Life-Cycle Assessment for Sustainable Inland Shipping on South Holland's Waterways

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by

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Preface

Writing an emotional text such as this preface comes harder to me than writing most of the rest of this report. However, as this is my master thesis, and marks the end of my time both as an Industrial Ecology student and as an intern at the Province of South Holland, some words deserve to be said.

I started as a student at the Applied Physics programme in 2017, and have made various small metaphorical excursions along the way, including into web development, teaching, and volunteering. But I have never felt more at home than at the Industrial Ecology programme, learning and working on topics that contribute to improving the world, albeit in tiny steps. I had the chance to learn from inspiring people and to have a unique experience during my two years at GreenTU, helping to accomplish the sustainability ambitions of TU Delft itself. More importantly, I have met amazing people and made friendships that I hope will endure long into the future.

As for this thesis: I am grateful for the opportunity provided to me by the Province of South Holland to apply and further my knowledge by assessing a real-life challenge using Industrial Ecology methods. I have been part of the organisation, taken seriously as a colleague, and given the freedom to shape my research, and my input has been valued. My thanks go out especially to Ewald Vonk, my supervisor for this project, who had the grace to meet me while I was searching for a thesis topic *nine months* before actually starting, as well as to all colleagues and other contacts who have spent time with me to discuss and improve the study and its results.

I would of course like to thank my university supervisors Lauran van Oers, of CML (Universiteit Leiden), and Jeroen Pruyn, of ME (TU Delft), who have provided me with their expertise on life cycle assessment and maritime engineering respectively, and have been available to answer my every question even at short notice.

A final thanks to all my friends who have given me support and insights along the way, including Jasmine, Thomas, Kristie and Hajar (the 'key group' – although I don't remember the anecdote that led to this name for our study group), Puck and the rest of our GreenTU board, and Laura. And especially to Roser, my partner, for standing by me during this thesis as she has for the past eight years.

Quan van der Knokke
The Hague, February 2024

Abstract

Inland shipping is an efficient way of freight transportation, especially in the Province of South Holland (the Netherlands), but this sector faces a significant challenge in further reducing climate change effects and local health and environmental impacts caused by the combustion of diesel fuel.

In this study, an analysis of the inland shipping sector in South Holland and its challenges and opportunities regarding a transition to "zero-emission" shipping is performed, based on a life cycle assessment (LCA). This LCA compares the environmental impacts of the annual operations of a medium-size, short-route inland barge, comparing different engine technologies and energy carriers: diesel in a combustion engine, hydrogen (grey/blue/yellow) in a combustion engine, hydrogen (grey/blue/yellow) in a fuel cell-electric power system, and electricity in a battery-electric power system. Results are obtained for 2020, 2030, 2050, and 2100, based on the SSP2 pathway for future socio-economical development wherein the electricity grid mix decarbonises and fossil-based diesel is phased out in favour of biodiesel and synthetic diesel, and assessed using the EF v3.1 assessment family.

The results indicate that the most significant sources of emissions are barge operations (for combustion engines, especially for diesel, and most of all for older diesel engines) and the fuel supply chain (for diesel and hydrogen), as well as some contribution from the production of batteries (for the battery-electric alternative) and fuel cells (for the hydrogen fuel cell alternative). Contributions from the life cycle of the barge hull, lubricant and oil streams, and infrastructure are minor. The main contributor to climate change is CO_2, and the main contributors to local health and environmental impacts are emissions of particulate matter (PM), NO_x, and SO_x.

For the selected case study barge, a battery-electric system provides the strongest reduction in environmental impact (climate change, acidification, photochemical oxidant formation, and PM formation) even with background data for 2020, and its advantage increases further as the electricity grid decarbonises. The battery-electric and hydrogen fuel cell systems are the only ones which can be labelled as "zero-emission", although the life-cycle emissions of hydrogen are high in the short term and its advantage only becomes apparent beyond 2030.

Among the hydrogen variants assessed, yellow hydrogen – produced by electrolysis from the electricity grid – has the lowest life-cycle climate change impacts in the long term, although it is not a clear winner when considering local health and environmental effects (acidification, PM formation) from its production. A hydrogen fuel cell system provides a slight but consistent benefit over hydrogen combustion due to a higher efficiency and the absence of operational emissions.

Sensitivity analyses indicate that the advantage of a battery-electric solution disappears for barges transporting larger loads and sailing longer distances, due to the larger energy capacity this requires, and becomes entirely impractical for long routes, where a hydrogen fuel cell solution provides the lowest impacts overall. Hydrogen fuel cells lose their advantage over hydrogen combustion for barges requiring very high engine power due to the additional impacts from fuel cell production exceeding the reduction from emission-free operations. At the very longest routes and largest power requirements, combustion of bio- and synthetic diesel can prove to be the best solution both in terms of environmental impacts and practicality. However, this is not viable for fuelling the entire inland fleet, as the production of these alternate fuels results in a disproportionate pressure on land and water use. Alternatively, batteries and hydrogen could be made more viable for longer routes by planning in additional stops for refuelling or battery switching.

These conclusions fit in with overall policy trends at the provincial, national and international level. These include incentivising the replacement of older and polluting diesel engines with modern equivalents in the short term, and promoting the development and operation of battery-electric and hydrogen fuel cell barges in the long term. Based on the discussed findings, small-scale and medium-scale barges operating regionally are good candidates for a battery-electric power system, while barges operating on national and international routes are better suited for a hydrogen fuel cell system, especially as a larger supply of renewable energy becomes available over the coming decades, and very large barges on long trips could look towards the combustion of bio- and synthetic fuel. Some hybrid solutions (e.g. diesel-electric) are also imaginable to partially reduce emissions in the short term.

Future research into this area could either deepen the environmental assessment (e.g. with more alternate fuels and scenarios, or real-life emission measurements) or broaden the scope, by also looking at practical, social, and economical considerations, which have not been assessed in this study.

To facilitate the exploration of the LCA results, an online *LCA Viewer* has been developed. It allows the visualisation of LCA data from any *Activity Browser* project in an interactive way, across different scenarios and points in time, and sharing these results with project stakeholders.

Contents

Abbreviations

Chemicals and emissions

CO Carbon monoxide
CO_2 Carbon dioxide
N_2O Nitrous oxide (dinitrogen monoxide)
NO_x Nitrogen oxides
H_2 Hydrogen gas
PM Particulate matter
SO_x Sulphur oxides

Organisations

CCNR Central Commission for Navigation of the Rhine
EU European Union
PZH Provincie Zuid-Holland (Province of South Holland)

Other abbreviations

BE Battery-electric
CCS Carbon capture and storage
CO_2-eq CO_2-equivalent
DEF Diesel exhaust fluid
EF Environmental Footprint
EM Electric motor
FT Fischer-Tropsch (process)
GHG Greenhouse gas
GMST Global mean surface temperature
HFC Hydrogen fuel cell
IAM Integrated assessment model
IC Impact category
ICE Internal combustion engine
LCA Life-cycle assessment
LCCA Life-cycle cost analysis
LHV Lower heating value
LNG Liquefied natural gas
PEM Proton exchange membrane
SCR Selective catalytic reduction
SMR Steam methane reforming
SSP Shared Socioeconomic Pathway
TTW Tank-to-wake
WTT Well-to-tank

I

Introduction & methodology

Image: Luchtfoto Alpherium, by Peter Bakker

1 Introduction

Modern-day society has an ever-increasing demand of goods and services, while also needing to reduce emissions of hazardous substances and greenhouse gases as well as the extraction of non-renewable resources. If economic growth does not slow down, environmental targets can only be reached if environmental impacts are decoupled from economic growth. In practice, this means that every sector that has environmentally harmful emissions must decrease these emissions drastically – the sooner the better.

In this report, the environmental impact of a specific sector is studied: inland shipping. Specifically, a life-cycle assessment (LCA) is made of the impacts entailed by the inland shipping sector in the Province of South Holland (the Netherlands), where inland shipping plays a large role, and where climate and environmental sustainability are becoming increasingly important in policy-making. In this introductory chapter, this challenge is described in a problem definition, leading to a research question that will be the focus of this study. Finally, an outline is made of what can be expected of the rest of this report.

1.1. Problem definition

A sector that faces a significant challenge in reducing emissions is the transport sector. In 2020, transportation was responsible for 800 Mt CO_2–eq of greenhouse gas (GHG) emissions, representing 16.2 % of total global GHG emissions. These emissions come mainly from road and air transport, but shipping – transportation over water – is also a notable contributor, responsible for approximately 840 kt CO_2–eq emissions anually. While shipping is more efficient per mass and distance transported than road or air, the emissions of the shipping sector nevertheless represent 1.7 % of total global GHG emissions (Ritchie et al., 2020). And the environmental impact of the sector goes beyond the emissions of greenhouse gases: industrial and transportation activities, including shipping, are responsible for significant emissions of substances harmful to the local environment and human health, such as nitrogen oxides (NO_x) and particulate matter (PM) (Rijksoverheid, 2021).

Shipping is a complex sector, occurring both globally and locally, with different types of vessels and on different types of water bodies. In this study, focus will be laid on a specific regional scope: the inland shipping sector of the Province of South Holland, in the Netherlands. This province has various properties that make its inland shipping sector especially interesting. It is home to the Port of Rotterdam – one of Europe's largest ports – as well as the Rhine river and other natural or man-made waterways. As of 2016, this led to inland shipping having a 41 % share of the province's freight modal split – among the largest in the country (van der Geest & De Leeuw van Weenen, 2016). South Holland's provincial government recognises the importance of inland shipping in the province's transportation infrastructure, as well as its potential to be developed even further as a sustainable alternative for road transportation (Provincie Zuid-Holland, 2021b).

At the same time, inland shipping is a sector with its own environmental issues. Inland ships are long-lasting and are primarily fuelled by diesel in older, pollutant engines. The provincial government recognises these challenges, and also introduces some opportunities: new, more sustainable ways of powering inland ships are becoming more viable, and the province is assessing these in detail with the goal of determining which of these is the most appropriate for refitting the existing fleet of inland barges (Provincie Zuid-Holland, 2021b). This prospective transition is a complex challenge, involving a wide range of actors, both public and private, and on a regional, national and international level.

As matters stand, the internal combustion engines (ICEs) that currently dominate the sector are expected to either be replaced with more efficient and clean versions, or to be phased out in favour of emissionless electric motors. The choice of energy carrier necessary for sustainable inland shipping – bio-based or synthetic variants of diesel, hydrogen combustion, or adopting a new technology such as batteries or fuel cells – is less clear (EICB & TNO, 2021). It is likely that sufficient research exists into the environmental impacts of the usage phase of these energy carriers individually, but that data on the full life cycle (including fuel and equipment production, installation, and decommissioning) is not yet available, especially in the specific context of refitting an existing fleet in the specific geographical scope of South Holland.

1.2. Research question

This study aims to provide quantitative and qualitative support for the Province of South Holland in the above challenge, by answering the following research question:

> **Research question**
>
> What are the life-cycle environmental impacts, and processes that most contribute to these, of inland shipping in South Holland, considering a future energy transition, comparing combustion engines and electric motors as power systems, as well as comparing bio-based or synthetic fuels, hydrogen, or lithium-ion batteries as energy carriers?

The following sub-questions will aid in answering this research question.

1. Where do the opportunities and challenges lie ahead for a sustainability transition in the inland shipping sector of South Holland?
2. What are the stages and processes in the life cycle of an inland barge in the inland shipping sector of South Holland?
3. What are the life-cycle environmental impacts of inland shipping in the current situation, with an ICE powered by diesel, and in alternate scenarios, replacing the fuel with bio-/synthetic diesel, hydrogen, or lithium-ion batteries, and potentially replacing the engine with an electric motor?
4. Where do the main contributions to these environmental impacts lie, regarding lifecycle processes, environmental flows, and geographic regions?
5. How are these environmental impacts expected to evolve over time, considering projections for electricity and fuel production over the course of the 21st century?
6. How do the different alternatives compare to each other regarding their environmental impacts, and which of these, if any, shows the lowest impacts overall?
7. What conclusions for the overall sustainability transition of the inland shipping sector in South Holland can be drawn from the obtained results?

1.3. Problem approach

In this section, the data collection and research methods necessary for each sub-question are detailed.

1.3.1. Sub-question 1: data collection

To contextualise this problem and to make it possible to obtain conclusions for a sustainable transition in the provincial inland shipping sector, the quantitative analysis will be preceded by a brief overview of the socio-technical context in which this challenge occurs. During an internship at the Province of South Holland, a main stakeholder in the regional inland shipping sector, information is gathered to obtain an overview of the state of the inland shipping sector, relevant actors, and existing policy plans or initiatives for sustainable inland shipping.

1.3.2. Sub-question 2: LCA goal and scope & inventory analysis

This comparison of possible alternative energy carriers by their environmental impact is a prime candidate for an issue to be assessed using **life-cycle assessment** (LCA), an industrial ecology tool that compares the environmental impact of various alternatives used to fulfil a specific function by looking at their entire life cycle (Guinée et al., 2002). An LCA will be carried out in the form of a case study of a specific inland barge, representing an average barge for the inland shipping sector in South Holland. The current situation of this barge, sailing on diesel, will be compared to alternative scenarios in which this barge is refitted with an electrical engine and/or a novel energy carrier.

To determine the life-cycle stages and processes of inland shipping, data needs to be collected on the nature of inland shipping: what parts do ships contain and how are these manufactured, what are the characteristics of ship operation, and what happens to ship parts at the end-of-life phase? Some data is available in published literature, while some knowledge exists internally at the provincial government and can be collected during the internship. If important details are not known, these may be found by contacting the provincial government's industry contacts. This will result in an overview of the processes to be modelled and LCA flow diagrams for each of the alternatives.

Case study

As will be discussed further in Chapter 3, the inland shipping sector in South Holland is heterogeneous in many factors such as routes, ship types and sizes, and loads. For the LCA at hand, however, specific ship properties and behaviour must be selected and modelled.

A report commissioned by the Province of South Holland contains an inventory of barges that sail primarily on South Holland's provincial waters, as well as a list of criteria that make a ship a likely candidate to be refitted with a more environmentally friendly power system (van der Geest et al., 2023). An analysis of this inventory, aiming at selecting a ship that is the most representative of this sector (see Appendix A), yields the *Leendert-Angelina* as a good candidate (Figure 1.1). Table 1.1 contains some characteristics of this container ship, which sails mainly on the Gouwe, from Alphen aan den Rijn (South Holland) to Rotterdam (South Holland) or Antwerp (Belgium).

Table 1.1: Characteristics of the *Leendert-Angelina*, the selected case study barge (De Binnenvaart, 2023; van der Geest et al., 2023).

Characteristic	Value
Build year	2002
Load	1700 t
Length × beam × draught	85.96 m × 9.50 m × 3.00 m
Engine	Mitsubishi S12R-C2MPTK
Engine power	1278 hp ≈ 940 kW

Figure 1.1: *Leendert-Angelina* (De Binnenvaart, 2023).

1.3.3. Sub-questions 3 to 6: LCA impact assessment & interpretation

The LCA flow diagrams and process overview form the data necessary to create the LCA model. This must be done using LCA software, and the collected information will need to be supplemented with background data from a database. For this study, the open-source software *Activity Browser* is used, with data from the *Ecoinvent 3* LCI database. Using the tool *Premise*, the Ecoinvent database is adapted to reflect future scenarios, based on integrated assessment models (IAMs). This will produce an LCA model from which various quantitative results can be obtained, both for the present and for future scenarios. As this models a future state (a *prospective* LCA), assumptions or estimates about the development of certain technologies and infrastructure (e.g. the electricity mix) will be necessary to answer this question – including underlying assumptions in the selected database and IAM.

> **About the Activity Browser**
>
> LCA software, such as the Activity Browser, facilitates the creation of complex system models for LCA studies, and the subsequent assessment and analysis steps. The Activity Browser (Steubing et al., 2020) is an open-source interface for the LCA framework *brightway2*, and has been chosen for this study due to its speed, ease of use, and advanced analysis features.

> **About Ecoinvent**
>
> It is virtually impossible to fully model a system for the purpose of an LCA, due to many inputs (industrial products, energy, etc.) themselves being the product of even more complex systems. Life cycle inventory (LCI) databases, such as Ecoinvent (Wernet et al., 2016), contain inventory data for many common goods and waste treatment systems, based on previous research, which can be used as background data in an LCA study.

> **About Premise**
>
> Premise (Sacchi et al., 2022) is an open-source tool for prospective LCAs, which can produce LCI databases for future scenarios. It modifies the Ecoinvent LCI database based on a selected integrated assessment model (IAM), which contains projections for future socio-economic developments. This results in added datasets for new or more advanced technologies and changes to e.g. proportions in grid and fuel markets to reflect these future projections.
> It integrates with the Activity Browser via the *ScenarioLink* plugin.

A contribution analysis on the LCA model, describing the contribution to each alternative of different processes' environmental impacts in each impact category, can also be carried out in the Activity Browser.

These quantitative results must be visualised and analysed in order for them to lead to meaningful conclusions. It is likely that there will not be a clear-cut case favouring one alternative over all others: different technologies may score better in some assessed impact categories, and worse in others.

1.3.4. Sub-question 7: LCA interpretation & discussion

The approach to this question is twofold. Firstly, the LCA results are reviewed based on the priorities and challenges faced by the Province of South Holland and, if needed, extrapolated to a regional scope. This is done by further analysing the model, e.g. using contribution and sensitivity analyses focussing specifically on those impact categories that are most relevant to the provincial priorities. Secondly, these results are described within the overall context. Possible starting points are looking at which alternatives assessed align with initiatives or efforts that are already in place, while also considering possible wider impacts from e.g. large-scale biofuel production.

1.4. Outline of this report

In Chapter 2 of this report, a general overview of the LCA methodology will given.

The rest of the report is structured in three parts. Part II contains brief literature-based descriptions of the inland shipping sector in South Holland (Chapter 3) and its energy transition (Chapter 4), followed by a concise literature overview (Chapter 5), providing more context for the given research questions. In Part III, a life-cycle assessment is carried out to quantify the environmental impacts of novel energy carriers. This part follows the standard structure of an LCA report: goal and scope definition (Chapter 6), inventory analysis (Chapter 7), impact assessment (Chapter 8), and interpretation (Chapter 9). Finally, in Part IV, the LCA results and their implications are discussed (Chapter 10), and final conclusions are made and linked to the policy challenges faced by the Province of South Holland (Chapter 11).

2

Methodology: life-cycle assessment

The main analytical tool used in this investigation is life-cycle assessment (LCA). This type of assessment is used to analyse the environmental impact of the entire life-cycle of a product or service. Concretely, an LCA takes the production, use, and end-of-life phases of a subject into account, and includes indirect environmental externalities higher up in its production chain. This is achieved by creating an inventory of goods, wastes and services required for the production, use and disposal of the desired 'reference product', including the goods, waste and services which are in turn necessary for those, and so forth. The environmental emissions and extractions entailed by each process in this supply chain are then quantified and scaled to reflect the emissions necessary for the reference product, and are then categorised into different environmental impact categories which they affect.

An LCA is commonly used to compare multiple alternatives that can fulfil the same goal by assessing them under the same conditions and assumptions. Furthermore, an LCA commonly looks at a range of impact categories side-by-side instead of focusing on a single one (e.g. an assessment of only greenhouse gas emissions). Other impact categories that are commonly assessed are health impacts on humans and the environment, resource depletion, and local forms of land, air and water pollution.

It should be noted that an LCA study does not conclusively indicate which of the compared alternatives is 'best'. By default, an LCA study compares the selected alternatives only based on environmental impacts, and not on other merits such as real-life viability or economic feasibility. Even regarding environmental impacts there does not tend to be a clear 'winner', as each alternative may score better or worse in some of the impact categories assessed, and these cannot be compared one-to-one.

2.1. Phases of LCA

Although LCA approaches in literature are varied (Finkbeiner, 2014) and not always thorough (as will be seen in the literature overview in Chapter 5) a standardised approach exists as formulated in the ISO 14040 standard, as well as a commonly used *Handbook on Life Cycle Assessment* (Guinée et al., 2002), giving an operational guide based on this standard. Accordingly, an LCA is divided into four phases, which are depicted and described in Figure 2.1: goal and scope definition, inventory analysis, impact assessment, and interpretation. Although these phases are presented in a linear fashion, they tend to happen concurrently and with feedback between them, so that goal and scope or analysis steps may be updated based on preliminary assessment results.

In short, the **goal and scope definition** relates to defining the exact aims of the assessment, defining its geographical, temporal and technological scopes, and establishing the subject in the form of product alternatives and functional units. The second phase, **inventory analysis**, relates to studying the selected product system(s), usually depicting their constituent unit processes in a flow diagram and collecting input and output data for these processes (goods, wastes, and environmental flows). In the **impact assessment**, this inventory is analysed based on the embodied environmental impacts of the reference product, resulting from the modelled unit processes. Environmental impacts are then characterised in a group of environmental impact categories, using characterisation factors that indicate the relative impact of each emission towards each impact category. Along the process, the data and results are subject to **interpretation**, which includes an evaluation of the analysis and modelling choices made. Commonly, the LCA is evaluated based on the consistency and completeness of results, as well as their robustness and sensitivity to different modelling choices, followed by drafting conclusions and recommendations based on these results. A fifth phase, external to the LCA framework, is also depicted: ‘direct application’. This step represents actions that may be taken based on LCA results.

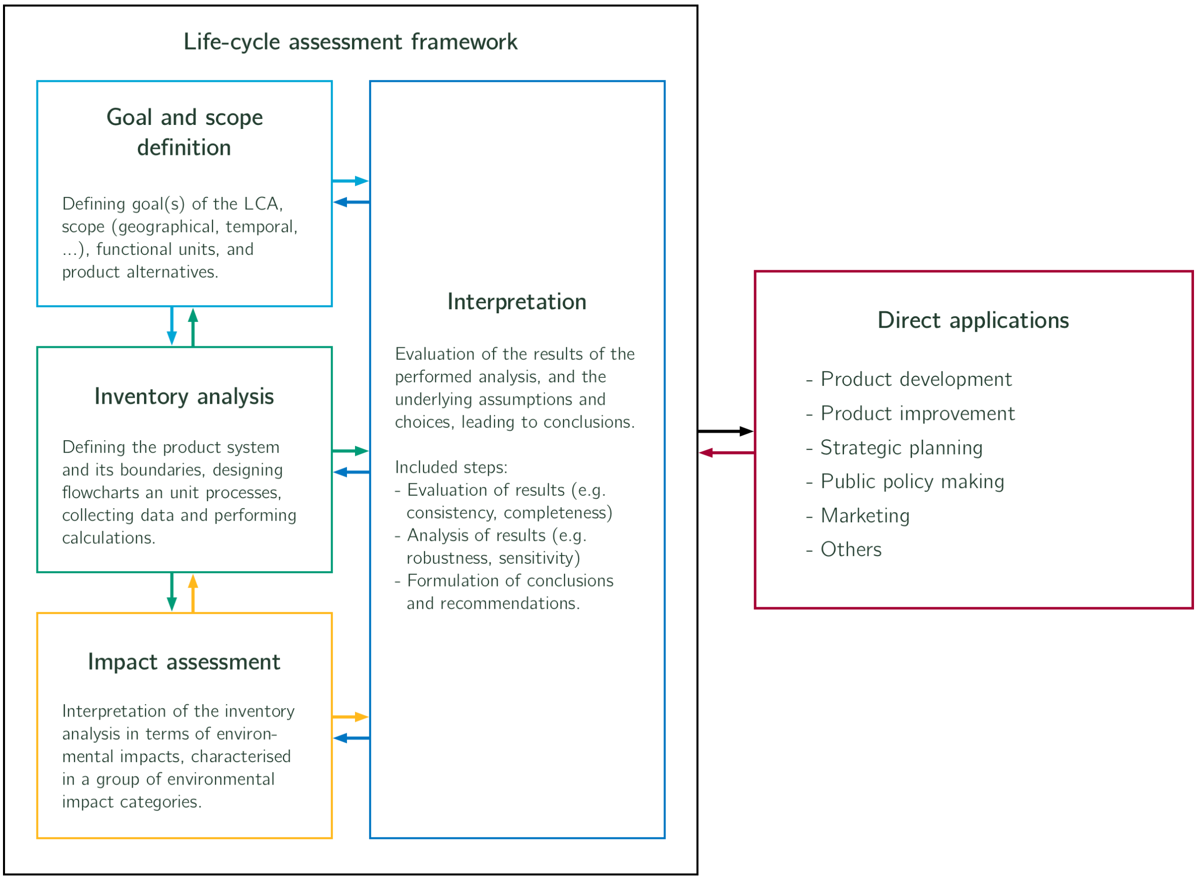


Figure 2.1: Phases of the methodological framework of LCA, according to ISO 14040. Figure adapted from Guinée et al. (2002), expanded with summaries of each phase.

2.2. Multifunctionality

A common challenge in LCA studies is **multifunctionality**, in which a single unit process has multiple useful outputs (co-products) which are not all used in the considered product system, raising the question as to which share of the environmental impacts belongs to which co-product (Guinée et al., 2002). There are various ways to deal with multifunctionality (Heijungs et al., 2021; Lai et al., 2021):

Subdivision Dividing a multifunctional process up into multiple sub-processes with a single function and separate environmental impacts.

System expansion Expanding the product system to include all co-products of a multifunctional process.

Substitution Quantifying the would-be impacts from the other co-products and subtracting these from the system's impacts as 'avoided burdens'.

Allocation Dividing the environmental impacts up between the co-products proportionally to a chosen factor: preferably by a physical proportion relevant to the co-products (e.g. energy content or mass), or otherwise by some other relationship (e.g. economic value).

Although the ISO 14040 standard recommends avoiding allocation when possible, instead using one of the other two options, Lai et al. (2021) find mass or economic allocation the most commonly used method for solving multifunctionality in their review of LCA studies in the metals production field. They also highlight the importance of the choice of allocation type, as this can yield strongly differing results.

2.3. Types of LCA

LCA studies can be classified in various ways.

Retrospective LCA Focused on describing the life-cycle environmental impacts of an existing product system (Weidema, 1998).

Prospective LCA Focused on describing the life-cycle environmental impacts of a future product system, based on a new technology and/or expected future changes or developments (Weidema, 1998).

Attributional LCA Considers the attribution of a portion of existing total environmental impacts to the studied product system or alternatives (Ekvall, 2019). Commonly, sector average data is used for additional demand of e.g. electricity.

Consequential LCA Considers how global environmental impacts would evolve due to the addition of the studied product system or alternatives (Ekvall, 2019). Commonly, marginal data is used for additional demand of e.g. electricity (i.e. the type of electricity generation most likely to be scaled up to meet the additional demand is identified and used).

2.4. Applying LCA

The aim of this investigation is to assess the life-cycle environmental impacts of the inland shipping sector, and especially comparing the impacts of diesel, the current most common energy carrier and fossil fuel, with those of using alternative energy carriers. This is a question for which LCA is a highly suitable tool. In Part III of this report, a full LCA will be carried out according to the four phases outlined above, and taking care to follow the procedures outlined in Guinée et al. (2002) as closely as possible (given certain constraints in resources and scope). In the final part of this report (Part IV), attention will also be given to the possible direct applications of the found conclusions.

II

The inland shipping sector and the energy transition

Image: Provinciehuis Zuid-Holland, by Fred Romero

3

Background information on inland shipping

Inland shipping, or inland water transport, refers to transportation via inland waterways, such as rivers, canals, and lakes. Both passenger and freight inland water transport are common, operated commercially or privately, but in this report 'inland shipping' is taken to refer specifically to the commercial transportation of freight. This chapter contains a brief overview of this sector in general and specifically in South Holland, as well as the main environmental concerns related to inland shipping, serving as a general context for the rest of the report.

