJ electricty required per MJ CH_4 liquified	E
	0.0113 of MJ of CH_4 flared per MJ CH_4 liquified	E
	0.034 g of fugitive CH_4 emitted per MJ of CH_4 liquified	E
LNG loading terminal	0.0009 MJ electricty required per MJ CH_4 loaded	E
	0.01 MJ of fugitive CH_4 per MJ CH_4 loaded	E
LNG sea transport	4,000 nautical miles travelled	E
	0.0263 MJ of CH_4 lost per MJ of CH_4 transported	E
	0.0222 MJ of heavy fuel oil per MJ of CH_4 transported	E
	0.00013 g of fugitive CH_4 emitted per MJ of CH_4 transported	E
	0.00009 g N_20 emitted per MJ of CH_4 transported	E
LNG unloading terminal	0.0009 MJ of electricty per MJ of CH_4 unloaded	E
	0.01 MJ of fugitive CH_4 per MJ CH_4 unloaded	E
Propulsion		
Emission source	*Assumption*	*Source ID*
TTW emission from engine	50% mechanical efficiency fuel to shaft	F

Source ID	*Reference*
A	Fthenakis V., Leccisi, E. Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends, 2021.
B	JRC, JEC_WTTv5_ Appendix 1_Pathways 0_Electrolysis, 2020
C	Mahdi et al, Techno-economic assessment of CO2 direct air capture plants, 2021
D	JRC, JEC_WTTv5_ Appendix 1_Pathways 2_CBM, 2020
E	JRC, JEC_WTTv5_ Appendix 1_Pathways 8_H2, 2020
F	Ricardo experience of typical efficiencies of modern engines

Blue ammonia

Electricity generation		
Emission source	*Assumption*	*Source ID*
Offshore wind farm	15 g of CO_2e per kWh	A
Hydrogen production		
Emission source	*Assumption*	*Source ID*
Natural gas extraction	Losses of 0.02 MJ CH_4 per MJ of CH_4 extracted	B
	1% of CH_4 extracted vented as CO_2	B
	0.0798 g of fugitive CH_4 emitted per MJ of CH_4 extracted	B
NG pipeline transport inside EU	31% efficiency of generator to power remote compression of CH_4	B
	0.0042 g of fugitive CH_4 emitted per MJ of CH_4 compressed	B
	0.0025 g of fugitive N_20 emitted per MJ of CH_4 compressed	B
	700 km distance pipeline	B
	2.269 MJ/t.km pipeline compression specific energy requirements	B
	0.0042 g of fugitive CH_4 emitted per MJ of CH_4 transported	B
SMR + CCS	1.365 MJ of CH_4 required per MJ of H_2 produced	B
	11.86 g CO_2 lost from carbon capture slip per MJ of H_2	B
	0.0159 g of fugitive of CH_4 emitted per MJ of H_2 extracted	B
Haber-Bosch process		
Emission source	*Assumption*	*Source ID*
H_2 pipeline	10 km distance pipeline	B
Syngas compression	Electricity provided by steam turbine with heat provided by the haber-bosch process	C
Haber-Bosch process	Electricity provided by steam turbine with heat provided by the haber-bosch process	C
Air separation unit	0.038 MJ electricity per MJ of NH_3	C
NH_3 condensation	0.028 MJ electricity per MJ of NH_3	C
Pipeline distribution		
Emission source	*Assumption*	*Source ID*
Ammonia storage	0.0001 MJ electricity per MJ of NH_3 produced	D
Ammonia bunkering	0.0009 MJ electricity per MJ of NH_3 produced	E
Propulsion		
Emission source	*Assumption*	*Source ID*
N_2O slip from Ammonia engine	20 gCO2e/kWh	F
TTW emission from engine	48% mechanical efficiency fuel to shaft	G

Source ID	*Reference*
A	Bouman, Evert A, A life cycle perspective on the benefits of renewable electricity generation, 2020
B	JRC, JEC_WTTv5_ Appendix 1_Pathways 8_H2, 2020
C	Pfromm P. H, Towards sustainable agriculture: Fossil-free ammonia, 2017
D	Eric R Morgan, Techno-economic feasibility study of ammonia plants powered by offshore wind, 2013
E	JRC, JEC_WTTv5_ Appendix 1_Pathways 8_H2, 2020 (LNG used as proxy)
F	Information supplied by a GIA member
G	Ricardo experience of typical efficiencies of modern engines