3.1. Inland shipping

Generally, inland shipping is done with barges, a type of flat-bottomed vessel intended for operating on inland waterways. The types of goods transported are varied, including containerised goods, bulk materials for e.g. construction, liquids in tanker barges, or waste for treatment. A prerequisite for inland shipping is the presence of inland waterways. These can be natural, such as rivers and lakes, or artificial, such as canals. Both natural and artificial waterways require maintenance to ensure their safety and navigability, and maintain or expand their capacity. Additionally, waterway infrastructure (e.g. locks, bridges, aqueducts) may be required, as are quays and inland ports for docking and the transfer of passengers and goods (Ministerie van Infrastructuur en Waterstaat, 2019).

The prevalence of inland shipping as a method of freight transport varies strongly by location, mainly dependent on the presence of natural and artificial waterways suitable for inland shipping. Worldwide, China is the country with the largest annual transportation (measured in tonne-kilometres, or tkm), centred around the Yangtze river. In Europe, the principal inland waterway is the Rhine, connecting the Port of Rotterdam with inland industrial and population centres in the Netherlands, Germany, and Switzerland (OECD, 2022).

Various parties forecast a growth of inland shipping (Barros et al., 2022; Ministerie van Infrastructuur en Waterstaat, 2019; Provincie Zuid-Holland, 2021b). This expectation is based on projected growth in transportation demand for e.g. containerised goods. Inland shipping can be more secure and cost-effective than other transport modalities, and inland waterway systems around the world have unused (potential) capacity to accommodate more transportation, while existing road and rail networks are reaching capacity limits. Furthermore, inland shipping is seen as more environmentally friendly than transportation by road or air, being more efficient, as well as having lower external safety risks and noise pollution levels. However, concerns remain regarding the environmental impact of inland shipping, as will be described in Section 3.3 and explored further in the rest of this report.

3.2. Inland shipping in the Netherlands and South Holland

The Netherlands is country with the largest fleet of inland ships in Europe (Ministerie van Infrastructuur en Waterstaat, 2019), and competes with Germany for the largest annual transportation by inland barge (OECD, 2022). In South Holland, one of the twelve provinces of the Netherlands, inland shipping has one of the largest shares in the modal split for freight transport: in 2014, 41% of goods in South Holland were transported over water (van der Geest & De Leeuw van Weenen, 2016). A main factor contributing to this is South Holland's generally flat geography, with a comprehensive network of inland waterways, as well as it being home to the Port of Rotterdam – the largest port in Europe, and one of the largest worldwide – and the Rhine river, connecting the Port of Rotterdam (as well as those of Amsterdam and Antwerp) with the inland of the Netherlands, Germany, and Switzerland.

Most of the goods transported by inland shipping in South Holland are transported to or from Germany via the Rhine, or to Antwerp in Belgium. A significant share (25% of goods exported from South Holland; 47% of goods imported to South Holland) remains within or comes from within the Netherlands (van der Geest & De Leeuw van Weenen, 2016). Of this share, most freight is transported to or from nearby North Holland or Zeeland, or remains within South Holland. This means the distances freight is transported over can vary strongly. For instance, the Gouwe, the main waterway in the shipping route from the Port of Rotterdam to container terminal Alpherium in Alphen aan de Rijn, both in South Holland, is just over 14 km long. But a barge travelling over the Rhine from Rotterdam to Basel, Switzerland, has a trip distance of approximately 750 km.

Figures 3.1 and 3.2 contain simplified maps of Europe and South Holland respectively, marking relevant waterways (including the Rhine) and major cities.

The main types of freight transported over South Holland's waterways are, in order from most to least common: chemicals and fuels, containerised goods, construction materials (sand, rock, stone), agricultural goods, and waste (van der Geest & De Leeuw van Weenen, 2016).

The types of barges common in inland shipping are also very varied, according to the waterways a ship needs to travel and the type of load it has to transport. In the Netherlands, infrastructure and water agency Rijkswaterstaat has classified common inland barge sizes in a numbered system, ranging from 'M0' for small vessels with a load capacity below 250 t up to 'M12' for the very largest vessels, measuring 135×17 m with a load capacity above 5600 t (Rijkswaterstaat, 2011). As listed in Table 1.1, the barge selected for this case study, selected based on the criteria in Appendix A, has a load capacity of 1700 t, and falls under the 'M6' class.

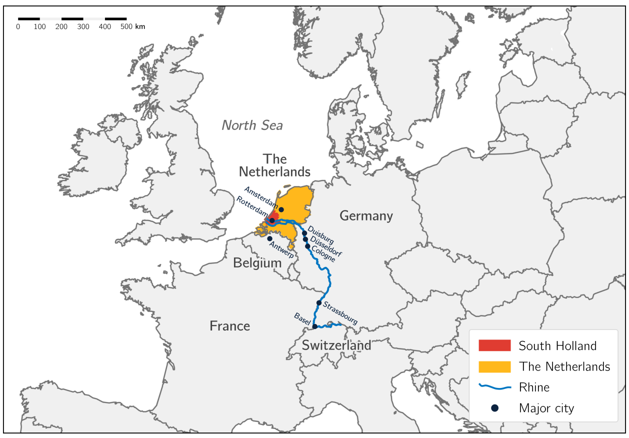


Figure 3.1: Map of Europe, marking South Holland, the Netherlands, and the course the Rhine from the North Sea until Lake Constance, including various major cities on or near the Rhine. Based on World in Maps (2022).

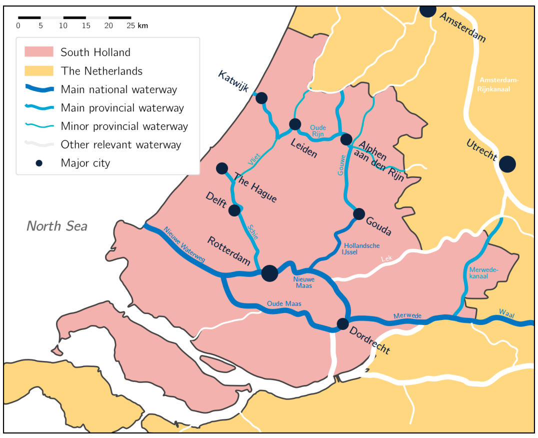


Figure 3.2: Map of South Holland, marking principal waterways and major cities. The waterways leading to the North Sea are branches of the Rhine Delta. Based on Rijkswaterstaat (2013) and van Wensveen (2011).

3.3. Environmental impact of inland shipping

Overall, the low friction involved in water-based transportation and the large range of possible vessel sizes makes inland vessels operate in a fuel-efficient way. Because of this, inland shipping is considered to be among the more sustainable modalities for freight transport, especially when compared to rail (freight train) or air (freight plane) transportation.

Even so, environmental impacts do remain. A distinction can be made between the emission of greenhouse gases such as CO_2, and the emission of e.g. nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM), which have adverse effects on human health and cause local environmental pollution, including acidification (Jochemsen-Verstraeten et al., 2016).

Virtually all inland barges use diesel, a fossil fuel, as energy carrier.[1] While energy-efficient, resulting in low emissions of CO_2 compared to other diesel-based transportation, these emissions are still significant. Furthermore, due to the long lifespan of barges and their engines, most barges in operation in South Holland operate using old engines, which have high emission rates of the aforementioned local environmental pollutants (van der Geest et al., 2023).

With eye both on climate impacts and local environmental/health effects, reducing emissions is a policy goal of authorities on various levels, including the Province of South Holland, the Government of the Netherlands, and the European Commission. With measured emissions of various types concentrated around the industrial clusters along the Rhine (Rijksoverheid, 2021), the inland shipping sector is increasingly becoming one of the principal targets of such environmental policies.

Over the past decades, increasingly strict environmental standards have been set for the internal combustion engines (ICEs) used in inland shipping. Often-mentioned standards mentioned for inland shipping in the Netherlands are those set by the Central Commission for Navigation of the Rhine (CCNR) or the European Union. Currently, the EU Stage V emission standard for non-road engines, implemented around 2020, is the regulation adopted by both these organisations, placing strict limits on the emissions of CO, hydrocarbons, NO_x, and PM, but not CO_2 (ECOpoint, 2021). Overall, these standards for inland shipping tend to 'lag behind' similar standards for road transport: Stage V is still less strict than the current EURO VI standard for road engines, despite being introduced approximately seven years later.

In conclusion, while steps have been made to reduce the local environmental impacts from inland barge engines, significant emissions remain, both of these local pollutants and of greenhouse gases.

[1] In literature, various terms can be found for the low-sulphur diesel fuel used in the inland shipping sector, including "marine diesel oil" (MDO), "marine gas oil" (MGO), or or "EN590" (a standard for low-sulphur diesel), which are generally equivalent (Jochemsen-Verstraeten et al., 2016; van der Kruk & Bolech, 2022). For the sake of simplicity, in this report the term "diesel" will be used.

4

The energy transition in inland shipping

The goals set by the Paris Agreement, limiting global warming to "well below 2 °C", require a strong reduction in emissions of greenhouse gases by 2030, and net-zero greenhouse gas emissions halfway through the twenty-first century (Arias et al., 2021). The European Union, the Netherlands, and South Holland have all committed to significant emission reductions in line with these requirements, which are aimed principally at the energy and transportation sectors.

The emission standards for diesel engines described in the previous chapter are targeted at reducing the emissions of local pollutants, but do not address the main greenhouse gas, CO_2. In fact, since the production of CO_2 is an intrinsic part of the combustion reaction, this cannot be avoided for a conventional ICE in which diesel is burned – CO_2 emissions per unit energy can only be reduced via small efficiency gains, offsetting (the effect of which is disputed) or carbon capture (which is not available on an industrial scale). This has spurned efforts for an **energy transition** in inland shipping, shifting away from the combustion of fossil fuels entirely. This is seen as a required part of achieving a "climate-neutral" inland shipping sector (van der Geest & Menist, 2019).

In this chapter, a brief overview is given on current developments in inland shipping, both at the technological level (novel technologies and energy carriers) and the societal level (policy trends and initiatives). These will respectively serve as basis and context for the analysis in this study.

4.1. Novel technologies and energy carriers for sustainable inland shipping

A shortlist for technologies suitable for sustainable inland shipping, elaborated based on environmental benefits as well as technical and economical feasibility (EICB & TNO, 2021), summarises the possibilities into two technologies: **cleaner combustion engines** and **electrification**.

Continuing to use ICEs for inland shipping would involve further strengthening of environmental regulations targeting the emissions of these engines, such as the implementation of the EURO VI standard for inland barge engines (Dekker, 2020), or the installation of exhaust treatment systems. To reduce CO_2 emissions, potential non-fossil-based energy carriers that can be used in such ICEs include the following often-mentioned fuels (Arcos & Santos, 2023; Cozzolino, 2018; EICB & TNO, 2021; European Commission, Joint Research Centre & Moirangthem, 2016; Valera-Medina et al., 2018):

Biodiesel A biofuel comparable to diesel, made from plant-based oils or animal fats. It can be counted as a sustainable fuel (net zero CO_2 emissions) when produced from a renewable source, e.g. cultivation of rapeseed oil. Used cooking oil can also be used to produce biodiesel, although this supply is too limited to support a sector-wide energy transition.

Synthetic diesel A diesel alternative that can be produced in various ways, most commonly via the Fischer-Tropsch process, converting a gas into a liquid fuel. It can replace diesel with less engine adjustments than biodiesel. As with biodiesel, it can be considered sustainable if the feedstock for its production is renewable, e.g. gasification of wood from sustainable forestry.

LNG Liquefied natural gas (LNG) is natural gas, mainly consisting of methane (CH_4), cooled and compressed into a liquid state for a higher energy density. Bio-based versions (bio-LNG) exist and can have minor environmental benefits over biodiesel.

Methanol Methanol is a gaseous fuel, produced mainly from natural gas or coal gasification. It is attractive as a fuel due to its low sulphur content and the existence of bio-based alternatives, even on an industrial scale (European Commission, Joint Research Centre & Moirangthem, 2016).

Ammonia Ammonia (NH_3) is a fuel that can be produced in various ways, including from synthesising hydrogen – which, if the hydrogen supply is produced sustainably, makes this ammonia a sustainable fuel with practical advantages over hydrogen itself. Despite being a commonly mentioned novel fuel, it is considered too unsafe to be implemented in inland barges.

Hydrogen Hydrogen gas (H_2, the lightest molecule) is a gas only consisting of hydrogen atoms. It can be produced from water (using fossil fuels or electricity), and can be used as an energy source emitting only water (or, if combusted, some trace pollutants – but no CO_2).

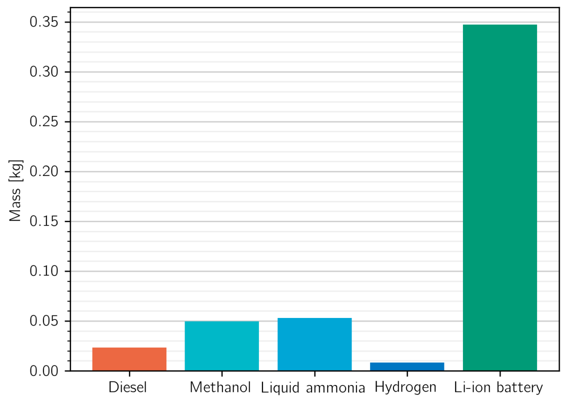
E-fuels Electrofuels (commonly shortened as e-fuels) are fuel substitutes for e.g. methanol, diesel, or methane, produced from hydrogen and captured carbon dioxide using electricity. When using renewably sourced hydrogen and electricity, these fuels can be considered sustainable, while having the same practical advantages as the fuels they substitute.

Alternately, a barge can be fully electrified, removing combustion from the barge propulsion system in favour of an electric motor. Two variants can be discerned: electric lithium-ion batteries, which can be charged on-board or placed in swappable containers, or fuel cells, which use hydrogen or e.g. biomethanol as an energy carrier to produce electricity without combustion.

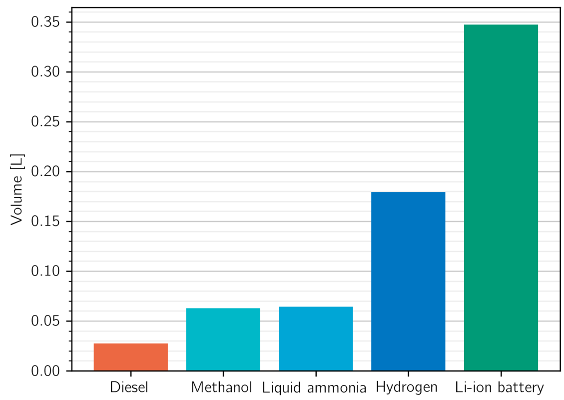
4.1.1. Economical and practical tradeoffs of energy carriers

A significant challenge faced in a transition to novel energy carriers is the tradeoff between environmental benefits and practicality. Conventional diesel fuel (as well as bio-/synthetic diesel) has an energy density exceeding that of all other energy carriers discussed, both in terms of mass and of volume (visualised in Figure 4.1).

The contrast is especially stark for lithium-ion batteries, while for hydrogen the main challenge lies in its volume. A liquid fuel such as methanol is more similar to diesel, but is still just half as energy-dense. In practice, this means that a barge that can transport the same freight load over the same distance on a single tank or charge needs to carry more weight and dedicate more freight space to fuel tanks or batteries when sailing on one of these novel fuels than it would need for diesel. Future developments in e.g. battery technology may affect this tradeoff, but these are not a certainty at this point in time.



(a) Necessary energy carrier mass per 1 MJ of energy.



(b) Necessary energy carrier volume per 1 MJ of energy.

Figure 4.1: Energy density (inverse) of a selection of relevant energy carriers (EICB & TNO, 2021; Valera-Medina et al., 2018; Wolfram, 2022).

Economically, a similar tradeoff exists, especially in the present and near future. The production of combustion engines and diesel fuel is well-developed and cheap compared to the other technologies and fuels mentioned, especially fuel cells and hydrogen, which can be 2-3 times more expensive (EICB & TNO, 2021). Looking ahead, beyond 2030, biofuels or high-frequency battery-electric sailing can reach acceptably low costs (less than 50% higher than diesel combustion). E-fuels are even more expensive and complex to produce than biofuels or hydrogen, and are not yet developed on an industrial scale.

Extra infrastructure, e.g. for the transportation of novel fuels or recharging of electric batteries, is also required. The implementation of novel technologies and energy carriers will require significant investment from the private and public sector – according to EICB, this means that careful selection of only one or a few novel energy carriers must be mdade – and may result in increased costs for shipping companies or their clients.

4.1.2. Types of hydrogen

Hydrogen gas (H_2), which can be used both in an ICE or a hydrogen fuel cell (HFC) for low-emission barge operations, can be obtained or produced in various ways (Arcos & Santos, 2023). While the resulting hydrogen is identical, these production methods have very different consequences for the environmental impacts of hydrogen fuel.

Grey hydrogen Produced from natural gas via steam methane reforming (SMR), and the main type of hydrogen available at an industrial scale. Based on a fossil fuel, this process involves high CO_2 emissions, and does not fit in with zero-emission targets.

Blue hydrogen Produced from natural gas via SMR, with carbon capture and storage (CCS) to reduce CO_2 emissions from the SMR process.

Yellow hydrogen Produced from water via electrolysis using grid electricity. Greenhouse gas emissions are dependent on the grid electricity mix.[1]

Green hydrogen Produced from water via electrolysis using fully renewable energy. As this involves minimal CO_2 emissions, this is the type of hydrogen most energy transition plans aim for. However, as of present, the low supply of (surplus) renewable energy makes green hydrogen production not possible on a large scale.

White hydrogen Hydrogen produced by naturally-occurring processes, involving no anthropogenic greenhouse gas emissions. While various deposits have been identified and overall potential for white hydrogen remains unassessed, it is not considered plentiful enough for use on an industrial scale.

Other types of hydrogen exist (e.g. black, from coal gasification, or pink, from electrolysis using nuclear energy), but these are less relevant in the context of the Netherlands. Hydrogen can also be a byproduct of industrial processes (usually classified as yellow or white), but this supply is too limited to meet forecast future demand for hydrogen.

[1] In this report, this is the definition used, as hydrogen from grid electricity is one of the main energy carriers studied. In some other sources, "yellow hydrogen" instead refers to hydrogen produced via electrolysis from solar energy only.

4.2. Policy trends and initiatives relevant to sustainable inland shipping

4.2.1. Province of South Holland

The Province of South Holland has significant interest in inland shipping within the province, due to its responsibility for the maintenance and operations of transportation infrastructure and waterways. As a regional authority, it also has strong links with the inland shipping sector, industry, the Port of Rotterdam, and other local authorities.

The provincial administration recognises the significant role of inland shipping in its freight transportation, as well as the environmental advantages and unused potential this modality has (Provincie Zuid-Holland, 2021b). It has commissioned various studies (e.g. by EICB, TNO and Panteia) on the current and future state of inland shipping and a potential energy transition in the sector, which are cited in this report.

At the same time, the provincial administration does not have a direct regulatory role regarding the inland shipping sector. Its efforts are mainly based on supporting initiatives and facilitating collaboration and partnerships, as well as facilitating necessary infrastructure. This includes participation in e.g. Refit Alliantie, RH_2INE, and being the lead partner in CLINSH, the European consortium for promoting clean inland waterway transport. It also invests in infrastructure for shore power, and is looking at the infrastructure necessary for the recharging or refuelling inland barges using novel energy carriers.

A selection or initiatives or businesses relevant to sustainable inland shipping operating in South Holland include:

Refit Alliantie[2] An organisation formed by shipbuilders, suppliers, financiers, education and research, public administration and shippers, with the goal of improving collaboration and innovation for clean inland shipping and refitting the existing fleet of inland barges, and introducing open standards.

RH_2INE[3] An initiative between the Province of South Holland and the Ministry of Economic Affairs, Innovation, Digitisation and Energy of North Rhine-Westphalia (Germany), with an extensive list of public and private partners, with the goal of creating a zero-emission transport corridor along the Rhine based on hydrogen fuel.

Condor H2[4] A project supported by the Port of Rotterdam, the Province of South Holland, and public and private partners, part of RH_2INE, aiming at facilitating the sailing of 50 hydrogen-powered vessels by 2030.

Future-Proof Shipping[5] A company aiming at creating a fleet of hydrogen-powered barges. Its first vessel, *H2 Barge 1* (formerly *FPS Maas*), powered by a HFC power system, started operating in 2023.

Zero Emission Services[6] A company offering battery packs in swappable containers, aiming at creating a network of loading points and vessels using these "as a service". The first Dutch inland vessel operating on this system, the *Alphenaar*, started operating in 2021.

CityBarge[7] A company offering inland waterway transport at a small scale, including inner cities, making use of small and flexible electric barges developed by Kotug.

The Province of South Holland is also part of policy trends and initiatives on the national or European level, a summary of which is given in the next two sections.

[2] https://www.refitalliantiebinnenvaart.nl/
[3] https://rh2ine.eu/
[4] https://www.portofrotterdam.com/en/port-future/energy-transition/making-logistics-chains-more-sustainable/condor-h2
[5] https://futureproofshipping.com/
[6] https://zeroemissionservices.nl/
[7] https://citybarge.eu/

4.2.2. The Netherlands

The Government of the Netherlands, like South Holland, recognises the potential and advantages of inland shipping. Agencies involved in inland shipping and its energy transition are the Ministry of Infrastructure and Water Management and the Ministry of Economic Affairs and Climate. In 2019, the *Green Deal Zeevaart, Binnenvaart en Havens* ("Green Deal Maritime Navigation, Inland Navigation, and Ports"), an agreement between government agencies and other parties on advancing sustainable navigation, was signed (Provincie Zuid-Holland, 2021a).

Inland shipping is also one of the sectors explicitly targeted by the *Schone Lucht Akkoord* (SLA; "Clean Air Agreement"), a collaboration between the national government and local authorities (municipalities and provinces – including South Holland) to reduce air pollution by 50% in 2030, compared to 2016 levels. The SLA measures for inland shipping include subsidies and regulations for the use of shore power when ships are in ports, emission labels, emission criteria in tenders for infrastructural construction work and ship operations, researching options for electrifying the publicly owned fleet, and the development of sustainable inland ports (Rijkswaterstaat, 2023).

Recent policy decisions include increasing requirements for shipping companies to monitor their CO_2 emissions by 2027, researching mandatory emission labels for inland barges and introducing subsidies for hydrogen fuel for inland shipping by 2025 (Heijnen, 2023). Subsidies already place include the aforementioned subsidy for shore power, as well as subsidies for equipping older engines with exhaust aftertreatment systems, and for refitting inland barges with Stage V engines or electric powertrains and battery containers.

4.2.3. European Union

In 2021, the European Commission introduced the NAIADES III action plan for "promoting and future-proofing" inland waterway transport in the European Union, in line with larger-scale policies such as the **European Green Deal** (European Commission, 2021a). The areas targeted include shifting more freight to inland shipping by improving the quality and integration of inland waterways, transitioning to zero-emission inland waterway transport by encouraging investment in research, innovation and zero-emission and zero-waste technology.

Overall, there are ambitious plans on the European level for the proliferation of renewable energy and sustainable inland water transport. The revised EU Emissions Trading System (**ETS**) will place an emissions cap on more sectors starting in 2027, including the maritime sector (ETS 2). This will create a financial incentive for shipping companies to reduce emissions, and gradually decrease overall emissions by lowering the emissions cap. Although inland barges are not yet within the scope of the proposed ETS2, the Dutch government has expressed the intention to include all fossil fuel consumption in its implementation of ETS 2, including smaller maritime vessels and the inland shipping sector (Heijnen, 2023). Other relevant recent EU policy plans include: the Renewable Energy Directive (**RED**), revised in 2023 to include a binding target of 42.5% renewable energy by 2030, which introduces a variety of sector-specific measures to reach its target, including scaling up electrification and the production of hydrogen or renewable fuels for sectors that are difficult to electrify (European Commission, 2023d); the Trans-European Transport Network (**TEN-T**), which supports the development of international transport infrastructure and is being revised to include a transition to "cleaner, greener and smarter mobility" with a 90% emissions reduction goal (European Commission, 2023e); the Energy Taxation Directive (**ETD**), which has been revised to homogenise taxation and tax fuels according to the pollution they entail (European Commission, 2021b); the Regulation for the deployment of alternative fuels infrastructure (**AFIR**), setting targets for electricity and hydrogen infrastructure including at inland ports (European Commission, 2023b); upcoming or recently introduced **CSRD** regulations requiring corporate sustainability reporting (European Commission, 2023a); and **CountEmissionsEU**, an upcoming framework for homogenising the quantification of greenhouse gas emissions across transport modalities (European Commission, 2023c).

In summary, there are many policy developments (on the regional, national and international level) that introduce opportunities for the development of a clean and sustainable inland shipping sector, which align with the technological developments that have been explored previously and that will be studied further in this report.

5
Literature overview

In this chapter, an exploration of existing literature on the selected research topic is given. This serves to identify a relevant research gap, giving an expanded justification for the research question proposed in Chapter 1.

5.1. Existing literature on sustainable inland shipping

Extensive research has been carried out in the area of sustainable shipping, including studies centred around LCA. Park et al. (2022) provide a thorough overview of the characterisation of shipping fuel-related publications since the 19th century, and show a gradual shift from a focus on technical know-how on fuels, engines, and system operations towards a focus on environmental issues in the maritime sector and the specific environmental impacts. Since the early 20th century, LCA has increasingly become a common tool for such research.

This existing research is varied in scope, methodology, and purpose. Some studies are aimed at performing a case study for a specific ship or ships (Huijsman, 2014; Mountaneas, 2014; Snaathorst, 2023). Tamis and de Vries (2015) carry out an LCA for a specifically designed sustainable ship for North Sea fishery, although their focus lies on ship design aspects instead of fuels.

Other reports do directly compare the impact of fuels, usually contrasting diesel as a baseline with various potential alternative energy sources. A 2016 review of the ‘state of the market’ is given, covering a wide range of alternatives: low-sulphur fuels, methanol/biomethanol, dimethyl ether, biodiesel, hydrogenation derived renewable diesel (HDRD), algae biofuel, liquefied petroleum gas (LPG) or liquefied natural gas (LNG), biomethane, electricity, synthetic Fischer-Tropsch (FT) diesel, pyrolysis oil, and hydrogen fuel cells (European Commission, Joint Research Centre & Moirangthem, 2016). However, studies in which an own LCA is carried out tend to focus only on a subset of these technologies. The most commonly studied alternative energy carriers are electricity from batteries, hydrogen fuel cells, and biofuels such as methanol.

A sustainable shipping plan developed for the Province of South Holland (EICB & TNO, 2021) consists of so-called “clean combustion engine” (powered by a biofuel or hydrogen combustion) or fully electrified solutions. In the case of electrification, the shortlist of suitable technologies is similar to the aforementioned commonly studied energy carriers: lithium-ion batteries, or fuel cells with green hydrogen or biomethanol as energy carrier.

5.1.1. Comparative studies favouring hydrogen as an energy carrier

Chen and Lam (2022) compare diesel with hydrogen cells for tugboats with hydrogen being sourced from electrolysis, with life-cycle results favourable to the hydrogen alternative except regarding ecotoxicity.

Evers et al. (2023) performed a meta-analysis of various other LCA studies for retrofitting existing (maritime and inland) vessels for zero-emission shipping, selecting an LCA functional unit of 30-year propulsion of an inland ship. The selected alternatives are diesel, compressed hydrogen, and liquid ammonia. As in Chen and Lam (2022), hydrogen – produced from renewable energy by electrolysis – has the lowest environmental impact. Evers et al. (2023), being a meta-analysis of LCAs instead of a new LCA, further expands its scope by discussing system-level implications of the different alternatives, such as the necessary energy infrastructure.

These results favouring hydrogen as an energy carrier for inland shipping have already led to some practical applications. In mid 2023, the *H2 Barge 1*, a barge refitted to use hydrogen fuel cells started operation – claimed to be the first inland barge sailing on green hydrogen worldwide (Lengkeek, 2023) – followed in late 2023 by *ms Antonie*, the Netherlands' first newly built hydrogen-powered inland shipping vessel (Kok, 2023).

5.1.2. Comparative studies favouring electricity as an energy carrier

Other studies show positive results for electricity from batteries as an energy carrier. This is the case for a study by Wang et al. (2021) for a ferry on the Thames river in the United Kingdom, although in this case this was the only alternative assessed, as well as for a study encompassing Croatia's inland shipping sector (Perčić et al., 2021), which also included methanol, ammonia, LNG, and hydrogen as possible candidates. In this case, the hydrogen was considered to be produced from natural gas instead of by electrolysis.

Fan et al. (2021) provide another overview of the sustainable future of inland shipping. Like other sources mentioned, Fan et al. mention electrification, fuel cells, and batteries as technologies that will play a significant role in this. An LCA is carried out, which compares diesel, natural gas, and battery-powered operation, including manufacturing of the required engines and battery, respectively, applied to two specific case studies. In both cases, the alternative solution is found to be more environmentally friendly than diesel.

5.1.3. Comparative studies favouring other energy carriers

In Fan et al. (2023), an LCA into sustainable inland shipping in China, the alternatives compared are diesel, methanol, and LNG (natural gas), leaving out more novel alternatives such as battery-sourced electricity or hydrogen. On the other hand, this LCA is well-developed, and details the ship construction and decommissioning phases. They conclude that, of the alternatives studied, LNG is the most advantageous one, and that it is the operational phases of well-to-tank (WTT) and tank-to-wake (TTW) that represent 90% of emissions, while the construction and decommissioning phases are less impactful over a ship's lifetime.

In general, LCAs comparing alternative energy carriers and propulsion for inland shipping appear to find the selected alternatives to have a lower environmental impact than diesel, regardless of which these are (batteries, fuel cells, biofuels, or LNG and other 'cleaner' fuels).

5.1.4. Studies with a regional scope

Some LCA studies focus on a regional scope, like the aforementioned papers of the Chinese and Croatian inland shipping sectors (Fan et al., 2023; Perčić et al., 2021). These contain interesting research elements on how to include the regional perspective in an LCA, including transportation emissions for materials and fuels sourced from other regions. At the same time, this means that the results of these studies do not directly translate to South Holland's waterways.

Another such study exists for the region of Flanders (located in Belgium, relatively close to this report's geographical scope of South Holland), where LCA was used to assess the current state of regional inland shipping (van Lier & Macharis, 2014). In its turn, this report does not assess any potential more sustainable alternatives: it is a description of the current state.

5.1.5. Studies on ship refitting

From a life-cycle perspective, refitting existing ships with newer, more environmentally friendly engines may be more effective at reducing the inland shipping sector's environmental impact than constructing entirely new ships. The reason for this is common-sense, with the reuse of existing goods as opposed to producing new ones avoids significant construction and decomissioning-related emissions. In this scenario, the case for refitting is strengthened by the long lifespan of inland ships, with the average *current age* of European inland ships being about 50 years – while a ship engine's lifespan is shorter than that of its hull and can be replaced partway through the lifetime of a ship (Chirica et al., 2019).

Chirica et al. (2019) explore various solutions for refitting existing inland ships for more sustainable operations and highlight the potential of this approach. The focus of this investigation lies mainly on design and practical considerations, and on cleaner combustion engines (including cleaner fuels and exhaust treatment), but not on alternative engine types altogether.

One of the cases studied in the study on battery and natural gas as energy carriers described in Section 5.1.2 is a refitting scenario. Here, a hybrid power solution (LNG generators and a battery pack) for an existing inland container ship is assessed, which would replace its existing diesel engine, but no other alternatives are presented (Fan et al., 2021).

Stark et al. (2022) carry out a study on the application of energy-saving devices to hydrogen-powered ships. This does not directly relate to the topic discussed in this report, as Stark et al. do not focus on the implementation of hydrogen propulsion systems themselves; nevertheless, various topics of interest appear in this paper, such as a brief introduction to the current state (as of 2022) of hydrogen in shipping.

Finally, Bui et al. (2022) present a life-cycle *cost* analysis for refitting marine ships with an innovative dual-fuel engine. This paper may be interesting due to it studying the life cycle of an innovation in ship refitting, even if not being directly relevant due to not focusing on novel energy carriers and not being directly concerned with environmental externalities.

5.2. Knowledge gap

As has been discussed, extensive research in the selected area already exists, with ample alternative energy carriers studied for a variety of purposes. However, as far as it has been possible to discern, no study exists which encompasses all the following properties:

- Carries out a life-cycle assessment, the steps and assumptions of which are clearly given and preferably follow the *Handbook on Life Cycle Assessment* (Guinée et al., 2002).
- Compares diesel (as a baseline) with various alternative energy carriers, at least including electrical batteries and hydrogen from electrolysis.
- Targets refitting ships in the inland shipping sector, but not a specific ship or route.
- Has a regional scope, specific or comparable to the Province of South Holland.

The existence of this gap is supported by a literature search combining varied search terms targeting these criteria. This yields around 10 peer-reviewed articles, most of which are reviews, or do not carry out an own LCA. A good example among these is Perčić et al. (2021) which only considers grey hydrogen, produced from natural gas via SMR, as opposed to potential "green hydrogen" produced from electrolysis as favoured by the Province of South Holland, but is otherwise an exemplary article within the regional scope of Croatia.

III

Life-cycle assessment

Image: Alphenaar, by GVA

6 Goal and scope definition

6.1. Goal

The goal of this study is to assess the life-cycle environmental impacts of inland shipping, and the effect on this of different novel energy carriers which can be embedded in existing ships by way of refitting, and in this way answering the research questions postulated in Part I of this report.

It has the aim of comparison of different alternatives and of identifying 'hot spots' in the environmental impacts of the system assessed. This study has been commissioned by the Province of South Holland, as part of a larger assessment of opportunities and challenges for sustainable inland shipping.

6.2. Scope

6.2.1. Geographical scope

The geographical scope of this investigation is centred around the Province of South Holland, in the Netherlands, which is where usage and maintenance of inland barges takes place (see the maps in Figures 3.1 and 3.2 for the geographical location and principal waterways). Refining of diesel fuel and production of hydrogen is also assumed to take place in South Holland, and electricity for activities taking place in South Holland is taken from the European average grid mix. The Dutch grid mix, while more appropriate to the scope, is not modelled separately in the studied scenarios, as will be discussed below.

Resource extraction and various production processes do not take place in South Holland specifically, in which case Ecoinvent processes for the European market (RER / Europe without Switzerland) are used, or global/rest-of-world data in their absence. To reflect the reality of modern-day shipbuilding, production of barge hulls will be assumed to take place in South-East Asia (with a necessary transoceanic transport step), although their maintenance and decommissioning does still take place in South Holland.

When needed, background processes from Ecoinvent are adapted to more accurately reflect the studied geographical scope, by changing the geography of the input and output economic flows. This will make it possible to break down some environmental impact categories by region. A detailed overview of data sources and modelling choices will be given in Chapter 7.

6.2.2. Temporal and technological scope

The technological scope of the studied product system is complex to determine, as it has many different factors with data from different sources. The intention is to use a technological scope that accurately reflects the present (in the case of well-developed technologies such as combustion engines and diesel refining) or the near future (in the case of hydrogen and battery technologies). Some background processes sourced from Ecoinvent have older temporal scopes, although in the case of established technologies this is not expected to be a significant source of error.

The technological scope is closely linked to the temporal scope. To study the effects of a shifting technology over time, a total of four points in time are studied, based on the shared socioeconomic pathways (SSPs) presented by the IPCC in 2021 (Arias et al., 2021). Integrated assessment models (IAMs) translate these pathways into quantitative data, and the Premise tool is used to adapt the Ecoinvent LCI database to a specific pathway according to the data of a selected IAM (Sacchi et al., 2021). This results in an updated LCI database with changed processes, such as updated input shares in electricity mixes, supplemented by additional processes for novel technologies, such as renewable fuel production and electric transportation, sourced from literature.

For this study, the *REMIND* family of IAMs is selected, which has "a special focus on the development of the energy sector and implications for our world climate" (Baumstark et al., 2021). The SSP2 pathway is chosen, representing a scenario with future socioeconomical development extrapolated from current and past trends. Within this pathway, various scenarios are available based on projected climate policies, including:

SSP2 - Base, extrapolated development trends without significant climate policies, resulting in $\sim 3.5\,°C$ global mean surface temperature (GMST) increase by 2100.

SSP2 - RCP2.6, extrapolated development trends with climate policies aligned with the Paris Agreement, resulting in $\sim 1.6\,°C$ to $1.8\,°C$ GMST increase by 2100.

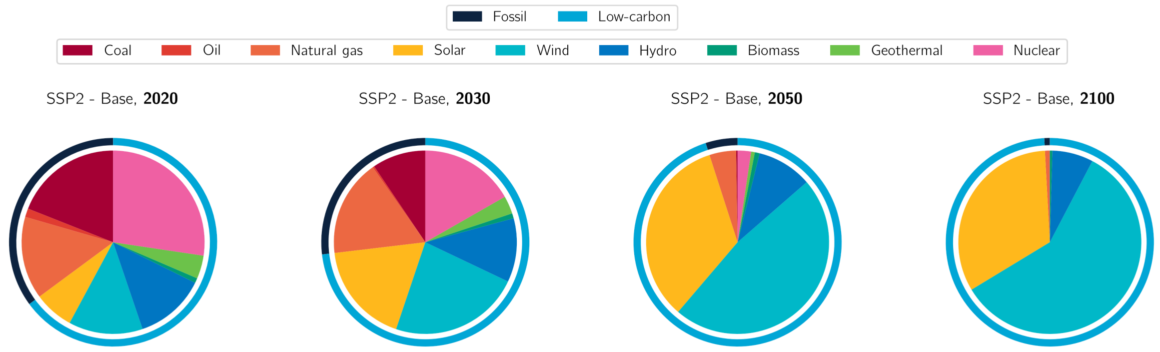
SSP2 - RCP1.9, extrapolated development trends with ambitious climate policies aligned with the Paris Agreement, resulting in $\sim 1.2\,°C$ to $1.4\,°C$ GMST increase by 2100.

The focus of the REMIND IAM is principally on socio-economic development and the energy sector. This is especially relevant to this study, as the electricity sector is predicted to strongly decarbonise over the coming decades, which is a prerequisite for low-emission or zero-emission inland shipping on batteries or hydrogen. Furthermore, these scenarios give a pathway for the phase-out of fossil fuels in transportation, even for diesel, which is gradually replaced by low-carbon (bio-based or synthetic) substitutes. This is relevant for an alternative in which diesel (either fossil-based or low-carbon) remains the principal energy carrier for inland shipping. Other considerations, such as efficiency improvements in electricity production, the use of battery or hydrogen-based storage for electricity grid stabilisation, and overal changes in supply and demand of specific fuels and energy types, are also included in these models.

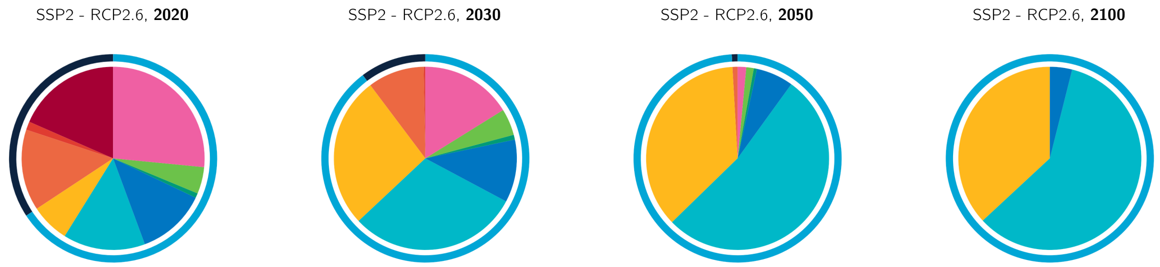
The available IAMs do not include detailed information for specific European countries such as the Netherlands, instead using Europe-wide market groups. Figure 6.1 contains a comparison of the European electricity grid mix in each of these scenarios, at four key points in time: 2020 (representing the present day), 2030 and 2050 (target years in many climate policy ambitions), and 2100 (the end of the century). Figure 6.2 shows the evolution of the total European electricity supply over the century according to these scenarios. Figure 6.3 and Figure 6.4 contains a similar depiction of the future mix and total supply of diesel and low-carbon diesel alternatives (synthetic and biodiesel) within Europe.

> **How to interpret Figures 6.1 and 6.3**
>
> Each chart represents the European electricity or diesel mix in a given year according to one of the future pathways, the coloured slices indicating the share of the mix corresponding to each energy source. Each row of charts represents a different pathway, and each chart represents a different point in time within that pathway.

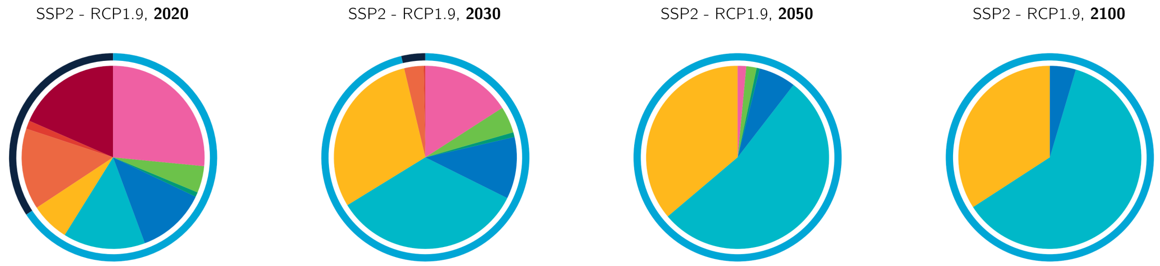
Of these three pathways, the most interesting one is **SSP2 - RCP2.6**, considering that meaningful climate policies are having worldwide effect, but that the barrier of $1.5\,°C$ GMST increase may already have been breached in 2023 (McGrath et al., 2023). This scenario will be used for the main analysis in this study. The other two scenarios, thus representing a more conservative (SSP2 - Base) or ambitious (SSP2 - RCP1.9) approach to the energy transition, will be used in a sensitivity analysis.



(a) Electricity grid mix in the SSP2 - Base pathway.



(b) Electricity grid mix in the SSP2 - RCP2.6 pathway.



(c) Electricity grid mix in the SSP2 - RCP1.9 pathway.

Figure 6.1: Comparison of the electricity grid mix at the four considered points in time, as projected in three SSP2 scenarios. The outer ring of each chart gives an indication of the ratio between fossil and low-carbon electricity generation.

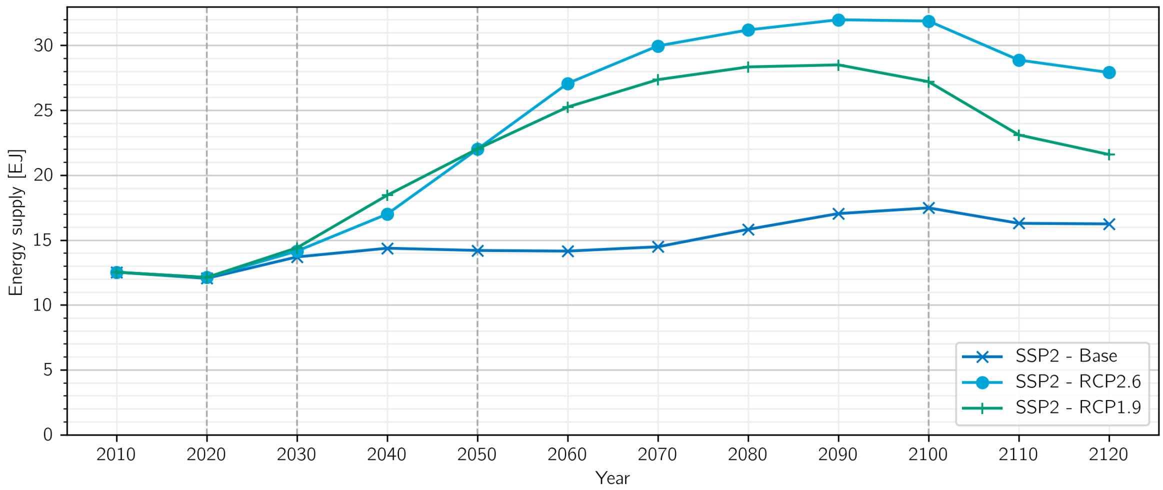
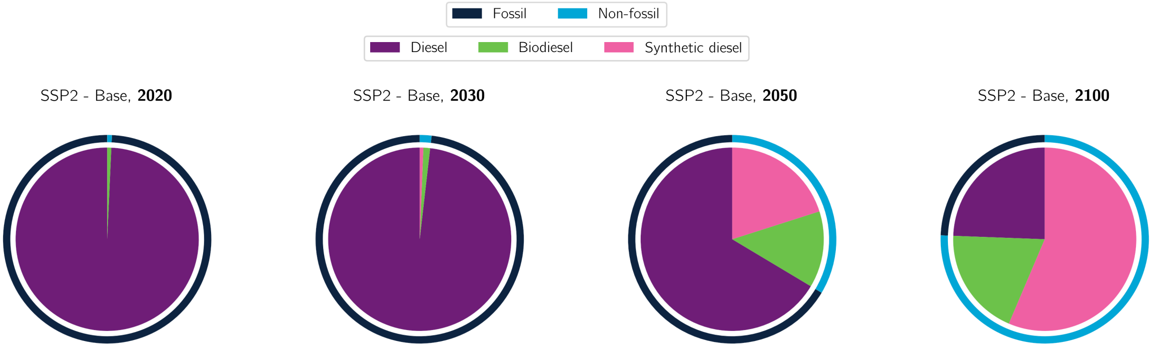
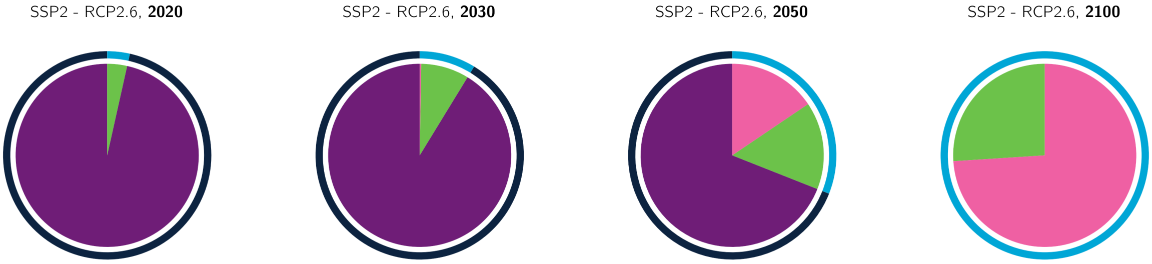


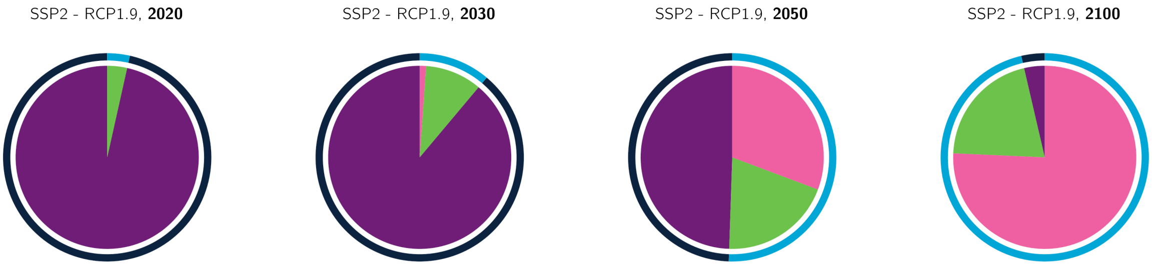
Figure 6.2: Evolution of the total electricity supply in Europe as projected in three SSP2 scenarios.



(a) Diesel mix in the SSP2 - Base pathway.



(b) Diesel mix in the SSP2 - RCP2.6 pathway.



(c) Diesel mix in the SSP2 - RCP1.9 pathway.

Figure 6.3: Comparison of the diesel mix at the four points in time, as projected in three SSP2 scenarios. The outer ring of each chart gives an indication of the ratio between fossil and non-fossil diesel sources.

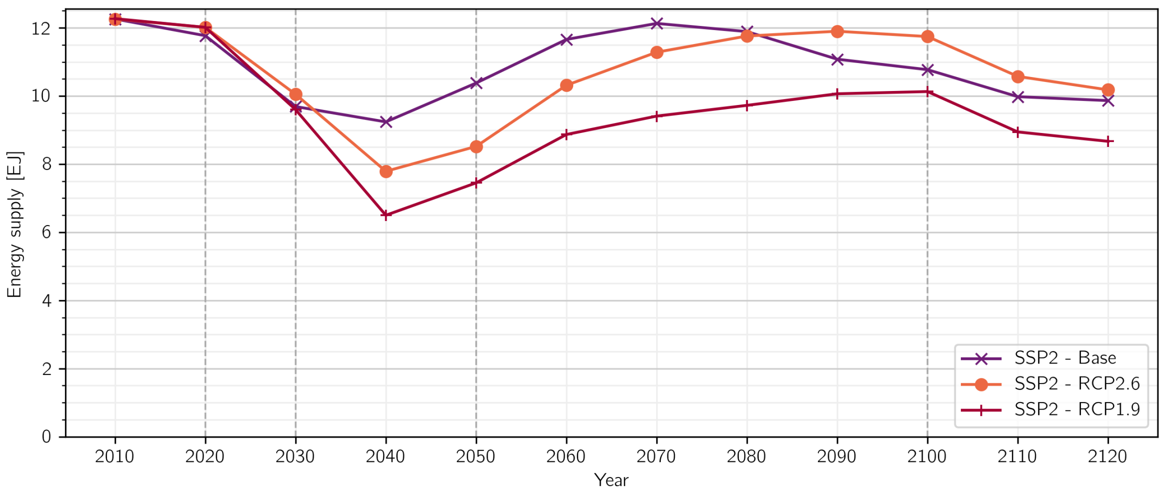


Figure 6.4: Evolution of the total diesel supply in Europe as projected in three SSP2 scenarios.

6.2.3. LCA method

As far as possible and feasible within the context of this study, a detailed LCA method will be used, aligned with the procedures described in Guinée et al. (2002). An **prospective**, **attributional** LCA method is selected for this research. As an attributional LCA, average data for energy and good supplies will be used to obtain an assessment on the share of global environmental impacts that can be attributed to the studied system. Choosing for an attributional method keeps the research focused on the shipping system and decreases its reliance on projections or estimates for future energy systems. This comes at the expense of leaving out of scope the effects of the alternatives' resource demands on the overall economy. For example, the possible shift in the electricity grid mix due to an increase in electricity demand, which in reality (especially in the short term) is likely to be met by a specific, marginal technology instead of a balanced increase in all electricity sources, is not considered (Weidema et al., 1999).

A cradle-to-grave approach is used, in which the full life cycle of the compared alternatives will be considered, from raw material extraction and processing to the operational phase, and to disposal of waste at end of life. Specifically, the following aspects are considered:

Barge operation The operation of an inland barge (sailing). In case of an internal combustion engine, this is expected to be the primary source of direct emissions.

Barge production The production of a barge as well as of the alternative-dependent **power system** (engine, batteries, fuel cells...). This includes the extraction and processing of raw materials, production processes, and transportation of goods, and component inputs scaled according to their lifespan.

Barge maintenance Material and energy demand for the regular maintenance of a barge.

Barge end-of-life Decommissioning of a barge, and recycling or final disposal of extracted material wastes.

Energy supply The production and transportation chain associated with the fuel or other energy carrier necessary for barge operation.

Infrastructure Construction and maintenance of waterways; construction, maintenance and operations of ports; operations of provincial bridges – to the extent to which these can be allocated per ship. Excluded from the scope is the construction of bridges, which are considered part of road infrastructure.

Other minor inputs and wastes Shore power consumed by ships in ports, ICE lubricant, diesel exhaust fluid (DEF) for modern ICEs, and waste bilge oil from ICE operation.

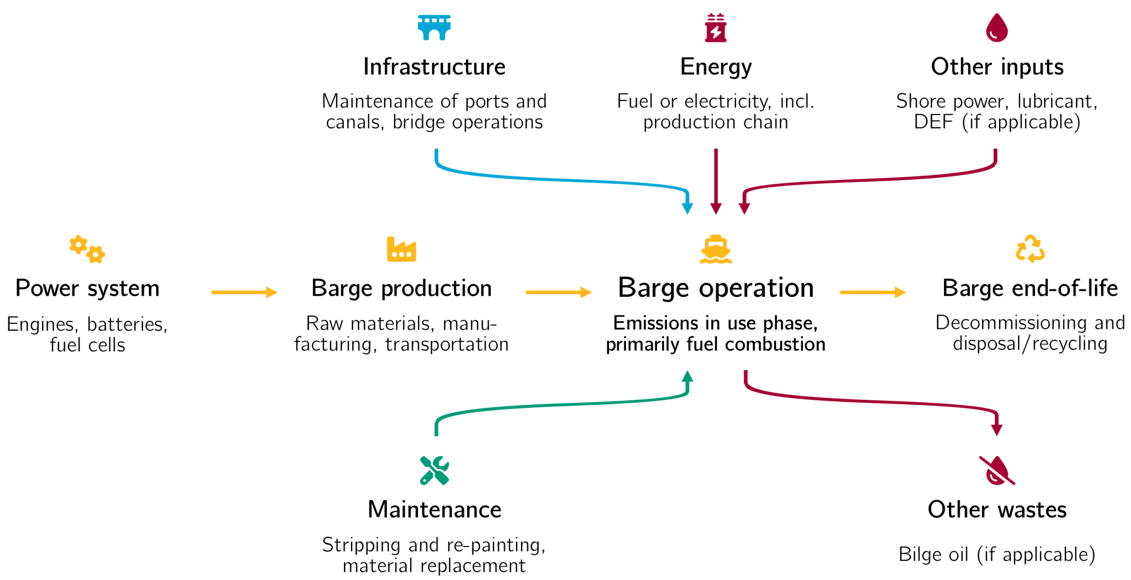


Figure 6.5: Aspects considered in the scope of this LCA, centred around the main process of barge operation. For each of these elements, the direct and indirect (embodied) emissions are taken into account.

Figure 6.5 contains a simplified diagram of how these aspects relate to each other (full LCA model flow diagrams will be provided in Chapter 7).

6.2.4. Modelling decisions

Allocation

As will be seen in the next chapter, no foreground multifunctional processes appear. However, multifunctionality is still present in the underlying data, especially relevant for the recycling of wastes such as scrap steel, the main material of a barge hull. Markets for waste treatment processes must use some method of allocation, as discussed in Chapter 2.

The *allocation, cut-off by classification* version of the Ecoinvent database is used. In this system model, the environmental burdens for recyclable goods are allocated to the first producer of these goods. Concretely, this means that the use of recycled goods in the system only entails those emissions that occur during the recycling process, but not for the initial resource extraction and processing. On the other hand, environmental burdens of the system cannot be reduced entirely by making them available for recycling. This is described as an implementation of the 'polluter pays' principle (Ecoinvent, 2020).

The selection of this system model is considered appropriate from an environmental standpoint, where the reuse or recycling of materials should be encouraged, while the extraction of new resources should be discouraged. In the studied product system for inland shipping, the main resource used in barge production is steel, which can be recycled and reused indefinitely.

Biogenic CO_2

CO_2 emissions that are produced from the combustion of biomass and other organic matter are referred to as biogenic or non-fossil. If the obtention of this organic matter happens in a sustainable way – for instance, using sustainable forestry practices instead of irreplaceably cutting down rainforests – the net difference of CO_2 in the environment is zero over a life cycle (before considering additional fossil fuel-based emissions from industrial forestry, transportation, etc., which would not become biogenic by definition).