HVO

Electricity generation		
Emission source	*Assumption*	*Source ID*
Onshore wind farm	12.5 g of CO_2e per kWh	A
Cultivation		
Emission source	*Assumption*	*Source ID*
Cultivation	0.0821 g of N per MJ of soy bean	B
	0.7142 g of P_2O_5 per MJ of soy bean	B
	0.6869 g of K_2O per MJ of soy bean	B
	4.157 g of CaO per MJ of soy bean	B
	0.0562 g of pesticides per MJ of soy bean cultivated	B
	1.3317 g of seeding material per MJ of soy bean cultivated	B
	0.0315 MJ of diesel to power vehicles per MJ of soy bean cultivated	B
	0.00004 g CH_4 emitted per MJ of soy bean cultivated	B
	3.0938 g of CO_2 emmitted from soil neutralisation per MJ of soy bean cultivated	B
	0.0428 g of N_2O field emissions per MJ of soy bean cultivated	B
Local transport of soybeans	30 km distance to transport soybeans	B
	0.8111 MJ/t.km of diesel to power vehicles transporting soybeans	B
	0.0034 g/t.km of CH_4 emissions	B
	0.0015 g/t.km of N_2O emissions	B
Oilseed drying 13%	0.0001 MJ of diesel to power onsite vehicles per MJ of Soy bean dried	B
	0.0001 MJ of CH_4 per MJ of Soy bean dried	B
	0.0004 MJ of LPG per MJ of Soy bean dried	B
Oilseed drying 11%	0.0029 MJ of CH_4 per MJ of Soy bean dried	B
LUC Domestic (Based on Century; sa/100cm)	Soy Biodiesel Case	C
LUC Direct (Based on Winrock)	Domestic Emissions Modeling Scenario	C
LUC Indirect (Based on Winrock)	International Emissions Modeling Scenario	C
Hydrogen production		
Emission source	*Assumption*	*Source ID*
Natural gas extraction	Losses of 0.02 MJ CH_4 per MJ of CH_4 extracted	D
	1% of CH_4 extracted vented as CO_2	D
	0.0798 g of fugitive CH_4 emitted per MJ of CH_4 extracted	D
Hydrogen SMR	1.315 MJ of CH_4 required per 1 MJ of H_2	D
	72.4236 CO_2 emitted per 1 MJ of H_2	D
	0.0016 g of fugitive CH_4 emitted per MJ of H_2	D

HVO process		
Emission source	*Assumption*	*Source ID*
Raw oil production w/ meal export	0.3475 MJ of oil per MJ of dried soy beans	B
	0.1101 kg of soya meal per MJ of oil	B
	0.0818 MJ of heat per MJ of oil	B
	0.01459 MJ of electricity per MJ of oil	B
	0.0036 MJ of n-Hexane per MJ of oil	B
	0.2484 g of CO_2 emissions per MJ of oil (from n-hexane)	B
	-0.976 kg of animal feed substitution per kg of animal feed	B
Hydrogenation of oil	0.09767 MJ of HVO per MJ of oil	B
	0.0848 MJ of H_2 per MJ of HVO	B
	0.0168 g of H_3PO_4 per MJ of HVO	B
	0.027 g of NaOH per MJ oh HVO	B
	-0.0016 MJ electricity surplus per MJ of HVO	B
	-0.0079 MJ heat surplus per MJ of HVO	B
Truck distribution		
Emission source	*Assumption*	*Source ID*
Local transport	30 km distance to transport HVO to port	B
	0.8111 MJ/t.km of diesel to power vehicles transporting and unloading HVO	B
	0.0034 g/t.km of CH_4 emissions	B
	0.0034 g/t.km of N_2O emissions	B
Propulsion		
Emission source		*Source ID*
TTW emission from engine	50% mechanical efficiency fuel to shaft	E