Based on this reasoning, in this study the emissions from biogenic CO_2 will be considered to not count towards climate change. An impact category will be chosen that excludes biogenic CO_2. This choice is relevant for bio- and synthetic fuels, the environmental advantage of which is based principally on their CO_2 emissions being biogenic.

6.3. Function and alternatives

The **function** of the system studied is to provide a service: the transportation of containerised goods over inland waterways. In concrete terms, a specific route is selected: from Rotterdam to Alphen aan de Rijn and back, with the average load and sailing conditions of the selected inland ship *Leendert-Angelina*, as described in Chapter 1.

The **functional unit** will equal the average yearly transportation of goods provided by the *Leendert-Angelina* (consequences if scaled up to the total annual volume of provincial inland shipping will be discussed at a later stage), equalling 11 689 225 t km (metric tonne kilometre).

The alternatives considered should cover various possible energy carriers:

Diesel A fossil fuel, and the principal energy carrier for inland shipping at present.

Diesel substitutes Bio-based and synthetic fuels that could replace diesel. The replacement of diesel by these over the course of the century is included in the used IAM scenarios.

Hydrogen Produced from natural gas by SMR (grey), by SMR while capturing emitted CO_2 (blue), or by electrolysis from the electricity grid (yellow).

Electricity Stored in lithium-ion batteries.

The alternatives considered should cover two different options for the used engine and power system:

ICE Continuing to use a combustion engine, suitable for fossil-based diesel and bio-based or synthetic substitutes, as well as for the combustion of hydrogen.

Electric motor Refitting ships with an electric motor (EM) and power system, to be powered by lithium-ion batteries, or hydrogen via fuel cells.

This results in the complete list of alternatives shown in Table 6.1. The corresponding **reference flows** are "11 689 225 t km of transportation of containerised goods over inland waterways in a barge", powered by each alternative energy carrier and power system. Table 6.2 gives an overview of power system and energy supply details for each alternative. A more thorough overview on how these alternatives have been selected is given in the remainder of this chapter, while more details on the data used to model each alternative will follow in Chapter 7. It bears highlighting that alternatives ICE.I.Diesel and ICE.V.Diesel also include the replacement of fossil-based diesel by non-fossil diesel substitutes over the course of the century, as modelled in the used scenarios. Furthermore, in a scenario where the electricity grid mix is sourced only from renewable energy, yellow hydrogen becomes equivalent to green hydrogen.

Table 6.1: List of all alternatives studied in this LCA.

Short name	Formal name *Transportation of containerised goods over inland waterways on a barge powered by...*
ICE.I.Diesel	... diesel[1] in a Stage I ICE, with emissions as defined in standard.
ICE.V.Diesel	... diesel[1] in a Stage V ICE, with emissions as tested from a Mitsubishi S12R-MPTAW-3 engine
ICE.V.H_2.Gr	... H_2 in a Stage V ICE, with grey H_2 produced by natural gas SMR
ICE.V.H_2.Bl	... H_2 in a Stage V ICE, with blue H_2 produced by natural gas SMR, CO_2 captured and stored
ICE.V.H_2.Yl	... H_2 in a Stage V ICE, with yellow H_2 produced by electrolysis from the electricity grid[2]
HFC.H_2.Gr	... HFCs, with grey H_2 produced by natural gas SMR
HFC.H_2.Bl	... HFCs, with blue H_2 produced by natural gas SMR, CO_2 captured and stored
HFC.H_2.Yl	... HFCs, with yellow H_2 produced by electrolysis from the electricity grid[2]
BE	... electricity stored in lithium-ion container batteries, charged from the electricity grid[2]

Table 6.2: Power system and energy supply details for all alternatives studied in this LCA.

Alternative	Energy source	Fuel production	Energy carrier	Power system
ICE.I.Diesel	(a) Crude oil (b) Rapeseed oil (c) Wood chips	(a) Refinery (b) Transesterification (c) Wood gasification, FT	Mix[1] of (a) diesel, (b) biodiesel, (c) synthetic diesel	ICE, Stage I
ICE.V.Diesel	(a) Crude oil (b) Rapeseed oil (c) Wood chips	(a) Refinery (b) Transesterification (c) Wood gasification, FT	Mix[1] of (a) diesel, (b) biodiesel, (c) synthetic diesel	ICE, Stage V
ICE.V.H_2.Gr	Natural gas	SMR	Hydrogen	ICE, Stage V
ICE.V.H_2.Bl	Natural gas	SMR with CCS	Hydrogen	ICE, Stage V
ICE.V.H_2.Yl	Electricity grid[2]	PEM electrolysis	Hydrogen	ICE, Stage V
HFC.H_2.Gr	Natural gas	SMR	Hydrogen	PEM HFC, auxiliary battery, EM
HFC.H_2.Bl	Natural gas	SMR with CCS	Hydrogen	PEM HFC, auxiliary battery, EM
HFC.H_2.Yl	Electricity grid[2]	Electrolysis	Hydrogen	PEM HFC, auxiliary battery, EM
BE	Electricity grid[2]	Direct (via charging station)	Electricity	Lithium-ion battery containers, auxiliary battery, EM

[1] A mix of fossil-based diesel and bio-/synthetic diesel, shifting over time, as modelled in the used scenarios.
[2] The European electricity grid, with the grid mix shifting over time as modelled in the used scenarios.

6.3.1. Selection of diesel alternatives

For diesel fuel, multiple engine emission standards can be considered: Stage I, Stage II, and Stage V,[3] gradually decreasing emission limits since the turn of the century. Furthermore, various data sources for the entailed emissions can be considered, with values varying strongly in each case:

- The emission limits as set in these standards (ECOpoint, 2021; Hulskotte, 2018);
- Average emissions calculated in a previous study by TNO, for pre-Stage I and Stage II engines only (Jochemsen-Verstraeten et al., 2016; van der Kruk & Bolech, 2022);
- Actual laboratory-measured emissions from a specific engine in each emission class: Mitsubishi S12R-MPTK (Vermeulen, 2023b), Mitsubishi S12R-C2MPTK (Vermeulen, 2023a), and Mitsubishi S12R-MPTAW with a "Koedood Engine Emission System" (KEES) (Koedood Marine Group, 2022; Ruers & van Schaijk, 2021). Of these, the S12R-C2MPTK is the current engine of the *Leendert-Angelina*, falling under the Stage II standard, while the S12R-MPTK and S12R-MPTAW are an older (Stage I) and a more recent (Stage V) model of equivalent specifications.

Table 6.3 contains a list of environmental flows assigned to each alternative variant of the diesel combustion process. The emissions of sulfur dioxide (SO_2), dinitrogen monoxide (N_2O), ammonia (NH_3), arsenic (As) ion and heavy metals are taken from van der Kruk and Bolech (2022) and, as in this TNO report, are assumed to not differ between standards. The emissions of hydrocarbons (HCs) are considered as one homogenous category in the engine emissions reports and standards, and so the proportions given in van der Kruk and Bolech (2022) are used, scaled for the total HC emissions for each alternative. The emissions for carbon monoxide (CO), nitrogen dioxide (NO_2) and particulate matter (PM) are included in each emissions report or standard. Finally, the emission of carbon dioxide (CO_2) varies only slightly between pre-Stage I and Stage II in the TNO report and is not mentioned in the S12R-MPTK or S12R-C2MPTK emissions reports, nor is it set in the standards. This is understandable, given that CO_2 is an inherent product of the combustion of a fossil fuel such as diesel and as such its emission per unit mass of fuel cannot be significantly reduced – and so, for the options where CO_2 emission data is not provided, the average of the TNO report values are used.

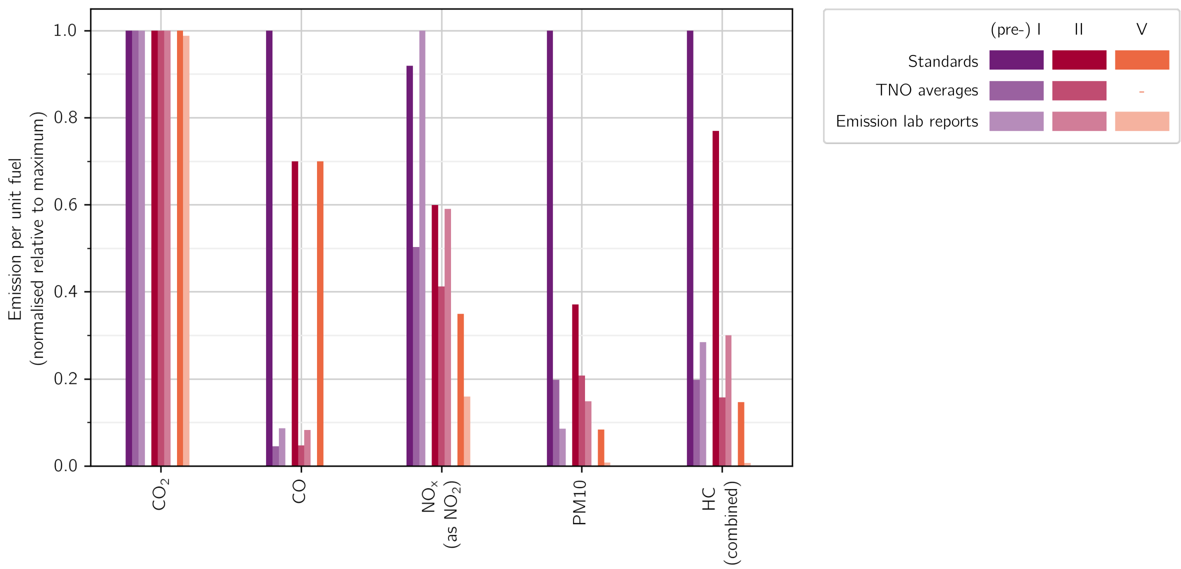


Figure 6.6: Comparison of diesel fuel emissions according to different data sources. Included are CO_2 emissions as well as the four emissions limited in the emission standards.

[3]Various competing emission standards exist. In Dutch-language literature, the naming CCR1 and CCR2 (referring to the norms set by the Central Commission for Navigation of the Rhine) is used for the standards set in 2002 and in 2007, and Stage V for the more recent standard set in 2016. However, the CCR1 and CCR2 norms are generally equivalent to the international Stage I and Stage II standards, except for their introduction date (Hulskotte, 2018). To keep naming consistent, only the "Stage" name is used in this report.

Table 6.3: Environmental flows for the diesel combustion process in the different potential alternatives, given in **g** emission per **kg** fuel. It can be readily observed that newer standards or models tend to have lower emissions, and that for most emissions the laboratory reports contain significantly lower emissions than the limits contained in the standards.

Emission	Standards			TNO		Emission lab reports		
	Stage I	Stage II	Stage V	pre-Stage I	Stage II	Stage I	Stage II	Stage V
Carbon dioxide	3.18×10^{3}	3.18×10^{3}	3.18×10^{3}	3.18×10^{3}	3.18×10^{3}	3.18×10^{3}	3.18×10^{3}	3.14×10^{3}
Carbon monoxide	2.67	2.81	5.94×10^{1}	4.16×10^{1}	4.16×10^{1}	5.11	4.87	0.00
Nitrogen dioxide	5.98×10^{1}	4.90×10^{1}	1.09×10^{2}	7.13×10^{1}	4.16×10^{1}	1.19×10^{2}	7.03×10^{1}	1.90×10^{1}
Particulate matter	1.27	1.33	6.42	2.38	5.35×10^{-1}	5.50×10^{-1}	9.50×10^{-1}	5.05×10^{-2}
Sulfur dioxide	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Dinitrogen monoxide	8.00×10^{-2}	8.00×10^{-2}	8.00×10^{-2}	8.00×10^{-2}	8.00×10^{-2}	8.00×10^{-2}	8.00×10^{-2}	8.00×10^{-2}
Ammonia	1.00×10^{-2}	1.00×10^{-2}	1.00×10^{-2}	1.00×10^{-2}	1.00×10^{-2}	1.00×10^{-2}	1.00×10^{-2}	1.00×10^{-2}
Arsenic ion	1.80×10^{-4}	1.80×10^{-4}	1.80×10^{-4}	1.80×10^{-4}	1.80×10^{-4}	1.80×10^{-4}	1.80×10^{-4}	1.80×10^{-4}
Heavy metals	2.80×10^{-1}	2.80×10^{-1}	2.80×10^{-1}	2.80×10^{-1}	2.80×10^{-1}	2.80×10^{-1}	2.80×10^{-1}	2.80×10^{-1}
Cadmium II	2.10×10^{-3}	2.10×10^{-3}	2.10×10^{-3}	2.10×10^{-3}	2.10×10^{-3}	2.10×10^{-3}	2.10×10^{-3}	2.10×10^{-3}
Chromium III	2.74×10^{-1}	2.74×10^{-1}	2.74×10^{-1}	2.74×10^{-1}	2.74×10^{-1}	2.74×10^{-1}	2.74×10^{-1}	2.74×10^{-1}
Copper ion	7.30×10^{-4}	7.30×10^{-4}	7.30×10^{-4}	7.30×10^{-4}	7.30×10^{-4}	7.30×10^{-4}	7.30×10^{-4}	7.30×10^{-4}
Lead II	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}
Nickel II	5.30×10^{-4}	5.30×10^{-4}	5.30×10^{-4}	5.30×10^{-4}	5.30×10^{-4}	5.30×10^{-4}	5.30×10^{-4}	5.30×10^{-4}
Vanadium V	2.38×10^{-3}	2.38×10^{-3}	2.38×10^{-3}	2.38×10^{-3}	2.38×10^{-3}	2.38×10^{-3}	2.38×10^{-3}	2.38×10^{-3}
Zinc II	2.45×10^{-4}	2.45×10^{-4}	2.45×10^{-4}	2.45×10^{-4}	2.45×10^{-4}	2.45×10^{-4}	2.45×10^{-4}	2.45×10^{-4}
Hydrocarbons	3.06	2.43	1.55×10^{1}	1.19×10^{1}	2.26	4.40	4.64	9.51×10^{-2}
Methane	1.12×10^{-1}	8.90×10^{-2}	5.67×10^{-1}	4.36×10^{-1}	8.29×10^{-2}	1.61×10^{-1}	1.70×10^{-1}	3.49×10^{-3}
Acrolein	3.49×10^{-2}	2.77×10^{-2}	1.77×10^{-1}	1.36×10^{-1}	2.58×10^{-2}	5.02×10^{-2}	5.30×10^{-2}	1.09×10^{-3}
Benzene	4.66×10^{-2}	3.70×10^{-2}	2.36×10^{-1}	1.81×10^{-1}	3.45×10^{-2}	6.71×10^{-2}	7.07×10^{-2}	1.45×10^{-3}
Ethylene	2.80×10^{-1}	2.22×10^{-1}	1.41	1.09	2.07×10^{-1}	4.03×10^{-1}	4.24×10^{-1}	8.71×10^{-3}
Formaldehyde	1.39×10^{-1}	1.10×10^{-1}	7.01×10^{-1}	5.39×10^{-1}	1.02×10^{-1}	2.00×10^{-1}	2.10×10^{-1}	4.31×10^{-3}
Toluene	3.39×10^{-2}	2.69×10^{-2}	1.71×10^{-1}	1.32×10^{-1}	2.51×10^{-2}	4.88×10^{-2}	5.14×10^{-2}	1.06×10^{-3}
Xylene	4.66×10^{-2}	3.70×10^{-2}	2.36×10^{-1}	1.81×10^{-1}	3.45×10^{-2}	6.71×10^{-2}	7.07×10^{-2}	1.45×10^{-3}
Phenanthrene	8.24×10^{-4}	6.54×10^{-4}	4.17×10^{-3}	3.21×10^{-3}	6.09×10^{-4}	1.19×10^{-3}	1.25×10^{-3}	2.56×10^{-5}
Anthracene	6.30×10^{-5}	5.00×10^{-5}	3.19×10^{-4}	2.45×10^{-4}	4.66×10^{-5}	9.07×10^{-5}	9.56×10^{-5}	1.96×10^{-6}
Fluoranthene	9.70×10^{-5}	7.70×10^{-5}	4.91×10^{-4}	3.77×10^{-4}	7.17×10^{-5}	1.40×10^{-4}	1.47×10^{-4}	3.02×10^{-6}
Chrysene	4.37×10^{-5}	3.46×10^{-5}	2.21×10^{-4}	1.70×10^{-4}	3.22×10^{-5}	6.28×10^{-5}	6.62×10^{-5}	1.36×10^{-6}
Benzo[*a*]anthracene	1.50×10^{-5}	1.19×10^{-5}	7.58×10^{-5}	5.83×10^{-5}	1.11×10^{-5}	2.16×10^{-5}	2.28×10^{-5}	4.67×10^{-7}
Benzo[*a*]pyrene	1.34×10^{-5}	1.06×10^{-5}	6.76×10^{-5}	5.20×10^{-5}	9.87×10^{-6}	1.92×10^{-5}	2.03×10^{-5}	4.16×10^{-7}
Benzo[*b*]fluoranthene	1.11×10^{-5}	8.85×10^{-6}	5.64×10^{-5}	4.34×10^{-5}	8.24×10^{-6}	1.61×10^{-5}	1.69×10^{-5}	3.47×10^{-7}
Benzo[*k*]fluoranthene	5.58×10^{-6}	4.43×10^{-6}	2.82×10^{-5}	2.17×10^{-5}	4.13×10^{-6}	8.04×10^{-6}	8.47×10^{-6}	1.74×10^{-7}
Benzo[*ghi*]perylene	4.37×10^{-6}	3.46×10^{-6}	2.21×10^{-5}	1.70×10^{-5}	3.22×10^{-6}	6.28×10^{-6}	6.62×10^{-6}	1.36×10^{-7}
Indeno[1,2,3-*cd*]pyrene	2.42×10^{-9}	1.92×10^{-9}	1.22×10^{-8}	9.41×10^{-9}	1.79×10^{-9}	3.48×10^{-9}	3.67×10^{-9}	7.53×10^{-11}
Naphthalene	5.82×10^{-3}	4.61×10^{-3}	2.94×10^{-2}	2.26×10^{-2}	4.29×10^{-3}	8.36×10^{-3}	8.81×10^{-3}	1.81×10^{-4}
Dioxins	2.42×10^{-10}	1.92×10^{-10}	1.22×10^{-9}	9.41×10^{-10}	1.79×10^{-10}	3.48×10^{-10}	3.67×10^{-10}	7.53×10^{-12}
NMVOC	2.36	1.87	1.19×10^{1}	9.17	1.74	3.39	3.58	7.33×10^{-2}
Selected as alternative?		-	-	-	-	-	-	

In Figure 6.6, the main emissions of each potential alternative are visualised. It can be seen that (with a minor exception) the highest emission values correspond to those set in the Stage I standard, while the lowest emissions values correspond to the emission reports for the Stage V engine. With the knowledge that use-phase environmental impacts of the system scale with these emissions, these two options are selected as alternatives for the LCA (ICE.I.Diesel and ICE.V.Diesel respectively), providing a range wherein actual emissions for the combustion of diesel lie. Engine producers indicate that engines are designed to perform well below the current standard to ensure their longevity. On the other hand, laboratory measurements are made under ideal conditions that do not reflect real-life usage scenarios.[4]

The studied scenarios project that, over the course of the century, diesel will be gradually replaced by biodiesel or synthetic diesel (see Figure 6.3). This is taken into account in these alternatives, which will use the available diesel mix as a proxy in the LCA model. Concretely, under SSP2 - RCP2.6 (the principal pathway studied), this results in a one-third reduction of fossil-based diesel by 2050, and a full phase-out by 2100. Considering that the non-fossil alternatives are chemically equivalent to the fossil-based fuel, this will not result in any significant change to the discussed emissions. However, the emitted CO_2 will be biogenic, with an equivalent amount of CO_2 having been taken up from the atmosphere in the production chain, and will not count towards the climate change impact category.

Besides biodiesel and synthetic diesel, other biofuels and synthetic fuels such as biomethanol or bio-LNG are often mentioned in inland shipping, decreasing fossil carbon emissions within existing power systems. These are not included in this study due to the limited emission data available for such fuels in inland shipping, while the main downsides (increased water and land use) of such fuels are already covered by the shifting diesel mix for the diesel alternatives.

It should be mentioned that hybrid sailing, where a barge is refitted with an electric motor which is then powered by a diesel generator, is also mentioned as a viable option (van Huizen, 2022). This can also lead to vessels being able to sail on electric batteries for short trips or near populated areas, while still being able to use a fossil fuel to cover long distances or overcome strong currents. The emissions of a diesel generator are similar to those of a diesel ICE, and may be slightly higher due to conversion inefficiencies (EICB & TNO, 2021), or lower due to more flexible and optimised sailing. However, this is considered out of scope for this study, and hybrid power systems are not assessed as a separate alternative.

6.3.2. Selection of hydrogen alternatives

In Chapter 4, various types of hydrogen were described, including grey (natural gas SMR), blue (natural gas SMR with CCS), yellow (grid electricity electrolysis), and green (renewable electricity electrolysis).

Green hydrogen is often mentioned in zero-emission pathways for various sectors. However, renewable electricity is not yet available at the required scale. As of writing, no industrial-scale production of green hydrogen exists in the Netherlands, although various projects are in progress (TNO, 2023). Because of this, only grey, blue, and yellow hydrogen will be considered in this study. However, in the studied future scenarios, the available electricity mix gradually becomes fully renewable. Because of this, in the long term (approaching 2100), the yellow hydrogen alternative is equivalent to green hydrogen.

Hydrogen can be burned as a fuel in diesel ICEs (with some adaptations), or converted into electricity in a hydrogen fuel cell (HFC). The former is more practical, requiring less modifications to existing ships and shipbuilding processes, but still entails some use-phase emissions from combustion. Powering a ship using HFCs and an electric motor has no use-phase emissions whatsoever. Both these options will be considered for each of the three types of hydrogen, resulting in six hydrogen-based alternatives: ICE.V.H_2.Gr, ICE.V.H_2.Bl and ICE.V.H_2.Yl, and HFC.H_2.Gr, HFC.H_2.Bl and HFC.H_2.Yl.

6.3.3. Selection of electricity alternatives

For electricity, only one alternative is considered: electricity from the European electricity grid, stored in lithium-ion batteries and used to power an electric motor (BE). Alongside yellow hydrogen, this alternative is expected to show the strongest variation over the course of the century, based on the projected decarbonisation of the electricity grid mix.

[4]Statements based on personal communication with engine producers and authors of previous research.

7
Inventory analysis

7.1. System boundaries

As is common for LCA studies, a distinction is made between the product system and the environment. All economic activities related to material extraction and processing, barge and energy system production, and wastes (see Section 6.2.3 and Figure 6.5) are considered as part of the product system. Extensions from these activities – release and uptake of chemicals, heat, gases, etc. into or from water or atmosphere – are considered to belong to the environment.

7.2. Flow diagrams

For each studied alternative, a flow diagram depicting the modelled system has been created. The flow diagram for alternative ICE.I.Diesel is shown in Figure 7.1, while the flow diagram for alternative ICE.V.Diesel (adding diesel exhaust fluid) is shown in Figure 7.2. Alternatives ICE.V.H_2.Gr, ICE.V.H_2.Bl and ICE.V.H_2.Yl share the diagram shown in Figure 7.3, with only the hydrogen production process and the label of the functional unit varying across the alternatives. Likewise, alternatives HFC.H_2.Gr, HFC.H_2.Bl and HFC.H_2.Yl are shown in Figure 7.4. Finally, the flow diagram for alternative BE is depicted in Figure 7.5.

How to interpret flow diagrams

The LCA flow diagrams represent the modelled system necessary to provide a reference product. Each box in the chart is a unit process, and each arrow indicates goods or wastes provided by one process to another. In these diagrams, the reference product is provided by the "Freight transport" process on the right of each chart, with the rest of the processes providing economic inputs for, or receiving waste outputs from, this process. Background processes (marked in grey) are sourced from Ecoinvent or Premise databases; the inputs and outputs of these are not included in the diagrams.

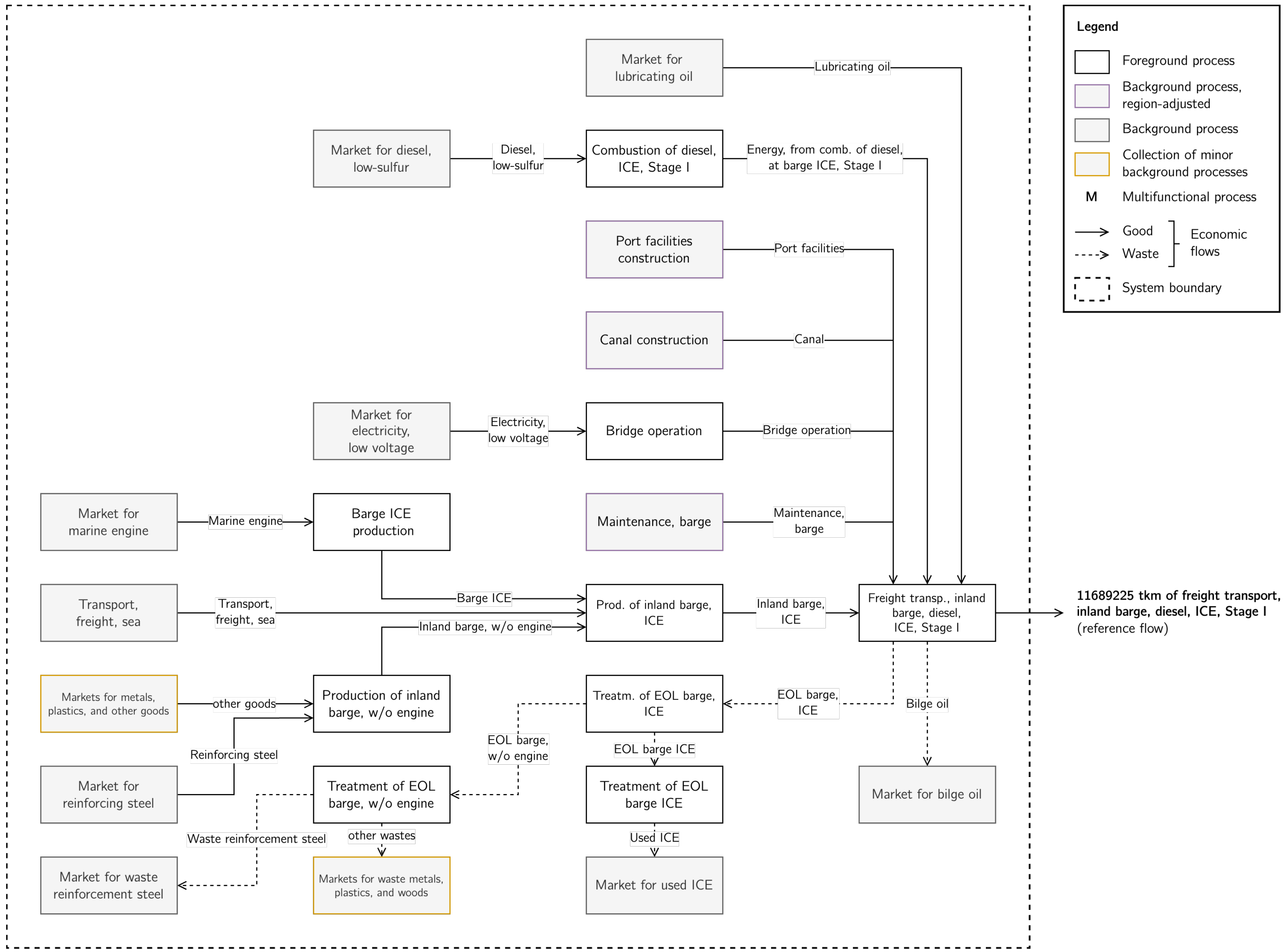


Figure 7.1: Flow diagram of the modelled system for a barge powered by diesel in a Stage I ICE (alternative ICE.I.Diesel).

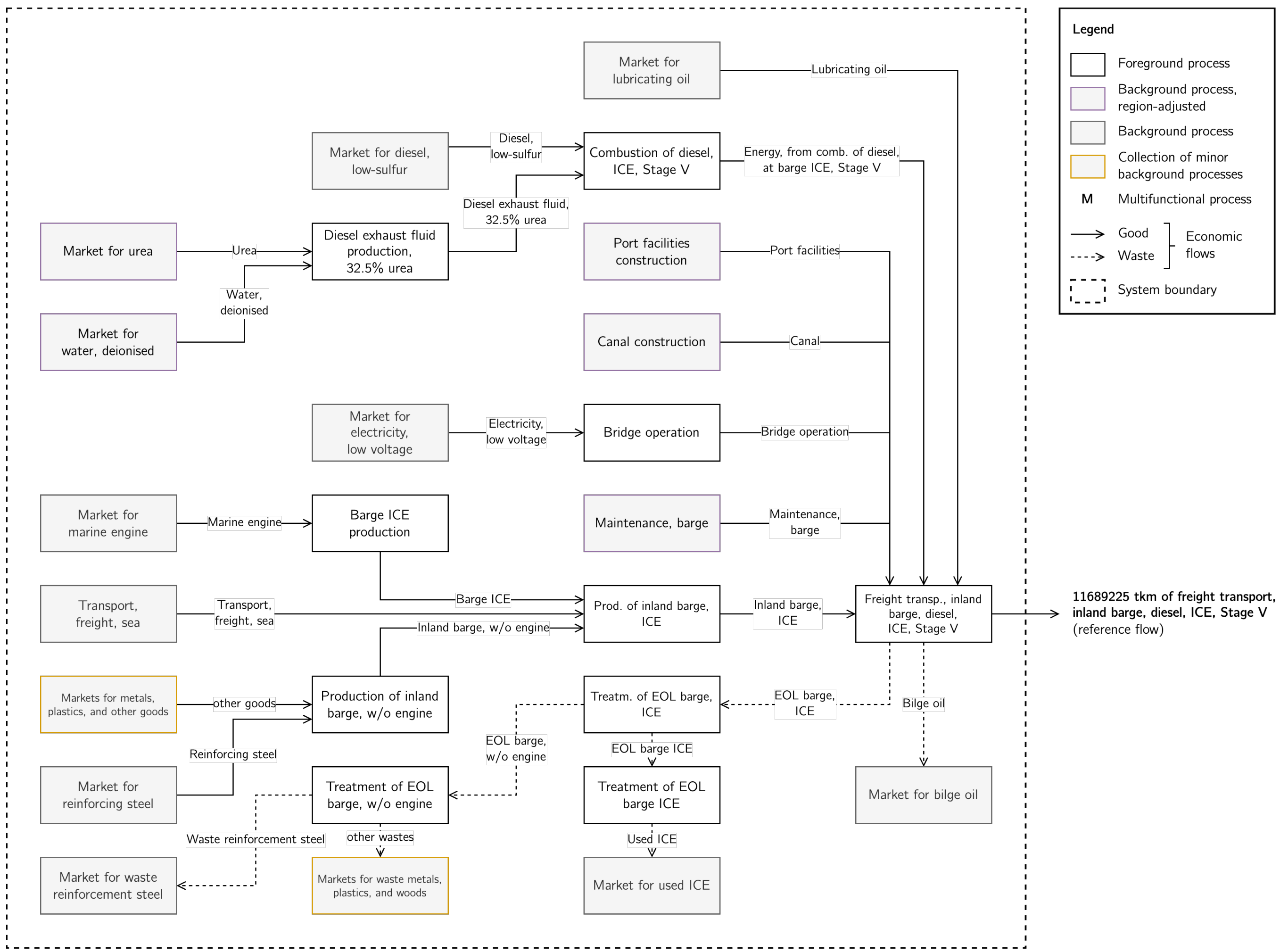


Figure 7.2: Flow diagram of the modelled system for a barge powered by diesel in a Stage V ICE (alternative ICE.V.Diesel). Note the addition of the diesel exhaust fluid (DEF) processes.

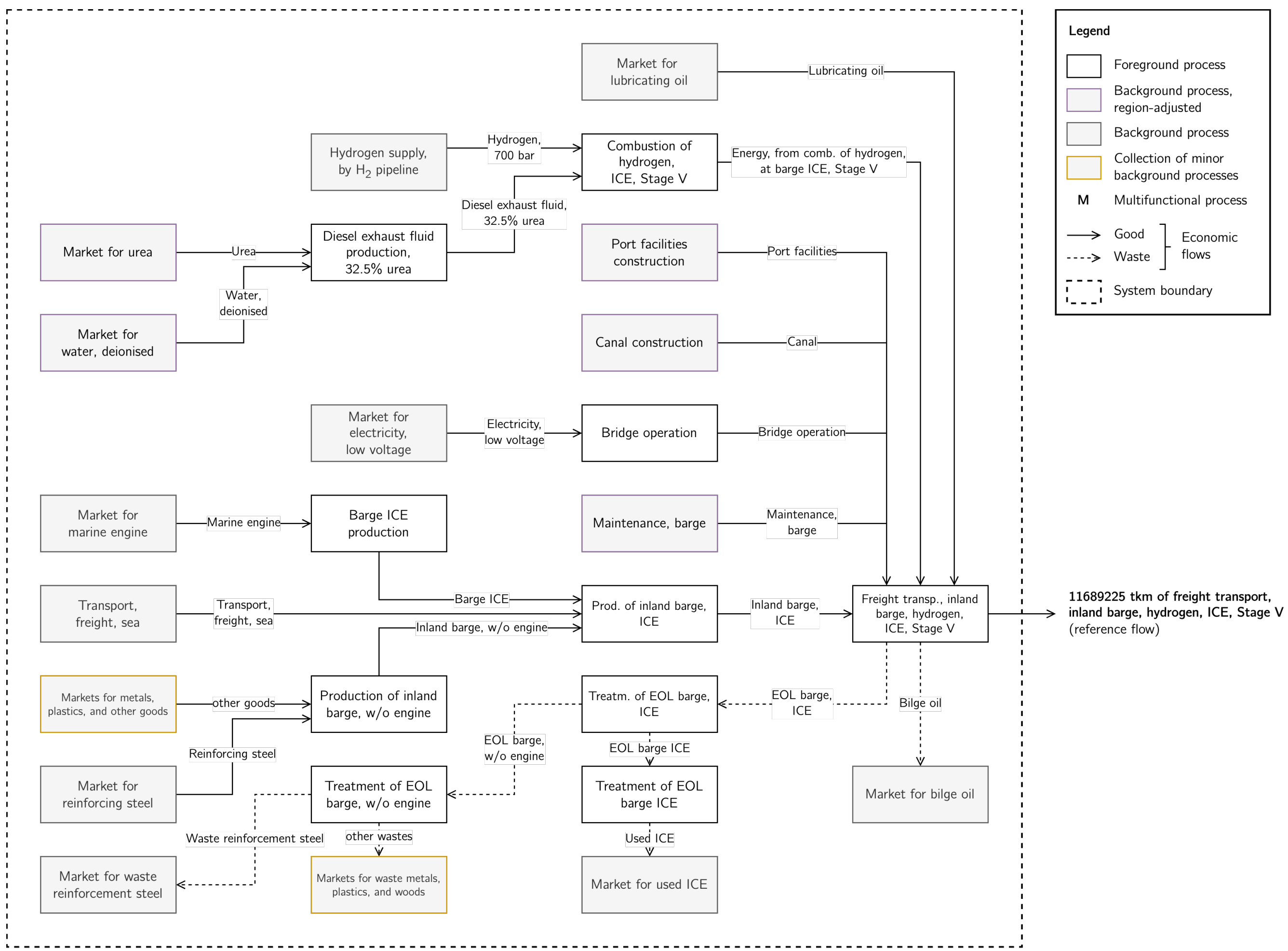


Figure 7.3: Flow diagram of the modelled system for a barge powered by hydrogen in a Stage V ICE (alternatives ICE.V.H_2.Gr, ICE.V.H_2.Bl and ICE.V.H_2.Yl). For each alternative, a different background process is used for the production of hydrogen (see Section 7.3.4).

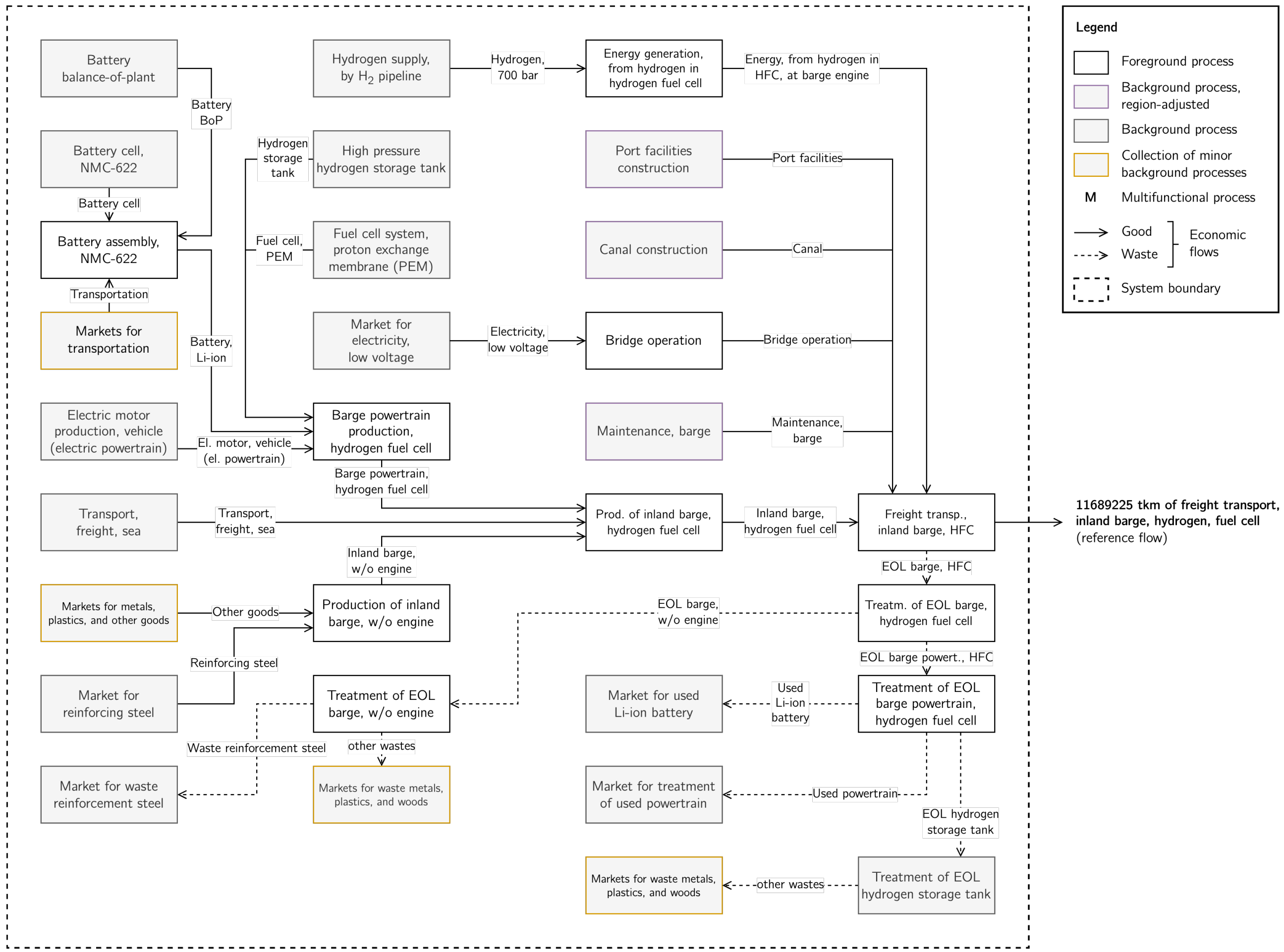


Figure 7.4: Flow diagram of the modelled system for a barge powered by a hydrogen fuel cell (alternatives HFC.H_2.Gr, HFC.H_2.BI and HFC.H_2.YI). For each alternative, a different background process is used for the production of hydrogen (see Section 7.3.4).

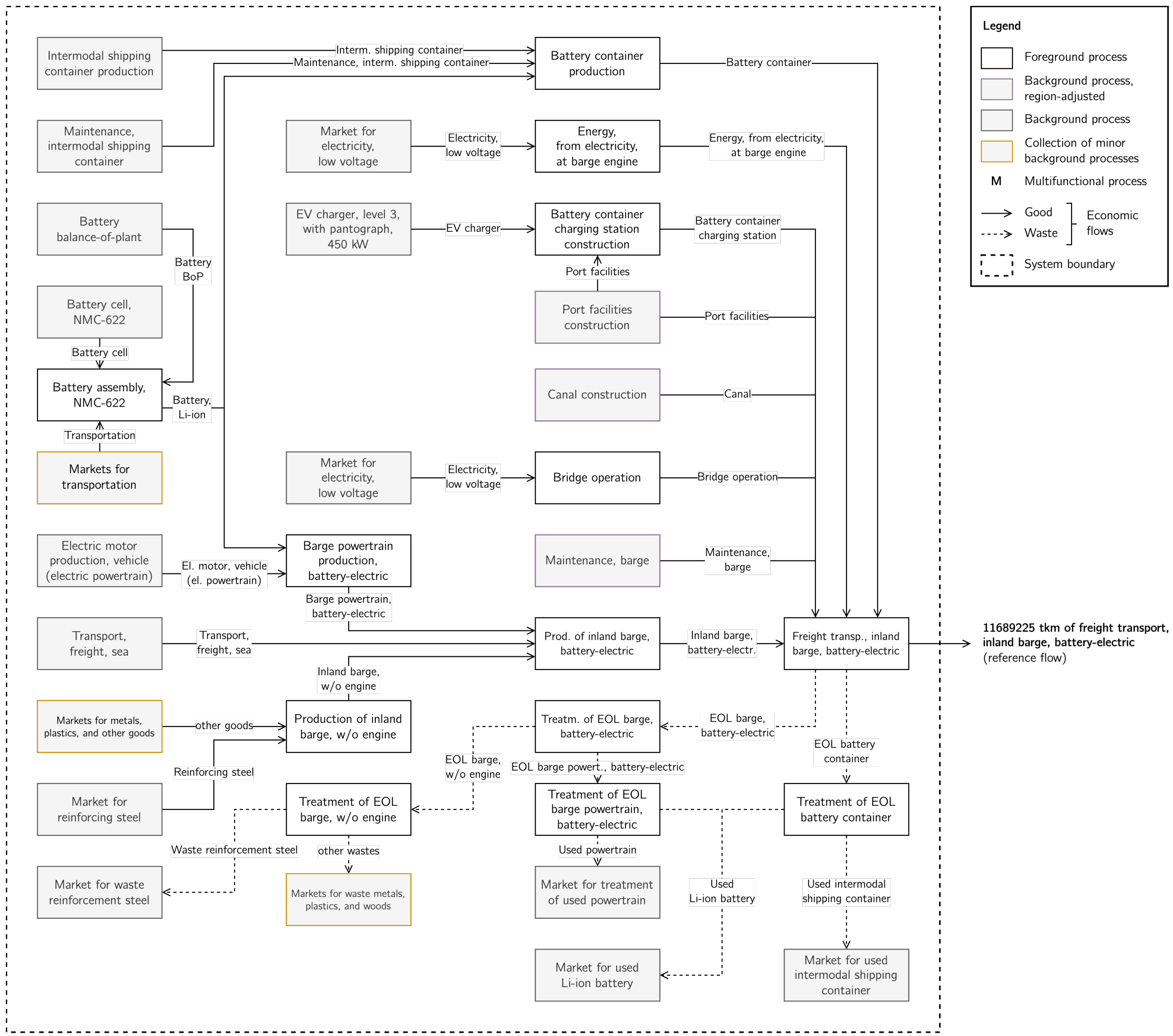


Figure 7.5: Flow diagram of the modelled system for a barge powered by electricity from lithium-ion container batteries (alternative BE).

7.3. Data collection

The system models have been created based on existing literature on inland shipping and information from the Province of South Holland or industry contacts. In this section, the data source for the main foreground processes is listed, grouped by life cycle phase.

A full overview of the unit processes and their corresponding economic and environmental flows, as exported from the Activity Browser, can be found in Appendix B.

7.3.1. Lifespans and efficiencies

In the LCA model, economic flows are rescaled according to their product lifespan. Furthermore, power system inputs and outputs are adjusted according to efficiencies – usually based on tank-to-propeller efficiencies (efficiencies in the energy usage/consumption processes in the operational phase). The most relevant of these lifespans and efficiencies are summarised in Table 7.1 and Table 7.2 respectively, along with the corresponding data sources.

Table 7.1: System component lifespans used in this study.

Component	Lifespan	Source
Barge (excl. engine)	60 y	van Hassel, 2013
ICE (excl. revision)	40 y	STC-Nestra et al., 2015
Electric engine	40 y	*see text*
Electric battery	10 y	ZES, 2021b
Shipping container	15 y	Ecoinvent, 2017
Hydrogen tank	10 y	Knop, 2022
Hydrogen fuel cell	15 y	Ecoinvent, 2017
EV charger	10 y	Sowder, 2023

Table 7.2: On-board energy efficiencies used in this study. For ICE and HFC, this refers to the tank-to-propeller efficiency. For BE, this refers to the grid-to-propeller efficiency.

Alternative	Efficiency	Source
ICE (Stage I, diesel)	36%	Abma and Verbeek, 2017
ICE (Stage V, diesel)	38%	Abma and Verbeek, 2017; Koedood Marine Group, 2022
ICE (Stage V, H_2)	33%	Heid et al., 2021
HFC	44%	Boersema et al., 2023
BE	75%	Albatayneh et al., 2020

7.3.2. Processes common to all alternatives

Barge production

The production of a barge is modelled after the Ecoinvent process "barge production", with various modifications to fit the scope of this study. It has been rescaled to fit the 1727 t load capacity of the *Leendert-Angelina*, and the geographical scope is changed to China (with appropriate inputs), with an extra transoceanic transportation process added for transportation to Europe, representing the transportation of a 298 472 kg barge (based on the background process) over a distance of 22 415 km.

Inland barge lifespans vary significantly, and tend to be longer than the lifespans of marine vessels. An estimated average lifespan of 60 y is used based on the average age of decommissioned barges (van Hassel, 2013), although some barges can last decades more based on usage and maintenance.

End-of-life barge treatment

The barge contents (as modelled in the production process) are separated and treated via market process. Barge deconstruction primarily happens in the Netherlands (even in South Holland specifically), and thus, no transportation input is added. The main waste stream is waste reinforcement steel, the market for which includes a mix of recycling and landfill.

Barge maintenance

Barge maintenance mainly consists of surface stripping and repainting, as well as some minor material replacement. This has been modelled based on the Ecoinvent process "maintenance, container ship", modified to reflect the regional scope of South Holland, where such maintenance would most likely occur for ships sailing on the provincial waters, and rescaled according to load capacity and lifespan.

Provincial bridge operation

The annual electricity expenditure on provincially administrated bridges in South Holland, based on internal data (*verbruiksrapportage*) for 2022, totals 1 094 740 kWh of low-voltage electricty. The share corresponding to one ship's movements is calculated by selecting only the electricity usage of bridges on the Gouwe, the main route of the *Leendert-Angelina* (181 293 kWh), and scaling this according to the fraction of shipping movements of the *Leendert-Angelina* over the Gouwe out of the total estimated ship movements on this waterway (268/21000). This results in 2313.6 kWh on an annual basis.

A second method was considered by adding up the electricity consumption of all provincial bridges, and scaling it by the fraction of total shipping movements of the *Leendert-Angelina* in provincial waterways to the total count of tracked shipping movements in the province. However, this results in a notably larger electricity usage to be attributed to the modelled barge (approximately twice the previously calculated amount). A plausible explanation is the higher prevalence of recreational ship movements on other routes, for which detailed statistics are not available. Thus, the results on the Gouwe are considered to give a better estimate.

Bridge construction is excluded, based on the consideration that bridges are part of road infrastructure. Only their opening and closing is to be attributed to the inland shipping sector.

Shore power

The owner of the *Leendert-Angelina* indicates an average weekly shore power consumption of 180 kWh based on their electricity bills, a number that is consistent with data from other skippers. This results in an additional annual electricity consumption of 9360 kWh.

Waterways

While not relevant for all shipping studies, waterways are relevant for inland shipping in South Holland, where most waterways are either artificial or canalised. The latter applies to the Gouwe, the main route of the modelled barge. The "canal construction" process from Ecoinvent is used (adjusted geographically) and, as with bridge operation, scaled according to ship movement count and as the Gouwe's 14 km length.

Port facilities

As in van der Kruk and Bolech (2022), the Ecoinvent process "port facilities construction" is used, with geographical adjustment. This process is especially useful to this investigation because it is modelled after the Port of Rotterdam, which is located in South Holland. The port construction input is rescaled proportional to the *Leendert-Angelina*'s yearly transport tonnage.

7.3.3. Power system production and decommissioning

Barge ICE production

The current engine of the *Leendert-Angelina* is a Mitsubishi S12R-C2MPTK engine, falling under the Stage II standard. An older equivalent (Stage I) is the S12R-MPTK, while a modern equivalent is the S12R-MPTAW. Online datasheets indicate that each of these engines, in the version delivering the 940 kW of power required for this barge, has a dry mass of 5320 kg (Mitsubishi Heavy Industries, n.d.-a, n.d.-b, n.d.-c). As such, these engines are all modelled based on an average market marine engine (from Ecoinvent), rescaled to this mass.

As with barges, the lifespans of barge engines can be decades, and vary greatly depending on factors such as usage intensity and maintenance. Overall, however, inland barge engines do not last as long as the barges themselves. An estimate of 40 y is used, based on statistics for barges in the size and power range of the *Leendert-Angelina* without the engine undergoing revision (STC-Nestra et al., 2015).

Treatment of barge ICE

An Ecoinvent market process, "market for used internal combustion engine", is used for the disposal of 5320 kg worth of engine. This market process contains an average mix of recycling and landfill processes for an average internal combustion engine.

Battery production and end-of-life

Various powertrain elements described below contain batteries. In this LCA, these are modelled using background processes provided by Premise (Baumstark et al., 2021; Sacchi et al., 2022), which expands the Ecoinvent database with more or more detailed processes for future energy systems, including electric and hydrogen vehicles.

Concretely, a battery assembly made of NMC-622 cells and battery balance-of-plant is used. This type of cell has a high energy density of 0.8 kWh kg^{-1}, making it suitable for EV applications (Tallman et al., 2021), and is used in the Premise processes for EVs. This battery solution, with inventory data sourced from Crenna et al. (2021) and Dai et al. (2019), has higher environmental impacts across all impact categories assessed and are more accurate than the battery inventories present in Ecoinvent (Sacchi et al., 2022). Additional transportation inputs are added to the battery production process to account for transportation to Europe, rescaled from the Ecoinvent market for lithium-ion batteries in the RER region.

High-capacity batteries such as the ones discussed here are expected to retain a significant part of their capacity even after their usable lifespan for EVs have passed. These batteries are good candidates for reuse in other sectors, such as grid balancing (White et al., 2020). ZES also mentions such possibilities for repurposing their EOL battery containers (Zero Emission Services, 2021b) However, the details and possible environmental benefits of these applications remain speculative, and as such all batteries are disposed of via the market for lithium-ion batteries present in Ecoinvent.

Electric powertrain production

The electric powertrain, used for the HFC and BE alternatives, is modelled using the Ecoinvent process "electric motor production, vehicle (electric powertrain)". Although existing ICEs are often overdimensioned for common use, the extra power capacity needs to be available incidentally (e.g. due to load and weather conditions), and so, an electric motor with the same power as the ICE alternative is selected. The mass required for a 940 kW powertrain is 498 kg, based on the Ecoinvent process data.

Due to fully electric barges being a novel development, no concrete statistics are available on the average lifespan of electric motors for inland shipping. The lifespan of 40 y for combustion engines is reused, a conservative estimate considering that an equivalent electric motor is likely to last at least equally long, based on the low maintenance and more simple nature of electric motors (Jerew, 2021).

Furthermore, when sailing with either swappable batteries or fuel cells, an auxiliary power source must be available as a backup solution, e.g. to be able to manoeuvre to a port in case of technical failure or fuel depletion. In either case, this is assumed to be a lithium-ion battery with a 500 kWh capacity (Boersema et al., 2023), produced and disposed of as described above.

The HFC barge model includes three extra components: a PEM fuel cell system capable of supplying 940 kW of power, an intermediate battery, again of 500 kWh capacity, and high pressure storage tanks. The fuel cell is based on the Premise process "fuel cell system, proton exchange membrane (PEM)", multiplied to meet the required power supply and lifespan. The high pressure storage tanks use the Premise process "high pressure hydrogen storage tank" (Wulf et al., 2018). To be equivalent to the battery-electric alternative with two 2563 kWh battery containers, and considering the efficiencies of the two power systems as listed in Table 7.2 as well as an energy density of 5.6 MJ L^{-1} at a common tank pressure of 700 bar (Møller et al., 2017), a capacity of 1930 L of hydrogen is required (77.2 kg, at this pressure).

Treatment of EOL barge powertrain, battery-electric

Modelled using Ecoinvent process "used powertrain from electric passenger car, manual dismantling", with the calculated engine mass of 498 kg. Manual dismantling is an effective and even profitable way to treat engines (Saidani et al., 2020). The end-of-life batteries are disposed of via the Ecoinvent "market for used Li-ion battery", as previously described.

For the HFC alternatives, end-of-life fuel cells and storage tanks are disposed of via market waste treatment processes for their constituent materials.

Battery container production

The battery-electric alternative is modelled after the concept of Zero Emission Services (ZES), a company aiming at providing a service of barge batteries in containers, which can be loaded and unloaded alongside cargo and charged in a network of charging stations (Zero Emission Services, 2021a).

Each battery container has a capacity of up to 2563 kWh (van der Geest et al., 2023), modelled as 22 482.46 kg of lithium ion battery, modelled as a NMC-622 battery as previously described. The shipping container itself also requires production and maintenance, sourced from Ecoinvent market processes "intermodal shipping container, 40-foot" and "maintenance, intermodal shipping container, 40-foot".

According to the ambition of ZES, rolling out this system across the inland shipping sector of the Netherlands will see 650 battery containers in use by 400 vessels in the year 2050, resulting in 1.625 battery containers per vessel. According to van der Geest et al. (2023), the 95th-percentile energy demand of the *Leendert-Angelina* (that is, the energy demand covering 95% of its trips) slightly exceeds the 2563 kWh capacity of a single container. Furthermore, to maximise the useful lifespan of batteries, a certain overcapacity should be available, in order to avoid fully charging and discharging each battery on every trip. To reflect these points, it is considered that the operations of the modelled barge require 2 battery containers on board at all times. As has been mentioned previously in this report, this may change with future advancements in battery technology, which are not considered within the scope of this study.

Treatment of EOL battery container

As for the equivalent production process, market processes are used for waste treatment: "market for used Li-ion battery" for the battery component, and "market for used intermodal shipping container, 40-foot" for the container.

7.3.4. Fuel production, transportation, and wastes

Production of diesel

The market process for "diesel, low sulphur" is used as a basis for the diesel fuel supply. In the scenarios studied, the composition of this good changes over time, starting out as (nearly) entirely fossil-based diesel, which gives way to biodiesel and synthetic diesel (see Figure 6.3). The underlying processes for these non-fossil alternatives are "biodiesel production, via transesterification, from rapeseed oil, energy allocation" (Cozzolino, 2018) and "diesel production, synthetic, Fischer Tropsch process, hydrogen from wood gasification, energy allocation" (van der Giesen et al., 2014), provided via Premise.