Source ID	*Reference*
A	Bouman, Evert A, A life cycle perspective on the benefits of renewable electricity generation, 2020
B	JRC, JEC_WTTv5_ Appendix 1_Pathways 4_Biodiesel, 2020
C	UChicago Argonne LLC, GREET1_2020, 2020
D	JRC, JEC_WTTv5_ Appendix 1_Pathways 8_H2, 2020
E	Ricardo experience of typical efficiencies of modern engines

Appendix 4 Approaches to multi-output processes and co-products

A brief overview of the ways in which the four selected methods handle multi-output processes and co-products is provided in Section 5.3.1. A more detailed explanation of the 'system expansion' and 'allocation' approaches is provided here, including illustrative examples of their differences.

System expansion

In the system expansion approach, the entire impact is first calculated, and then the boundary of the multi-output system (e.g., Plant AB in Figure 8-1 below) is expanded to include a set of alternative independent production pathways (e.g., Plant B'), which are capable of producing outputs that are deemed to be "functionally equivalent" to the various co-products of interest (e.g., product B' of plant B' assumed equivalent to co-product B of Plant AB). The impact assigned to one particular co-product (e.g., product A of Plant AB) is finally calculated as the difference between the entire impact of the original multi-output process (e.g., Impact AB = 10 in the Figure), and the sum of the impacts of the alternative independent pathways that produce functional equivalents of all the other co-products (e.g., Impact B' = 4).

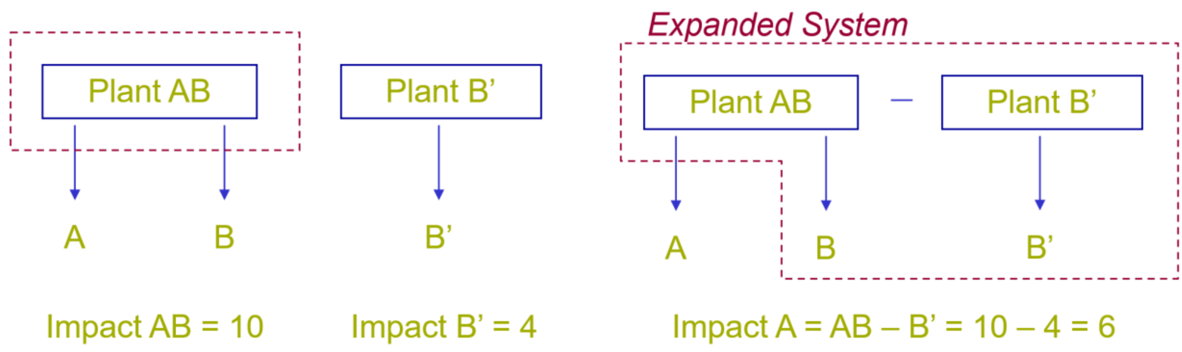

Figure 8-1: System expansion approach to co-product assessment.

System expansion is the preferred LCA approach according to the recommendations given by ISO (ISO 14044, 2006), and it is often adopted in "consequential" LCAs (where the emphasis is on system-level change rather than on individual product units). However, its implementation is not straightforward, as it entails a degree of subjectivity in determining which alternative products may be deemed functionally equivalent to each co-product. Additionally, even when a perfect replacement product can be identified, as, for instance, is the case of oil-derived glycerol as the equivalent of the glycerol that is produced as a co-product of biodiesel, there may be issues of scale that require careful attention. In this example taken as a case in point, it has been argued that, depending on the scenario being considered, a future massive up-scaling of biodiesel and glycerol co-production may result in the early saturation of the market for glycerol, after which the latter would no longer effectively be able to displace its oil-derived equivalent, thereby nullifying the validity of the theoretical premise that underpins the system expansion approach (Ulgiati, 2001).

In terms of applicability to this study, the system expansion approach is used in the JEC method, and it is also one of the available options in GREET.

Allocation

The alternative approach to co-product assessment is allocation, whereby the attempt is made to assign (i.e., allocate) different shares of the input and output flows, and hence of the overall environmental impact, of the operation of a multi-output process to the various co-products.