Production of hydrogen

The datasets provided by Premise also include a wide array of hydrogen production processes. The following three processes are used in the hydrogen alternatives:

ICE.V.H_2.Gr	HFC.H_2.Gr	hydrogen production, steam methane reforming of natural gas
ICE.V.H_2.Bl	HFC.H_2.Bl	hydrogen production, steam methane reforming of natural gas, with CCS
ICE.V.H_2.Yl	HFC.H_2.Yl	hydrogen production, gaseous, from PEM electrolysis, from grid electricity

Hydrogen is produced at comparatively low pressures, but must be brought up to 700 bar for usage in the modelled system. Furthermore, transportation and intermediate storage of hydrogen, which also account for resource use and efficiency losses, are processes that must not be discounted. For distances up to 2500 km, transporting hydrogen as compressed gas via pipelines or tanker ship "appears to be the cheapest option" (Ortiz-Cebolla et al., 2021). Hydrogen pipelines are similar to those already in place for the transportation of natural gas, although they may require improved protection to avoid material degradation and hydrogen leaks (US Department of Energy, n.d.-a).

The Premise datasets also include hydrogen supply processes, which include pressurisation to 700 bar, storage and 500 km of transportation by pipeline, ship, or truck (liquid or gaseous). For each type of hydrogen, a variant transported by hydrogen pipeline is used. The included range of 500 km may be an overestimation if all hydrogen is to be produced within South Holland, but an appropriate assumption when looking at potential hydrogen clusters elsewhere in the Netherlands or Northwestern Europe. The used production processes also have Europe as their geographical scope.

Diesel exhaust fluid production

The modelled Stage V engine reduces NO_x emissions via selective catalytic reduction (SCR), using diesel exhaust fluid (DEF), a solution of 32.5% urea and deionised water, at a rate of 76.7 kg of DEF per 1000 kg of fuel (Koedood Marine Group, 2022; Ruers & van Schaijk, 2021).[1] The production of DEF is modelled using urea and deionised water inputs from Ecoinvent market processes. Any other energy or material flows in this process are likely to be negligible and are not included.

For the hydrogen combustion alternatives, exhaust treatment with such a solution remains necessary to reduce NO_x emissions remains a necessity. Literature indicates that potential technological development may either improve efficiency (Walter et al., 2023) or remove the need for an urea solution altogether by injecting hydrogen in SCR system instead (Sterlepper et al., 2021). However, these developments appear to be in an early phase and no specifics relevant for the studied engines appear to be available. As such, in the modelled system, the same input of urea-based DEF is used for hydrogen combustion as for diesel combustion (scaled according to the fuels' energy content).

Lubricating and bilge oil

The barge ICE has a secondary input in the form of lubricating oil, as well as a bilge oil waste stream. The input stream is based on estimates from the *Leendert-Angelina*'s owner of 1000 L of *15W40* lubrication oil of density 887 $kg\,m^{-3}$ (Total Lubricants, 2019) per year, modelled as "lubricating oil" from an Ecoinvent market process. The bilge oil waste output is modelled as in the Ecoinvent process "transport, freight, inland waterways, barge", rescaled to the functional unit.

Battery container charging station construction

In the battery-electric alternative, no fuel input is needed, as the battery containers are charged directly from the electricity grid. However, this requires an extra piece of infrastructure: a battery container charging station requires, which includes not only an electricity connection, but also loading and unloading of the containers and physical space at a dock or port.

The charging stations are modelled using the same background process as the port facilities (the primary environmental impacts of which come from electricity in loading and unloading), scaled down by the amount of battery containers (2) out of the total container capacity of the modelled barge (45). Furthermore, the electricity connection and charger are modelled using the Premise process "EV charger, level 3, with pantograph, 450 kW" as a proxy, scaled according to its expected lifespan (approximately 10 years, according to a blog entry by Sowder (2023), although data is scarce) and the projections for the charging network given by ZES (Zero Emission Services, 2021a).

7.3.5. Operational phase and fuel combustion

Combustion of diesel

The diesel combustion process has an input of 1 t diesel, for which "market for diesel, low-sulfur" is used as a proxy . Environmental flows are set according to the emission data given in Table 6.3. The emissions of CO_2 are shifted from fossil to non-fossil, following the fuel proportions provided in the used scenarios.

Diesel is taken to have a lower heating value (LHV) of 42.8 $MJ\,kg^{-1}$, but the delivered energy is significantly less due to the relatively low efficiency of an ICE drivetrain (Table 7.2). Literature data on average ship engine efficiencies is lacking, and when quantitative efficiencies are mentioned they tend to vary from source to source, likely in part due to the energy consumption varying according to sailing conditions and techniques. In this report, the research performed by Abma and Verbeek (2017) is used as a source for diesel

[1] The additional waste stream is considered accounted for in the waste oil flow, and is not modelled separately, due to the predicted very minor contribution of waste oil treatment to the overall environmental impacts.

engine efficiencies, yielding an approximate 36% efficiency (combined diesel engine and gearbox) for speeds above 6 $km\,h^{-1}$. A Stage V engine is considered to be slightly more efficient, based on manufacturers' claims of up to 5% decreased fuel consumption (Koedood Marine Group, 2022). Hull and propeller efficiencies are not taken into account, as these apply to each alternative in a similar fashion.

Combustion of hydrogen

The basic reaction of hydrogen combustion (Burheim, 2017) is given by Equation 7.1.

$$H_{2(g)} + \frac{1}{2}O_{2(g)} \longrightarrow H_2O_{(g)} \tag{7.1}$$

In this theoretical reaction, the only material output is water vapour H_2O, at 1 mol H_2O per 1 mol H_2, or 8.94 kg H_2O per 1.00 kg H_2, alongside an uptake of 7.94 kg of O_2 from the environment (Wolfram, 2022). This reaction is modelled in a unit process, with hydrogen input as an economic flow from the hydrogen production and transportation processes described above, and the oxygen and water vapour as environmental flows from or to the atmosphere.

As hydrogen does not contain any carbon, its combustion does not emit any CO_2 or CO. However, due to the high combustion temperature and the gas mixture of the atmosphere, other emissions are produced, namely of nitrogen oxides. Inventories also indicate minor emissions of particulate matters and hydrocarbon. No data on hydrogen combustion in inland shipping barge engines appears to be available; however, LCI data for hydrogen ICE trucks are available alongside diesel ICE trucks in the 2022 release of the GREET model (Burnham et al., 2006). The emissions for a hydrogen ICE truck from this model are used, scaled to reflect the nature of a barge engine by using the proportion of the GREET diesel truck data to the used Stage V barge engine data. The included emissions are depicted in Table 7.3.

Table 7.3: Environmental flows for the hydrogen combustion process in a Stage V ICE, given in g emission per kg fuel.

Emission	ICE.V.H_2
Water	8.94×10^3
Nitrogen dioxide	4.49×10^1
Particulate matter	1.61×10^{-2}
Dinitrogen monoxide	1.30
Hydrocarbons	1.97×10^{-2}
Methane	1.36×10^{-4}
NMVOC	1.96×10^{-2}

The LHV of hydrogen is 120 $MJ\,kg^{-1}$ ($\sim$33.33 $kWh\,kg^{-1}$) (Møller et al., 2017), although the energy outputted to the barge propeller is lower due to the engine's efficiency. Although no data on hydrogen ICEs for inland barges appears to be available, data for truck engines – which are similar in properties to inland barge engines – indicates that as of present hydrogen ICEs are less efficient than equivalent diesel-powered engines (Heid et al., 2021; Table 7.2).

Energy, from hydrogen fuel cell

The basic reaction taking place in a hydrogen fuel cell is the one already discussed, given in Equation 7.1 (Burheim, 2017). Unlike for the combustion of hydrogen, no other emissions take place in this process. As such, a unit process with the only these environmental flows (as before, with hydrogen input as an economic flow, and the oxygen and water vapour as environmental flows from or to the atmosphere) is sufficient.

The LHV of hydrogen is again used as energy output. The total tank-to-wake efficiency of a fuel cell in an inland barge is estimated to be 44% (Boersema et al., 2023), which is higher than a hydrogen combustion engine.

Energy, from electricity

An electricity input from the European electricity market background process is used, reduced taking into account the inefficiencies in electricity conversion, battery charging and discharging, and an electric vehicle engine, resulting in an average grid-to-propeller efficiency of 75% (Albatayneh et al., 2020; Apostolaki-Iosifidou et al., 2017). However, it should be considered the possible overall efficiency range is large, as is the case for ICEs.

7.4. Inventory table

The full inventory table can be see in Appendix B.

A total of 2448 different environmental flows exist across the modelled alternatives, representing 909 unique flows (split into different environmental compartments). In the selected EF v3.1 impact family, a majority of these have characterisation factors, but 533 flows (270 unique) are uncharacterised. Most of the flows without characterisation factors are only found in trace amounts, are renewable natural resources such as solar energy or kinetic energy from wind, or are inert substances that do not pose any meaningful environmental impact. Some of these flows, however, must be highlighted:

- Water uptake and emissions, relevant for calculating the impact on water consumption especially in the case of hydrogen production, appears to lack characterisation factors unless explicitly emitted into air.
- Emissions of hydrogen into air do not have characterisation factors for climate change, despite being an indirect greenhouse gas (Sand et al., 2023) and there being upwards of 1900 kg of hydrogen gas emitted in the hydrogen alternatives.
- Emissions of water vapour into air do not have characterisation factors for climate change either, despite being a greenhouse gas. In this case, this is an acceptable simplification due to the short persistence of near-surface water vapour emissions, resulting in a low global warming potential (Sherwood et al., 2018).
- Emissions of NO_2 are not characterised in the relevant impact categories, despite it being a nitrogen oxide affecting e.g. acidification and photochemical oxidant formation. Instead, charaterisation factors are included for the generic emission of NO_x. To account for this, a flow of NO_x is used to represent the NO_2 emissions from the combustion processes.

The implications of the missing characterisation factors for water uptake and emission (water use) for hydrogen emissions (climate change) will be discussed in the next chapter, following the impact assessment.

8

Impact assessment

The environmental impacts of the modelled alternatives are obtained via a full impact assessment, using the EF v3.1 assessment family (European Commission, 2022). This impact family, present with characterisation factors in the default data of the Activity Browser, has been selected based on its wide range of impact categories, it having been updated recently, and it being authored by the European Commission, fitting a project with a scope within Europe.

In an impact assessment, each environmental flow embodied in a model is characterised, meaning that it is assigned to a specific impact category in the selected assessment family, according to its characterisation factor. Each impact category has a category indicator, which is a physical magnitude indicating the impact under consideration.

In this chapter, the characterisation results for a set of the most relevant impact categories are given, followed by a normalised version. A short discussion is dedicated to the potential impact of environmental flows without characterisation factors as well as cut-off economic flows.

8.1. Characterisation results

In this report, eight impact categories will be discussed in detail, based on their level of interest (e.g. showing important differences between the different impact categories), as well as relevance to the inland shipping sector and the environmental priorities of the Province of South Holland.

Figure 8.1 contains a visualisation of the characterisation results, each graph representing a different impact category, with each bar representing the environmental impact of a given alternative in a given year. The bars within each chart are grouped by the corresponding alternative. Figure 8.2 contains the same results, with the bars within each chart grouped by the corresponding year.

> **How to interpret characterisation results**
>
> The characterisation results consist of one chart per impact category. For each impact category, the bars indicate how much impact a given alternative entails at a given point in time, for the described functional unit (providing the annual transportation of the *Leendert-Angelina*). The bars for each alternative have a different fill colour or pattern; those for each subsequent year has a lighter shade.
> In this report, characterisation results are given on two pages. On the left page, the characterisation results within each chart are sorted by alternative, allowing to compare the progress of each technology over time. The right page contains the same results, sorted by year, allowing to contrast the different technologies at each point in time.

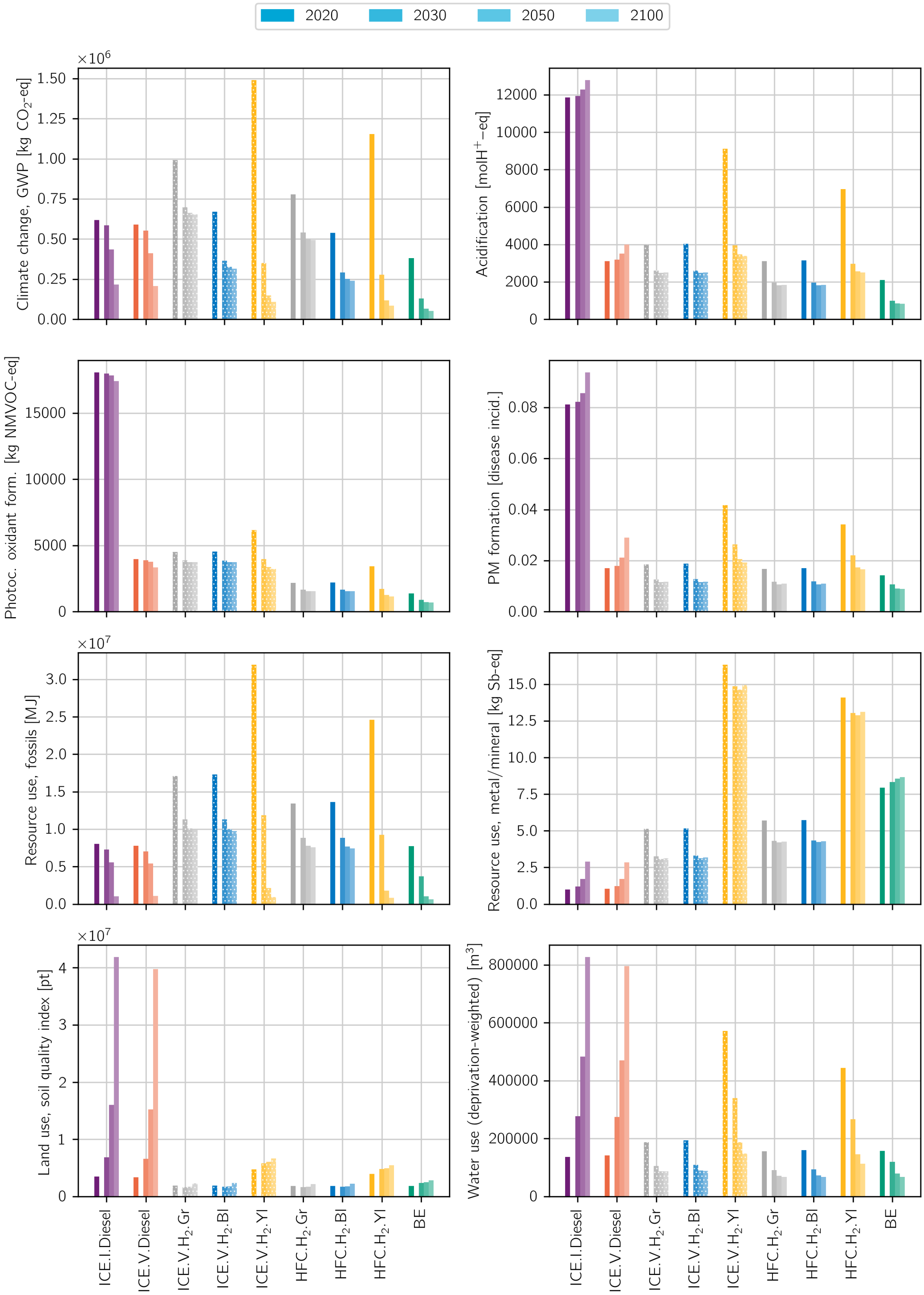


Figure 8.1: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category. Results grouped by alternative.

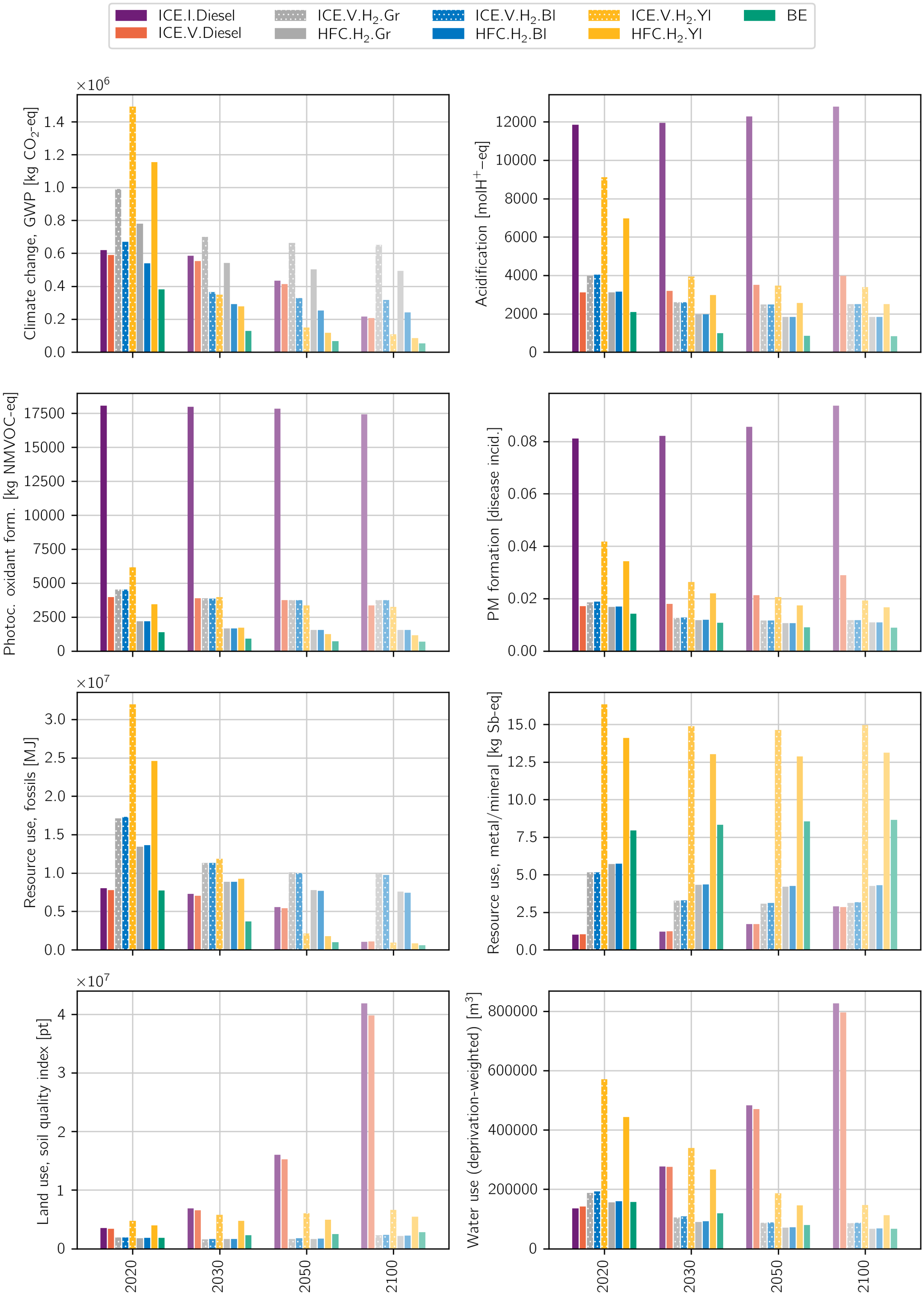


Figure 8.2: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category. Results grouped by year.

Interactive characterisation results

An online, interactive version of the characterisation results can be found in the web application *LCA Viewer* (https://qlcav.quan.cat/?project=inlandshipping), including all three scenarios, normalisation, and the possibility to filter on the desired impact categories, alternatives, and years. More information about this online tool, developed specifically for this thesis, can be found in Appendix C.

The characterisation results provide an initial overview of how the different alternatives compare to each other and how they evolve over time in the selected scenario. The following paragraphs will detail an overview of some of these observations.

For all alternatives, environmental impacts in **climate change** and **fossil resource use** (which is strongly linked to climate change) are projected to decrease over time. The battery-electric alternative consistently has the lowest climate change impact, while the order of the other alternatives varies over time: while initially yellow hydrogen has the highest environmental impact, it drops to have the second-lowest climate change impact over time, as the electricity mix decarbonises. The observation that the climate change impacts from yellow hydrogen are consistently higher than those of electric batteries, while indirectly using the same energy source, is consistent with the fact that the production of yellow hydrogen is less than half as efficient as using electricity directly. For yellow hydrogen, this electricity is first used to produce hydrogen fuel, which is stored and transported before it is used to again produce electricity, with losses and inefficiencies along the chain (European Commission, Joint Research Centre & Moirangthem, 2016).

The impact of the diesel alternatives also decreases over time due to the introduction of non-fossil diesel substitutes, although it does not outperform a yellow hydrogen or battery-electric solution in the long term. Grey hydrogen consistently has a larger impact than diesel, while the impact of blue hydrogen is slightly lower (similar to diesel in 2020, lower than diesel in 2030 and 2050, higher than diesel in 2100). Finally, a hydrogen fuel cell solution consistently outperforms a hydrogen ICE solution by a small margin.

For the different forms of local environmental pollution (**acidification**, **photochemical oxidant formation**, and **PM formation**), the results are different in various aspects. The main observable difference is the much larger impact of diesel in the older Stage I engine, which has higher overall emissions. While the novel alternatives' impacts decrease over time, the PM formation impacts of diesel increase, likely due to emissions in the diesel substitute production chain. For these three impact categories, battery-electric remains the alternative with lowest environmental impact. While for climate change yellow hydrogen had the second-best score, in these impact categories it is slightly outperformed by blue hydrogen. As before, a HFC solution slightly but consistently outperforms a hydrogen ICE solution.

In **resource use of metals and minerals**, the novel alternatives have significantly more environmental impact than diesel – especially yellow hydrogen (HFC or ICE), followed by BE. The impacts of diesel increase over time, likely due to the additional materials needed for the diesel substitute production chain, but remain lower than those of the other alternatives.

In terms of **land use** and **water use**, the diesel alternatives start off with low impacts, but these sharply increase over time. By 2100, the land and water use of diesel (or rather, the biodiesel and synthetic diesel in the diesel mix) overshadow all other alternatives. Among these other alternatives, yellow hydrogen has the highest environmental impacts, although this difference decreases over time.

8.2. Normalisation results

By dividing each impact category's results by the annual worldwide per-capita environmental impact in that category (European Commission, Joint Research Centre, 2023), normalisation results are obtained. These make it possible to contrast environmental impact across all alternatives. Figure 8.3 and Figure 8.4 contain the normalisation results (again grouped by alternative and by year, respectively). Figure 8.5 and Figure 8.6 contain the same results, with the *y* axis of the charts zoomed in to the lowest segment, making it possible to compare some of the lower-scoring environmental impacts.

How to interpret normalisation results

LCA characterisation results cannot be directly compared across impact categories, as they are different magnitudes with different units.
The normalisation results are based on the characterisation results, normalised against category totals for each impact category – in this case, annual worldwide per-capita environmental impact in that category. This makes it possible to compare the impact results in different impact categories to each other, and see which impact categories are more and less impacted by the studied alternatives.
Note that, while these values now share the same unit, this does not mean that the different categories can be summed together further, as they still represent different types of impact which are not necessarily comparable or equally weighted.
The *y* axes of the normalisation charts indicate multiples of the per-capita environmental impact. As a concrete example: the first bar in the first chart of Figure 8.3 indicates that, on an annual basis, the operations of an inland barge with a Stage I ICE fuelled by diesel emit as much CO_2 as 80 (global average) persons, and so forth.
In this report, the normalisation results are given in the same layout and format as the characterisation results.

Interactive normalisation results

In the online *LCA Viewer* (https://qlcav.quan.cat/?project=inlandshipping; Appendix C), the normalisation results can be viewed by turning on the Normalise toggle. The Zoom in toggle can be used to zoom in all *y* axes to the lowest segment and compare the lower-scoring alternatives.

Comparing the different impact categories in the normalisation results, it can be seen that resource use of fossils and metals/minerals score quite high, followed by climate change, photochemical oxidant formation, acidification, and PM formation. In the latter three, it is ICE.I.Diesel that stands out in particular.

Impacts to land use and water use are small in comparison – except for those of the diesel alternatives in the future, when the diesel mix consists mainly of biodiesel and synthetic diesel. In Chapter 10, these will be contrasted with the total freshwater consumption and land available in South Holland and the Netherlands.

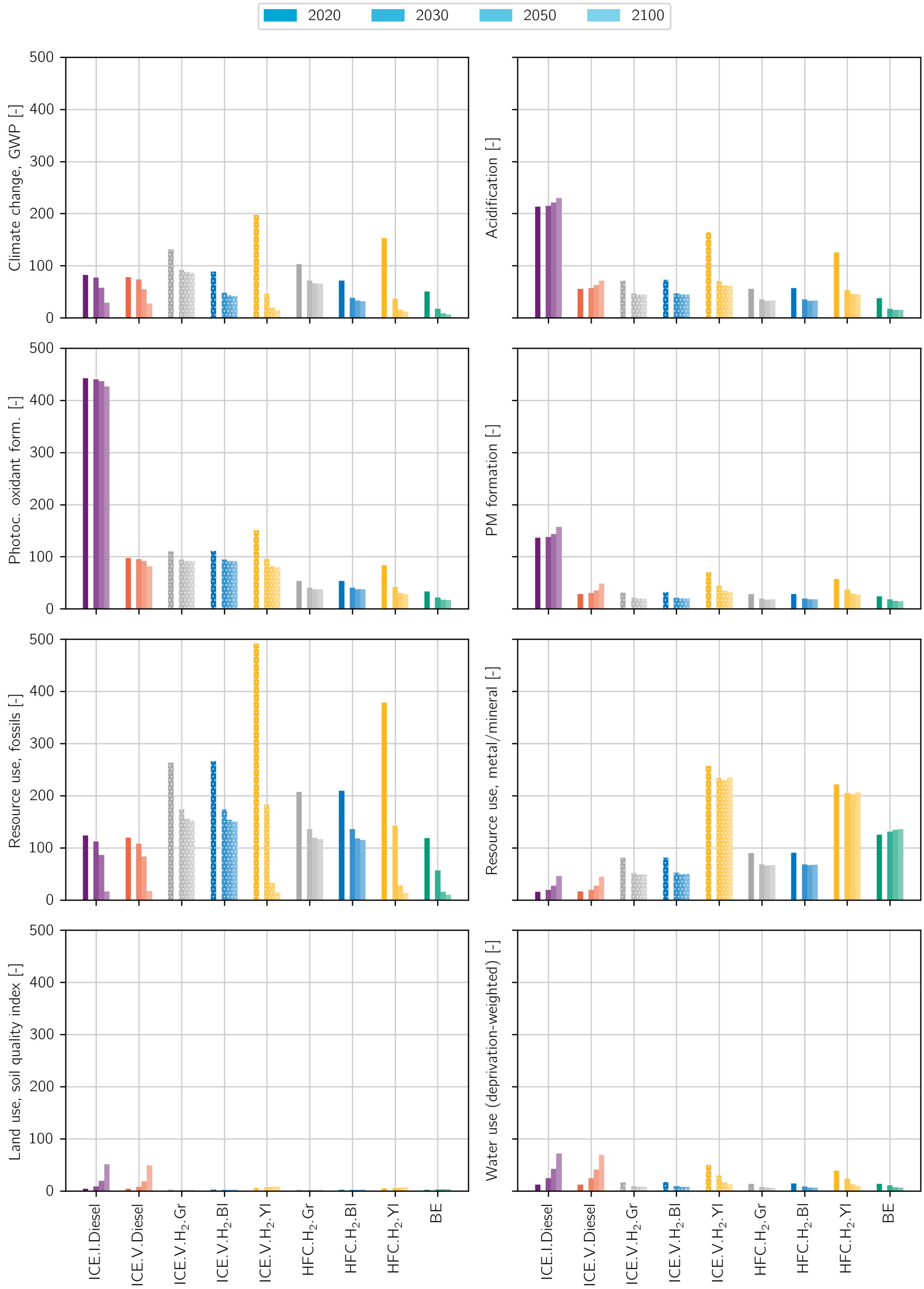


Figure 8.3: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category, normalised against annual per-capita impacts in 2010. Results grouped by alternative.

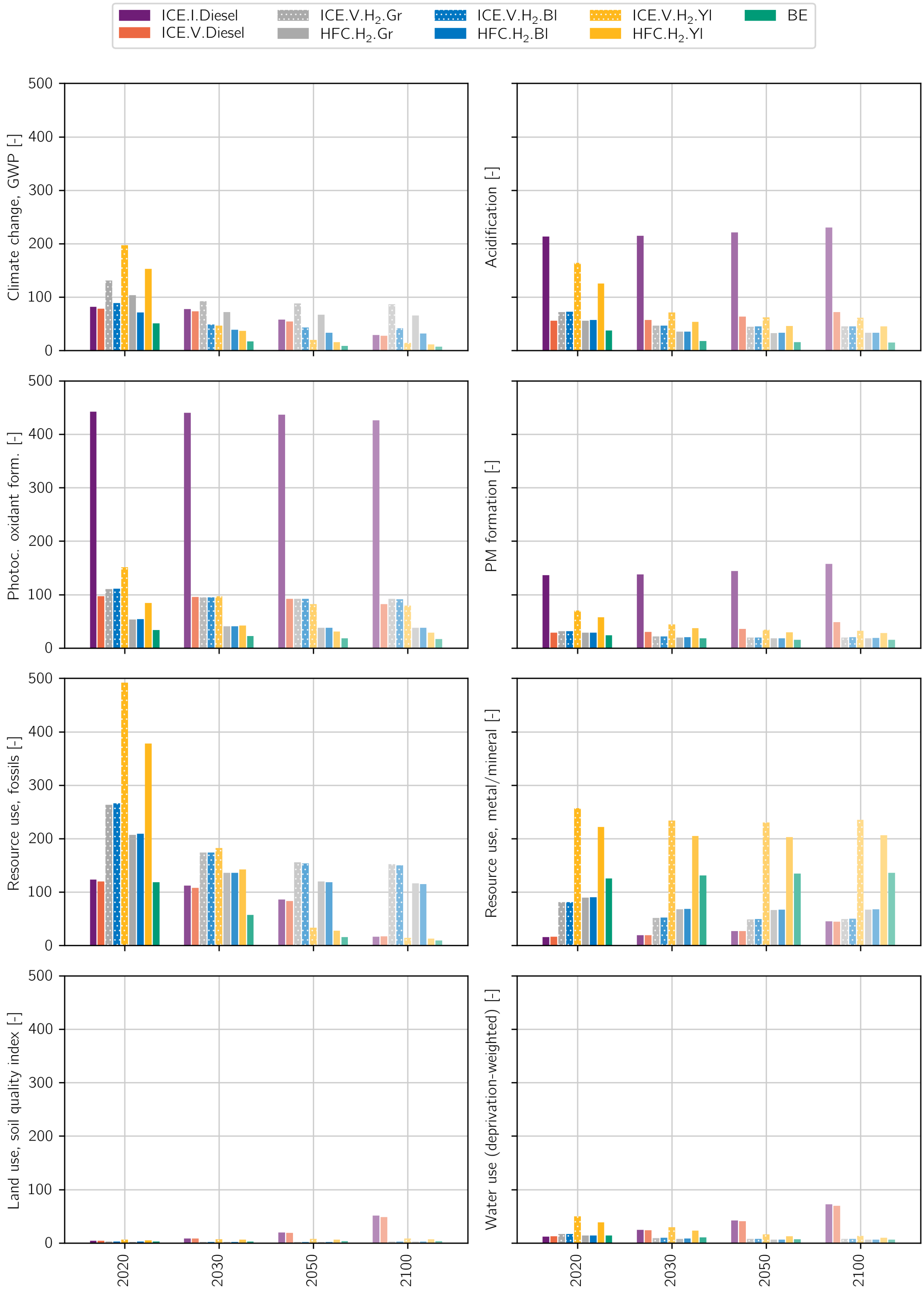


Figure 8.4: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category, normalised against annual per-capita impacts in 2010. Results grouped by year.

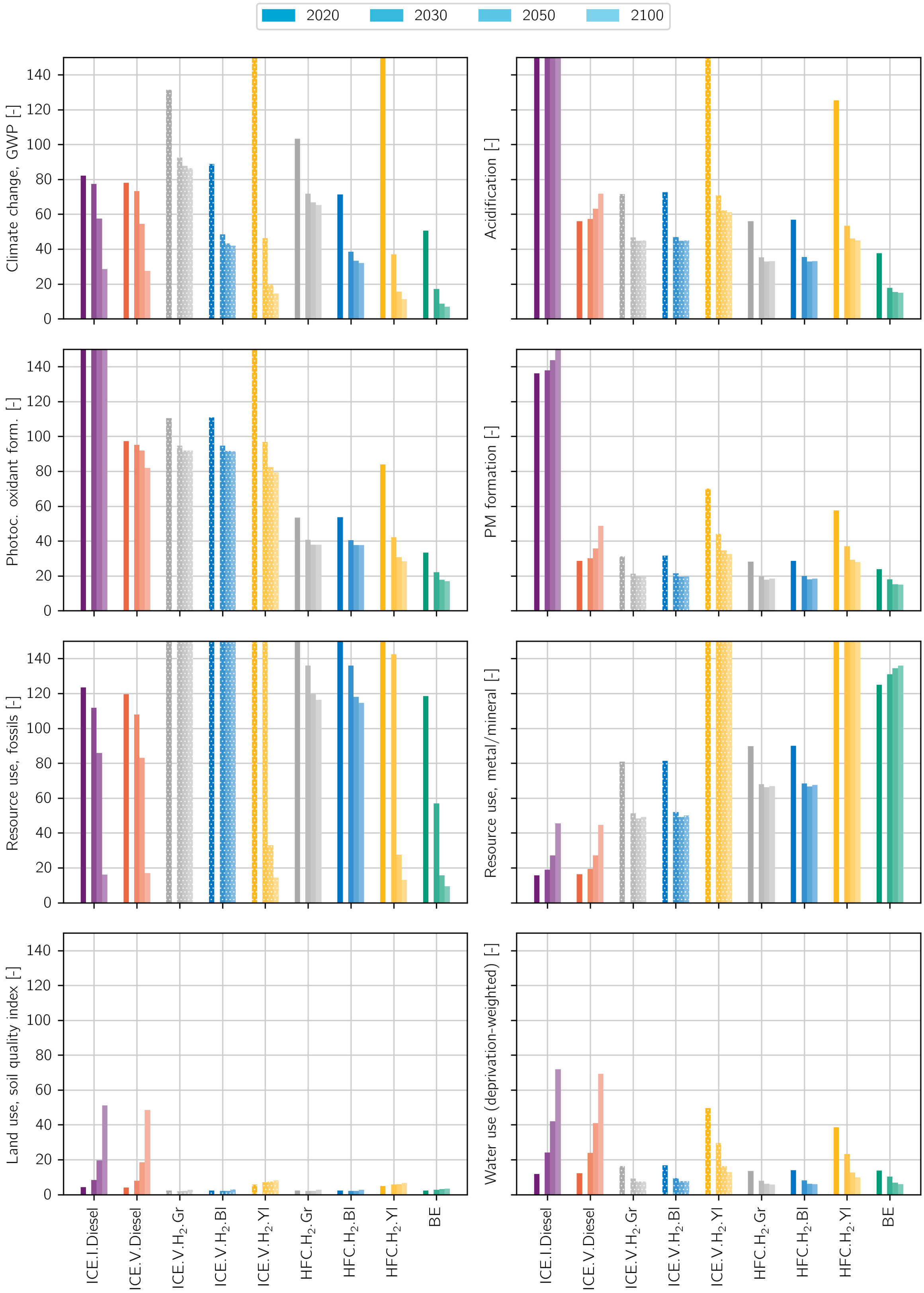


Figure 8.5: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category, normalised against annual per-capita impacts in 2010. Results grouped by alternative. *y* axis zoomed in and cut off.

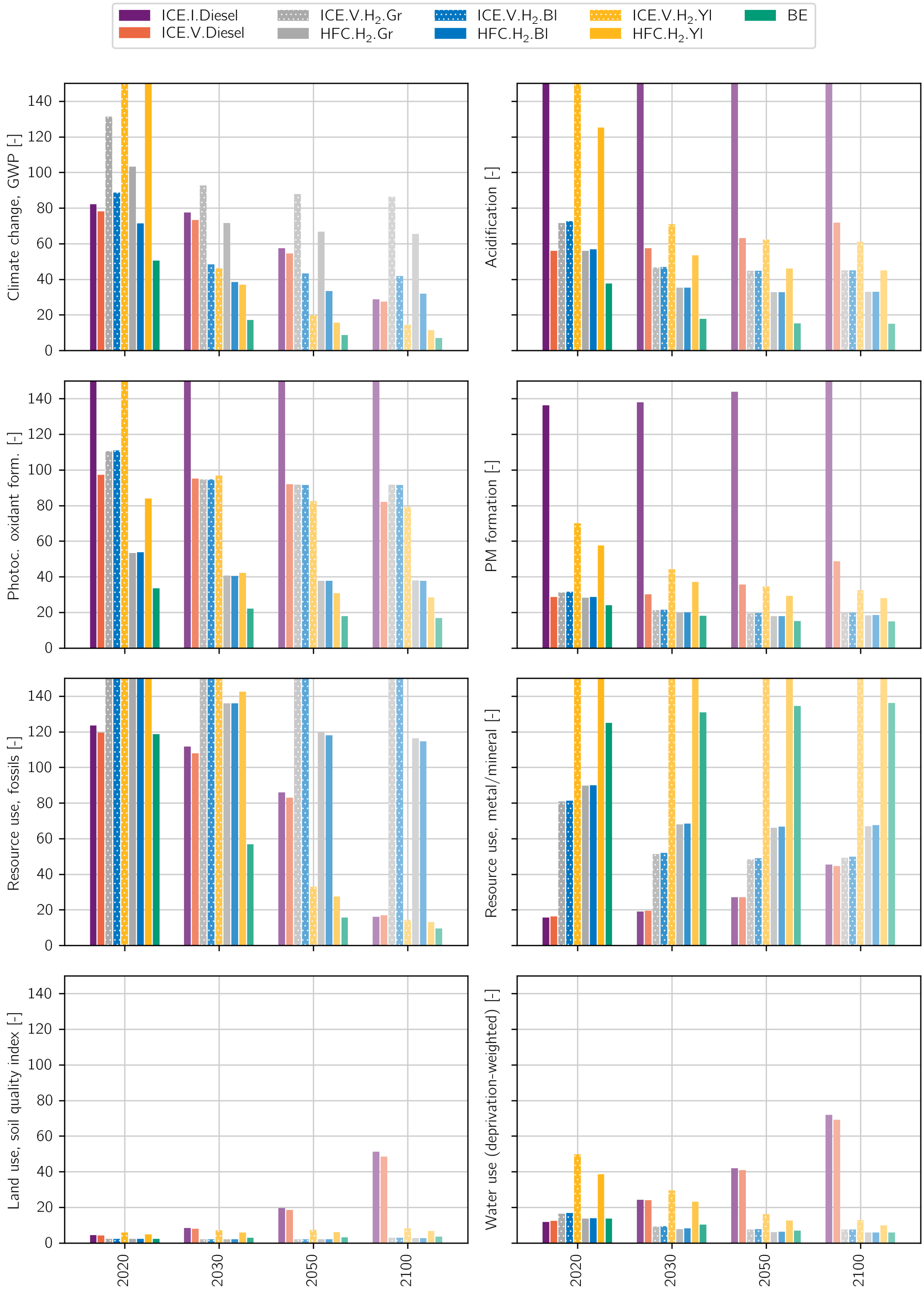


Figure 8.6: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category, normalised against annual per-capita impacts in 2010. Results grouped by year. y axis zoomed in and cut off.

8.3. Environmental flows for which characterisation factors are lacking

As mentioned in Section 7.4, there are two types of uncharacterised flows that need further analysis.

8.3.1. Emissions of hydrogen into air

In the modelled product systems, hydrogen is used as a fuel. However, production, transportation and storage processes in the hydrogen-fuelled alternatives are responsible for the emission or leakage of 1936.4 kg to 2978.3 kg of H_2 gas into air. Recent research by Sand et al. (2023) estimates hydrogen to have a global warming potential (GWP) of 11.6 kg CO_2–eq.

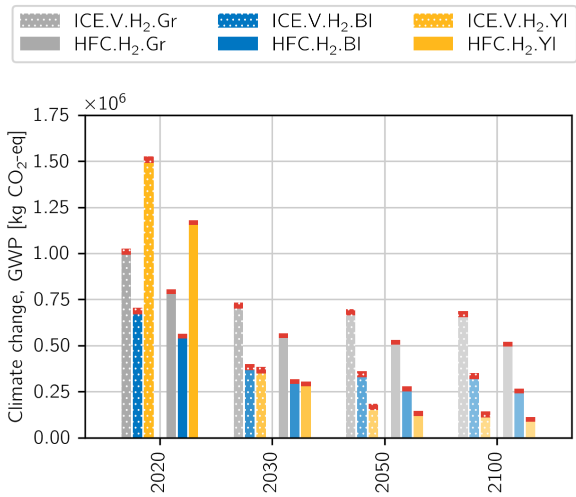


Figure 8.7: Climate change (GWP) characterisation results in the SSP2-RCP2.6 scenario. In red, the additional impact due to emissions of H_2 gas.

Repeating the performed assessment with a modified version of the EF v3.1 "climate change, global warming potential" impact category, adding hydrogen with this characterisation factor, yields slight increases in the climate change impact for the six hydrogen alternatives. In relative terms, the impact increase ranges from 2%, for those alternatives where the total impact is larger, to 32% for yellow hydrogen in 2100, where the total impact is comparatively small. This can be seen in Figure 8.7. While not negligible, this difference does not alter the order among alternatives seen in the climate change impact category (Figure 8.2).

8.3.2. Water uptake and emissions

Various type of water environmental flows can be distinguished: either freshwater (from/to groundwater or water bodies), salt water (principally from/to oceans) or water vapour (from/to air), and either as a natural resource (uptake from environment) or an emission (released into the environment).

The impact categories as implemented in Ecoinvent only characterise the emission of water vapour, despite documentation for the EF v3.1 assessment family instead characterising the uptake and release of liquid freshwater (European Commission, 2022), with emissions of liquid water back into water bodies having negative characterisation factors. The apparent reasoning behind this is the consideration that vapour emissions are the only disruption of the balance of available freshwater – despite this not being the phase where water is actually removed from the environment (Sonderegger & Stoikou, 2023).

For some systems, this should not influence the characterisation results. An example of this is an industrial process where a certain amount of water is taken up from a water body for cooling purposes, and where a certain share of the water is emitted into air as vapour while the rest is released back into a water body. Here, the amount of water vapour emission indeed equals result of subtracting the freshwater emission from the freshwater uptake. Or a process where hydrogen is produced from water via electrolysis, and then used in a fuel cell and producing water vapour as an emission, in the same amount as the water originally taken up. The only difference would be that the contributions to water use may originate in different processes than one would logically expect.

However, for other processes, this balance does not exist. For example, the production of hydrogen via SMR (Equation 8.1) uses only one water molecule per three produced hydrogen molecules (US Department of Energy, n.d.-b), even if the use of this hydrogen produces one water molecule per hydrogen molecule. In the Ecoinvent implementation of the impact category, this results in a water use impact that is three times larger than the freshwater actually removed from the environment. Another example relevant to the modelled system for inland shipping are agriculture and forestry processes, indirectly present in biomass for electricity and biofuel production, where freshwater is embedded into produced biomass (within the timespan considered by the LCA).

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \tag{8.1}$$

To obtain a better estimate of water use, a new impact category is created based on the characterisation factors given in the EF v3.1 documentation: positive for freshwater as a natural resource, negative for freshwater emissions, and zero for water vapour and salt water flows. As in the default implementation, the global deprivation weighing factor of 42.95 m^3 is used. The two impact categories (default and custom) can be compared in Table 8.1.

Table 8.1: Comparison of the water use characterisation factors in the default "EF v3.1 water use - user deprivation potential" impact category as defined in Ecoinvent, and the custom impact category aiming at obtaining a better assessment of water use.

Name	Type	Category	CF [m^3]	
			Default	Custom
Water, cooling, unspecified natural origin	Natural resource	natural resource, in water	0.00	42.95
Water, lake	Natural resource	natural resource, in water	0.00	42.95
Water, river	Natural resource	natural resource, in water	0.00	42.95
Water, turbine use, unsp. natural origin	Natural resource	natural resource, in water	0.00	42.95
Water, unspecified natural origin	Natural resource	natural resource, in ground	0.00	42.95
Water, unspecified natural origin	Natural resource	natural resource, in water	0.00	42.95
Water, unspecified natural origin	Natural resource	natural resource, fossil well	0.00	42.95
Water, well, in ground	Natural resource	natural resource, in water	0.00	42.95
Water, in air	Natural resource	natural resource, in air	0.00	0.00
Water, salt, ocean	Natural resource	natural resource, in water	0.00	0.00
Water, salt, sole	Natural resource	natural resource, in water	0.00	0.00
Water	Emission	air, low population density, long-term	42.95	0.00
Water	Emission	air, lower stratosphere + upper troposphere	42.95	0.00
Water	Emission	air, non-urban air or from high stacks	42.95	0.00
Water	Emission	air	42.95	0.00
Water	Emission	air, urban air close to ground	42.95	0.00
Water	Emission	water, ocean	0.00	0.00
Water	Emission	water, fossil well	0.00	−42.95
Water	Emission	water'	0.00	−42.95
Water	Emission	water, ground-, long-term	0.00	−42.95
Water	Emission	water, surface water	0.00	−42.95
Water	Emission	water, ground-	0.00	−42.95

For an updated impact assessment with this impact category, a modification to the system is needed as well. Analysis of preliminary characterisation results indicates an oversight in the SMR processes for the production of grey and blue hydrogen, provided by Premise and sourced from Antonini et al. (2020). A significant amount of cooling water is used as an input without an equivalent output, thus having a mass imbalance.[1] Extra environmental flows for freshwater and water vapour emissions are added to these processes, in the same proportion as in the Ecoinvent process "electricity production, natural gas, gas turbine, conventional power plant", which is a similar natural gas-based industrial process with an input of cooling water.

[1]Confirmed in communication with one of the authors of this LCI data, who indicates that water use was not a focus of the source research and that this would not be apparent in the original implementation of the impact category, and who agrees with the proposed approach to adjust the SMR processes.

Figures 8.8 and 8.9 display the previously obtained water use characterisation results alongside newly obtained characterisation results with the custom impact category. The relative results show some minor shifts between the alternatives, and especially the expected correction of grey and blue hydrogen having further decreased water use impact compared to yellow hydrogen. The absolute values are generally higher in the custom impact category due to the improved inclusion of water use impacts from processes where water use is embodied into a product, such as the production of concrete or biomass, which are indirectly present across all alternatives.

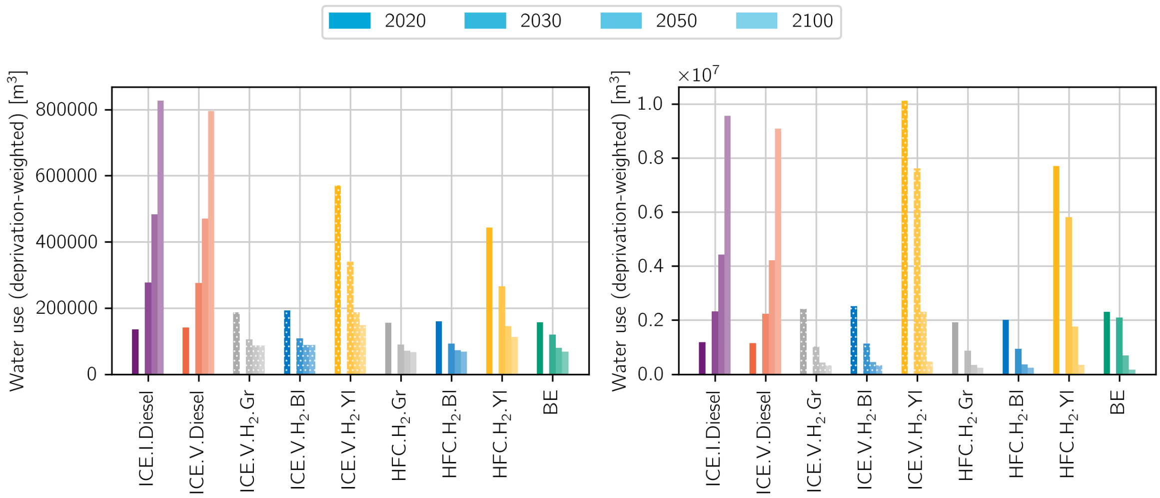


Figure 8.8: Characterisation results in the SSP2-RCP2.6 scenario, comparing the default and custom water use impact categories. Results grouped by alternative. Note the different y axis limits; the results in the custom IC are higher by an approximate factor 10.

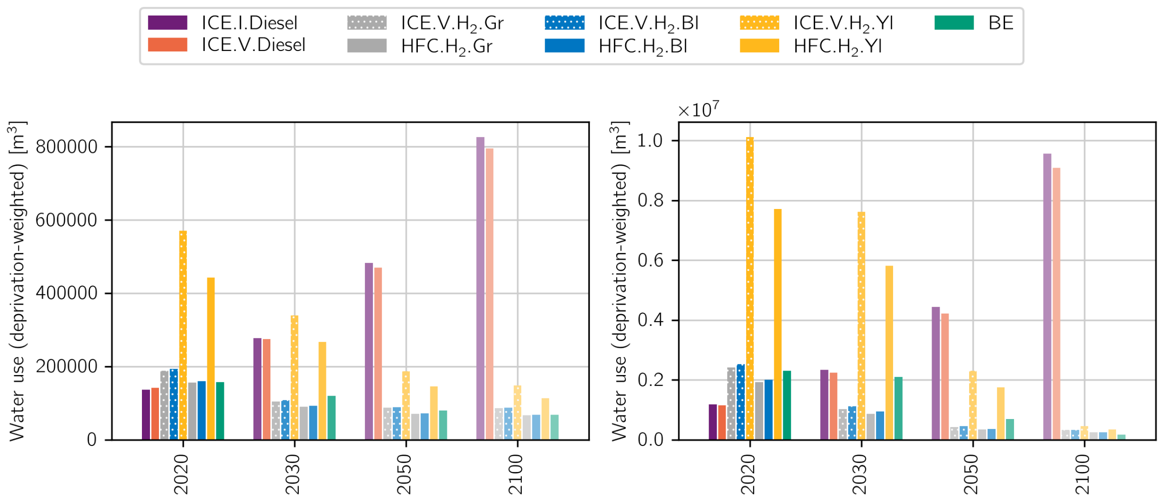


Figure 8.9: Characterisation results in the SSP2-RCP2.6 scenario, comparing the default and custom water use impact categories. Results grouped by year. Note the different y axis limits; the results in the custom IC are higher by an approximate factor 10.

8.4. Comparison with other transport modalities

Inland shipping is only one modality for freight transportation. Other common transportation methods that can provide the same function are freight lorries and freight trains, each of which has its own practical advantages and drawbacks. Lorries are most commonly fuelled by diesel, although battery-electric lorries are becoming more common, while freight trains are either diesel-powered or electric, powered by overhead lines.

It is relevant to compare the environmental impact results for inland shipping with different technologies to literature values for these other transport modalities. Figure 8.10 and Figure 8.11 contain the characterisation results obtained in this study, alongside new characterisation results for the same amount of transportation for each of the following processes:

- transport, freight, lorry, diesel, EURO VI, 26t load gross weight
- transport, freight, lorry, battery electric, NMC-622 battery, 26t load gross weight
- transport, freight train, diesel
- transport, freight train, electricity

The lorry processes are sourced from the Premise databases, based on research into the future of road freight transport by Sacchi et al. (2021). The train processes are taken from the Ecoinvent database. Note that the diesel-powered lorry and train follow the same fuel mix as the diesel-powered barge alternatives, so that their climate change impacts drop over time.

In these charts, transportation by lorry has a very high impact, especially at present. Battery-electric lorries have lower climate change, photochemical oxidant, fossil resource use, and land use impacts than diesel lorries, at the expense of having higher acidification, PM formation, metal/mineral resource use, and water use impacts. Diesel-powered trains score similar to the diesel-powered barge alternatives in most impact categories, while the electric train performs very similarly to a battery-electric barge, but with a lower use of metal/mineral resources. Furthermore, as an electric train is powered by overhead lines instead of batteries, it is unlikely to face scalability challenges (this will be explored for the barge alternatives in Section 9.4.2).

A cursory overview of these four other transport processes' inventories indicates these are consistent enough to be compared to the modelled barge systems, sharing similar data sources and having a similar scope (including the vehicle and power system life cycle, infrastructure, fuel, and operational emissions). Separate modelling of these transport modality systems to ensure they are fully aligned is not considered within the scope of this investigation.

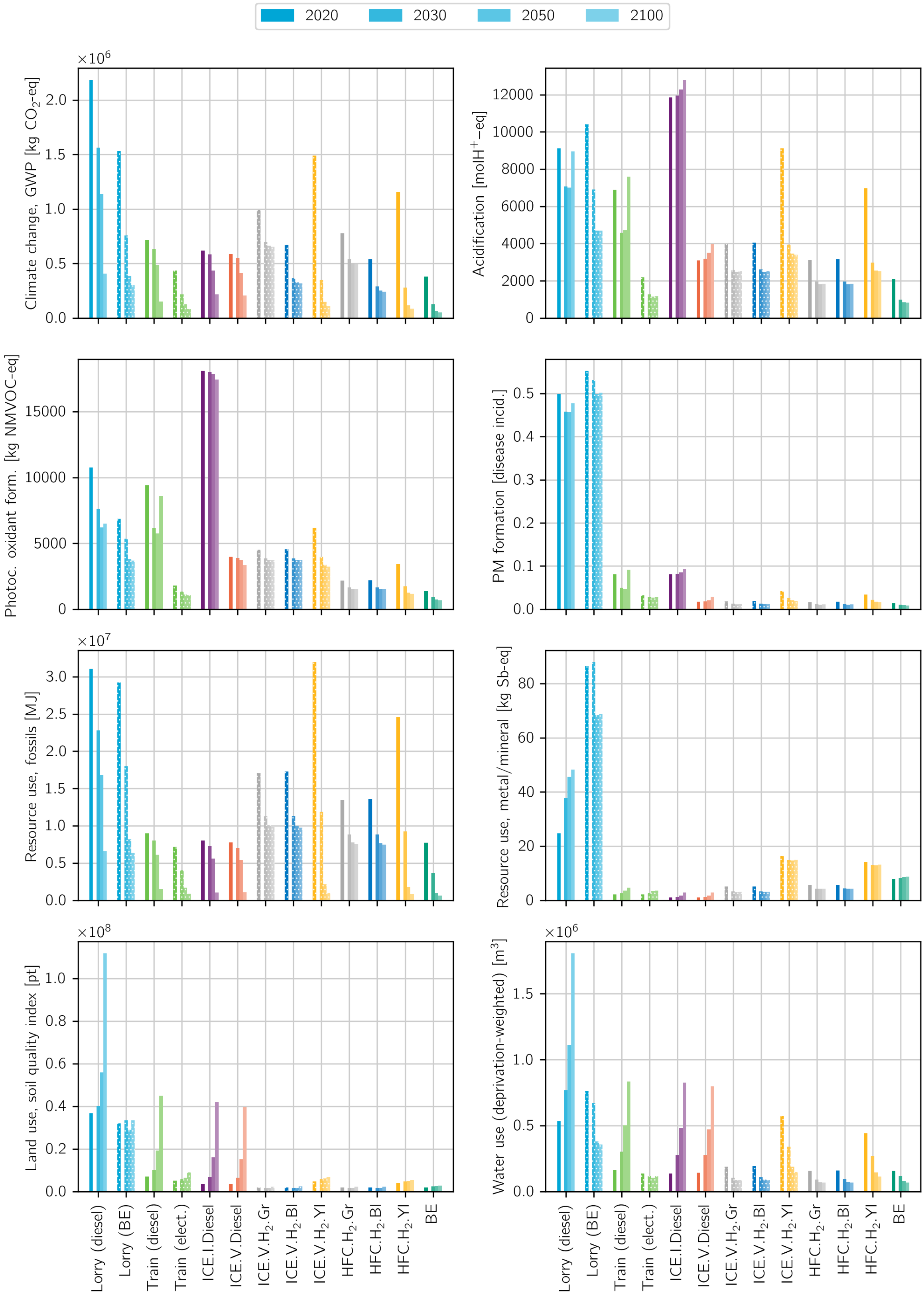


Figure 8.10: Characterisation results in the SSP2-RCP2.6 scenario, alongside characterisation results for other transport modalities. Results grouped by alternative.