There are three main separate possibilities, namely: mass, energy, and economic allocation. These all have their place, and each of the three approaches may be considered the most appropriate one, depending on the object of the study and the intended goal and scope of the assessment. The main difference between the three approaches is that while the first two (i.e., mass and energy allocation) only depend on physical, measurable quantities (respectively, the mass of the co-products and their energy content), economic allocation is performed on the basis of the respective market values of the co-product streams, which may and often do fluctuate over time. This makes the results of the analysis less stable and potentially inconsistent with previous results calculated for even identical systems but at different points in time. The main argument in favour of economic allocation is that it better captures the relative shares of responsibility that the various co-products ought to carry for the environmental damage brought about by the multi-output process that generates them, according to the premise that the main driving principle for the operation of the process itself is economic profit.

The different results obtained by the alternative adoption of economic *vs*. physical (in this specific case, mass-based) allocation are dramatically exemplified in Figure 8-2 which shows the results of a case-study performed by Argonne National Laboratory using GREET, which focuses on Cobalt extraction as a co-product of copper-cobalt ore mining in the Democratic Republic of Congo, and its subsequent processing to commercial Cobalt hydroxide, including fuel and electricity consumption (Dai, Kelly, & Elgowainy, 2018).

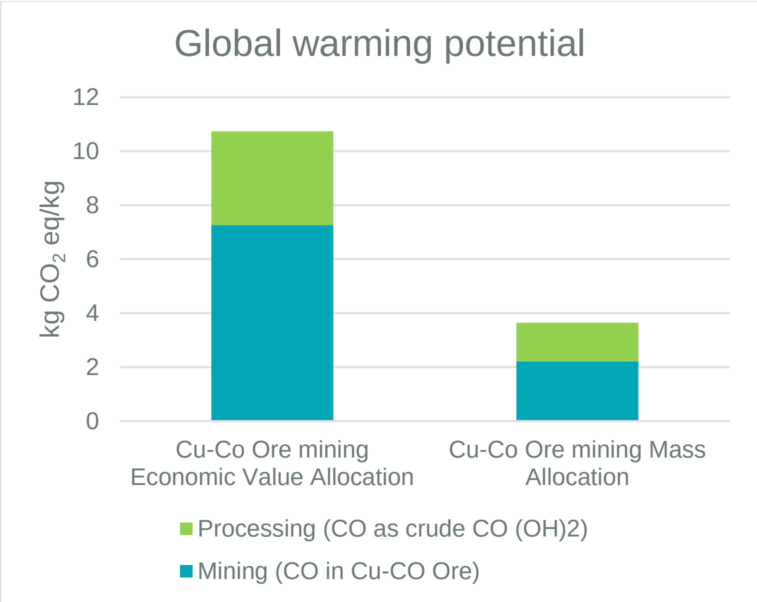

Figure 8-2: Economic vs Mass Allocation of GWP comparison example (Dai, Kelly, & Elgowainy, 2018)

As could easily be expected given the much higher unit economic value of Co *vs.* Cu, the GREET model results for Co extraction from copper-cobalt ore and processing to cobalt hydroxide ($Co(OH)_2$) show a significantly lower GWP impact when using mass allocation *vs*. when using economic allocation (i.e., less than 4 kg CO_2-eq/kg *vs*. over 10 kg CO_2-eq/kg). However, such lower numbers are arguably less indicative of the environmental “responsibility” attributable to the individual metals co-extracted by the joint mining activity, given that the latter is primarily motivated by the presence of cobalt in the ore (there is a large body of scientific LCA literature discussing this methodological point, which we cannot elaborate on further here for lack of space).

Having said all this, for the specific case of marine fuels and their co-products, physical (and in particular, energy-based) allocation is often arguably the most recommendable approach, at least in those cases where the co-products are also energy vectors. As a possible exception to this general rule, though, for biofuel supply chains entailing the co-production of both fuel and non-fuel co-products (in the case of the soy HVO case study, the products are the HVO fuel and animal feed), the adoption of economic allocation may sometimes be preferable in order to better reflect the difference between what may be a high-value main energy product on one hand, and a lower-value co-product or vice versa.

In terms of applicability to this study, energy-based allocation is used in the REDII and CORSIA methods, while both energy and economic allocation are available options in GREET.

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