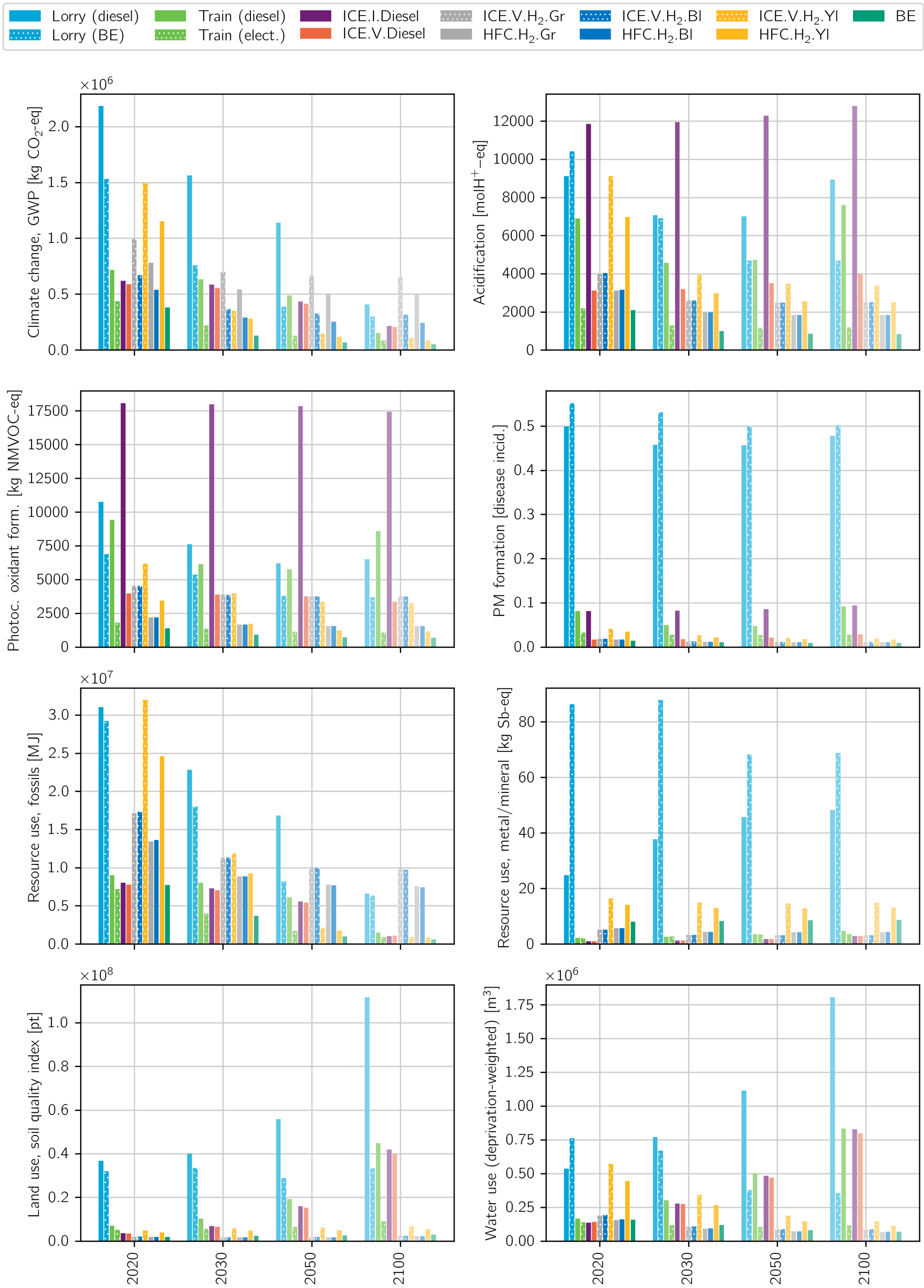


Figure 8.11: Characterisation results in the SSP2-RCP2.6 scenario, alongside characterisation results for other transport modalities. Results grouped by year.

9 Interpretation

9.1. Consistency check

The performed LCA has been checked for consistency among alternatives on the points below, and no major consistency issues have been found in this check.

Data sources Most data is sourced from or adapted from Ecoinvent and scenario databases generated by Premise, across all alternatives. Data on lifespans and efficiencies has been obtained from literature or industry. Data from other sources that differs between alternatives relates to the combustion of diesel and hydrogen in ICEs. The collection of this data has been discussed in detail in Chapter 6, and is considered to be of comparable quality to the common data.

Data accuracy As data is obtained from trustworthy sources that are similar across alternatives, data can be taken to be acceptably accurate. The results obtained, which will be discussed in more detail in the next chapter, give new insights without conflicting with the existing knowledge of the Province of South Holland nor with the literature discussed in Chapter 5.

Data age, technology coverage, and time-related coverage Not all data is equally recent in creation or in coverage. Some data in the Ecoinvent database, especially for well-established processes, has not been updated for many years and can be based on older research. Nevertheless, data covering the principal parts of the models (on-ship energy systems; production of hydrogen; batteries and fuel cells) is based on recent studies or reports for current or projected technologies, either directly or via Premise, across all alternatives.

Geographical coverage Not all modelled processes that are considered to take place in South Holland have been modelled with data specific to South Holland or the Netherlands. Most processes obtained via Premise include data at the European level, but not at the country level. This is most relevant for electricity production, which varies strongly across countries (e.g., the European grid mix includes large portions of hydro-electricity and nuclear energy, which are not present in the Dutch grid mix). It is important to take this into consideration in further discussions. However, this is not an inconsistency, considering that this applies to all alternatives and that the European market for goods and energy is well-integrated, so that results for the European geography are generally applicable to the Netherlands as well.

Differences in functions All alternatives fulfil the same function in the same way, giving no issues regarding consistency.

9.2. Completeness check

The created models, as depicted in the flow diagrams seen in Chapter 7, have been extensively discussed with experts at the Province of South Holland and its partners in public administration and the inland shipping sector. The data and results have also been compared to existing LCA literature on (inland) shipping and with the default Ecoinvent processes for transportation by inland barge. Individual processes have been checked on their inputs and outputs to ensure mass balances are correct and all relevant economic and environmental flows are present.

No noteworthy absences of processes or flows exist beyond the scope choices discussed in Chapter 6 and, due to the inclusion of processes such as waterway and bridge infrastructure, this assessment is more complete than various other existing studies on inland shipping. Furthermore, each alternative is considered to be equally complete, and no non-characterised flows are expected to have any significant impact, besides the ones addressed in Section 8.3.

9.3. Contribution analysis

For the contribution analysis, only alternatives ICE.V.Diesel, ICE.V.H_2.BI, ICE.V.H_2.YI, HFC.H_2.BI, HFC.H_2.YI, and BE are considered, as well as a selection of six impact categories.

How to interpret contribution analysis results

The contribution analysis results described in the following sections are given in a series of horizontal bar charts, each chart corresponding to a different impact category.
Within each chart, every bar corresponds to a specific alternative and year. The bars are split up into coloured segments proportional to the contributions of system components / environmental flow to that alternative's impact in that year and impact category. As a concrete example: the purple segment in the first bar in Figure 9.1 indicates that approximately two-thirds of the climate change impact of alternative ICE.V.Diesel (in 2020) comes from the emissions during barge operations.

9.3.1. Contributions by system component

For each of the selected alternatives and impact categories, the impact contributions have been split up between nine system components:

- Waterway construction and maintenance
- Port construction and maintenance, facilities, and shore power
- Provincial bridge operation
- Barge production, maintenance and disposal (excl. power system)
- Power system production, maintenance and disposal (e.g. engines and fuel cells; excl. batteries)
- Battery production and disposal
- Fuel supply chain (resource extraction, conversion, transportation, storage, etc.)
- Production and disposal of other consumables (DEF, lubricating oil, bilge oil)
- Operational emissions (fuel combustion)

The results of this characterisation analysis can be seen in Figures 9.1 to 9.6, each graph corresponding to a different impact category.

In these charts, various trends can be observed. The main contributor to the baseline ICE.V.Diesel (2020) is the operational phase (combustion of fossil fuel), and the operational phase also contributes significantly to the acidification and PM formation impacts from diesel or H_2 combustion in an ICE.

The fuel supply chain dominates in nearly every other alternative and impact category. This explains trends observed in the characterisation results, such as the increase of land and water over time for diesel, which is due to the additional impacts of biofuel and synthetic fuel production. Other large contributions come from battery production (for the HFC and especially the BE alternative; especially regarding PM formation and metal/mineral resource use) and power system production (especially for the production of fuel cells for the HFC alternatives).

The life cycle of the barge itself gives a minor but consistent contribution, and should also not be neglected. Meanwhile, the impacts from port facilities, shore power and bridge operations, which mainly come from electricity usage, are expected to decrease over time in most impact categories as the electricity mix decarbonises.

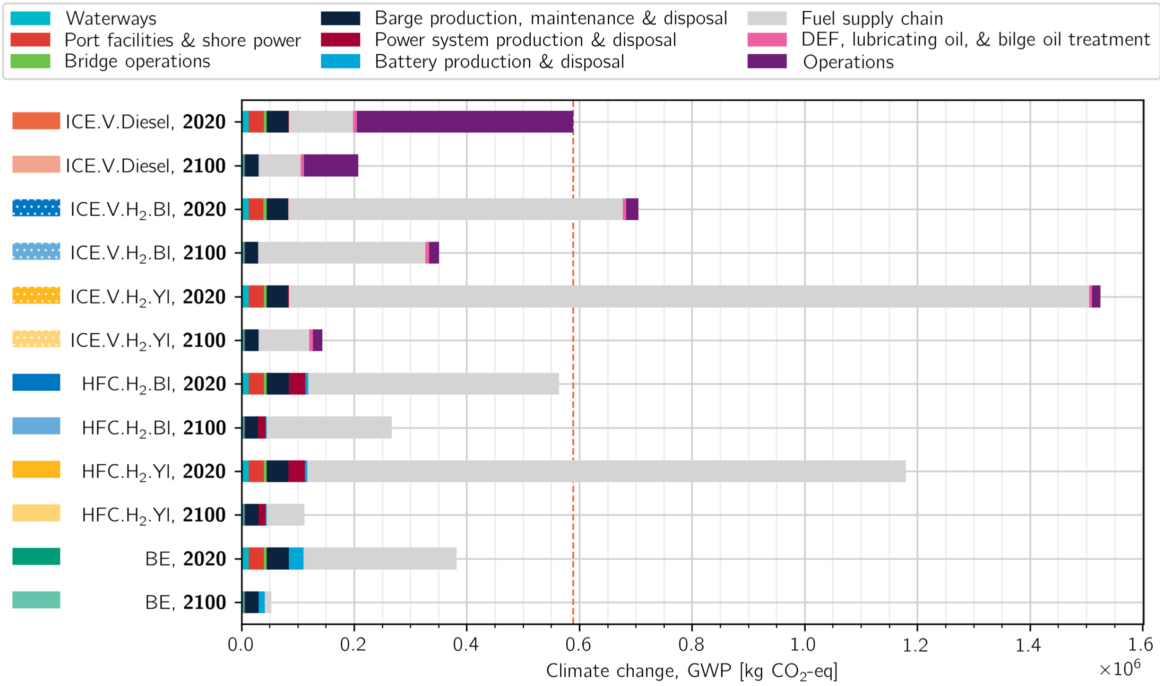


Figure 9.1: Contribution analysis per system component in the impact category climate change (updated to include characterisation factors for hydrogen gas emissions). In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

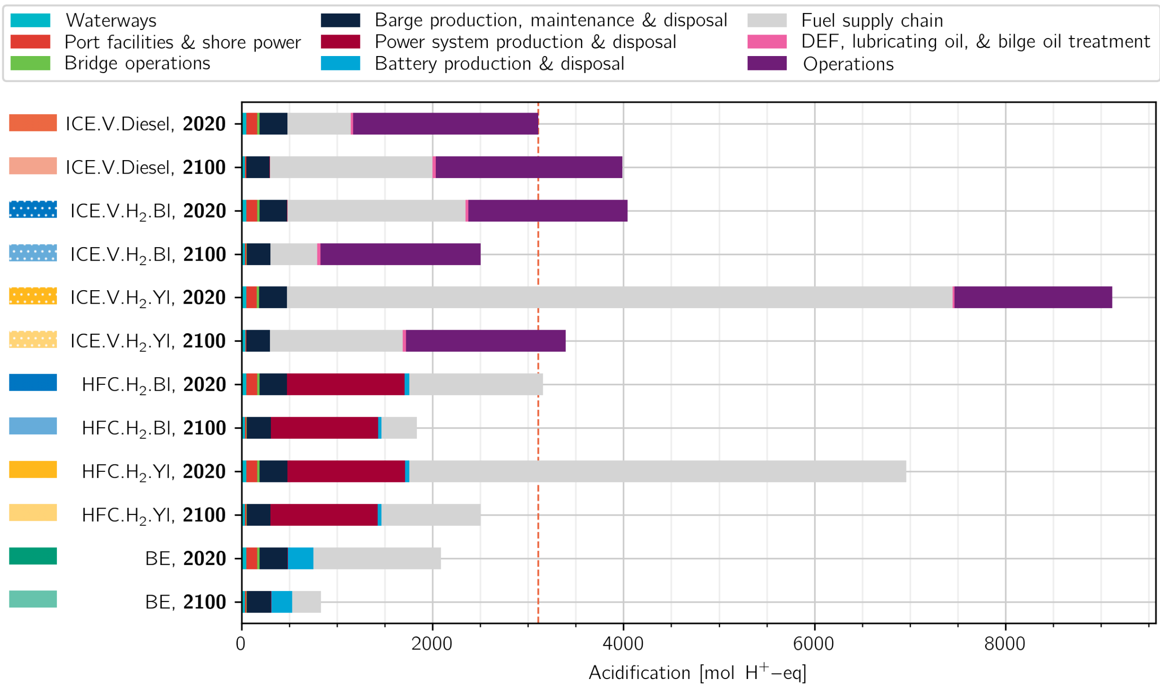


Figure 9.2: Contribution analysis per system component in the impact category acidification. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

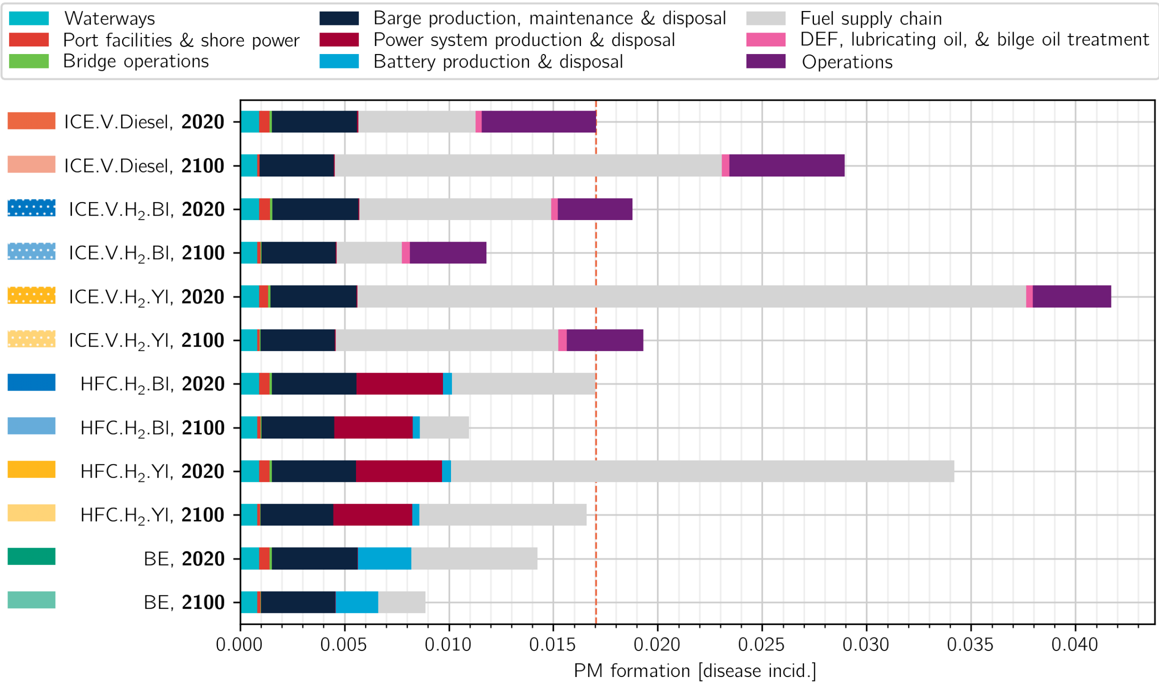


Figure 9.3: Contribution analysis per system component in the impact category particulate matter formation. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

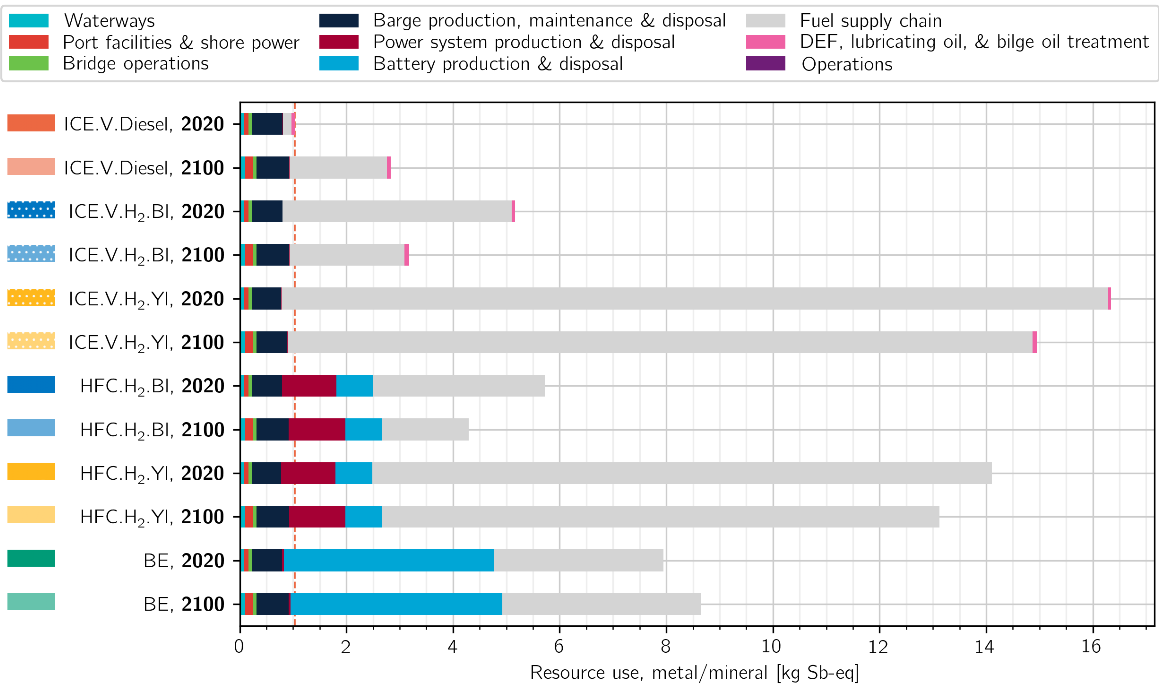


Figure 9.4: Contribution analysis per system component in the impact category material resources, metals/minerals. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

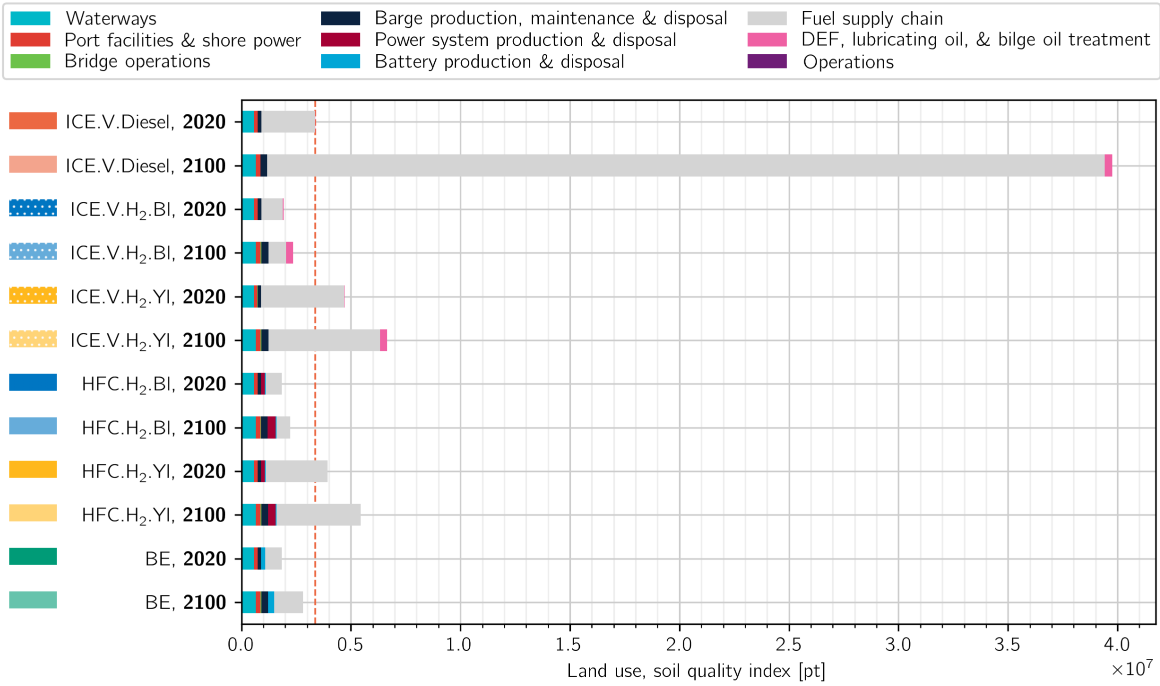


Figure 9.5: Contribution analysis per system component in the impact category land use. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

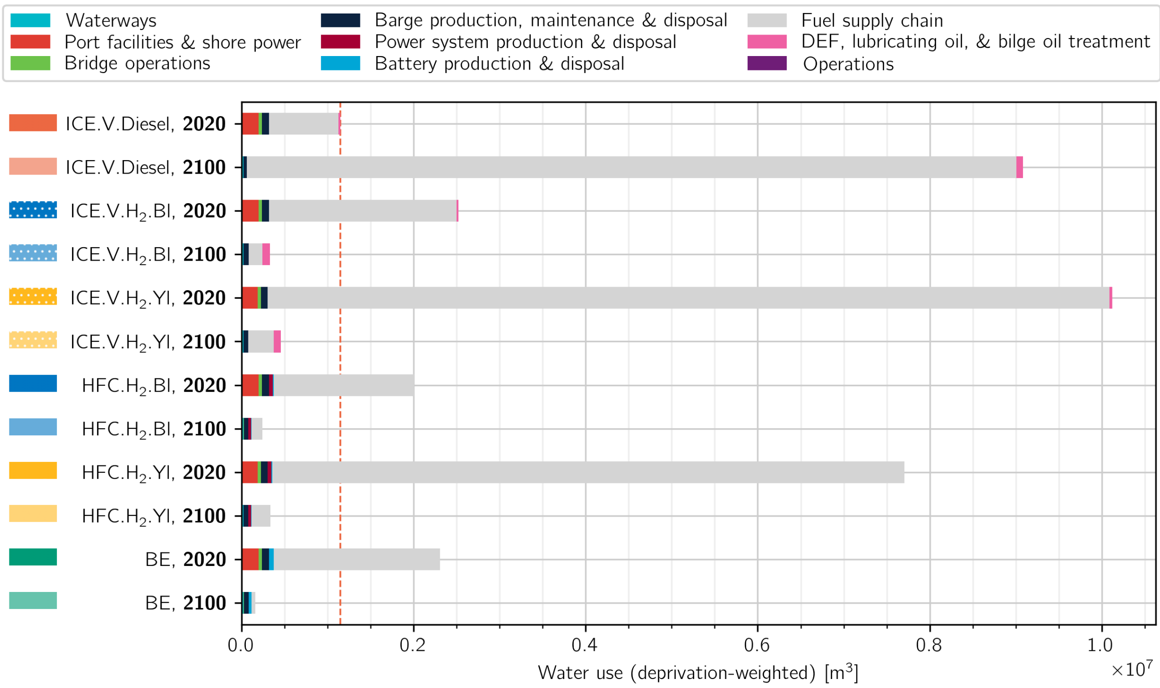


Figure 9.6: Contribution analysis per system component in the impact category water use (updated to characterise water extraction and emissions instead of evaporation). In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

9.3.2. Contributions to fuel supply chain by life cycle component

The previous contribution analysis indicates that for most alternatives and impact categories, the fuel supply chain is the most significant contributor to environmental impacts. Figures 9.7 to 9.12 contain a second contribution analysis, splitting the fuel supply chain up into its principal components:

- Fossil fuel supply (diesel, natural gas)
- Fossil fuel refining
- Biofuel supply
- Biofuel refining
- Synthetic fuel supply
- Hydrogen production (SMR or electrolysis)
- Electricity supply (direct for energy carrier)
- Transportation, storage and infrastructure for the distribution of the final energy carrier

In this component division, only direct input of electricity and fuel to the production chain of the final energy carrier is counted into these categories. For instance, the electricity input for electrolysis to produce yellow hydrogen is counted as electricity supply, but the large input of electricity required for the distribution of hydrogen is counted towards distribution.

Furthermore, in this contribution analysis the fuel supply chain is analysed per kWh (= 3.6 MJ) of fuel involved, before applying barge power system efficiencies. The contribution of the fuel supply chain to the total environmental impact for each alternative can be seen in the previous contribution analysis (Section 9.3.1).

This contribution analysis again confirms that the increase over time for the metals/minerals use, land use, and water use of diesel comes from the production of diesel substitutes. It can also be seen that a main contributor to the impacts of blue and yellow hydrogen comes from the transportation and storage of the produced hydrogen, although this contribution is projected to shrink over time due to the decarbonisation of the electricity mix. These charts also confirm that the changing electricity mix will is projected to yield a drop in emissions for yellow hydrogen and electricity as energy carrier. Among these two, direct usage of electricity tends to be twice as efficient per kWh produced.

Counterintuitively, only a small fraction of the water use for hydrogen fuel is needed for the production of hydrogen itself (only 12% of the total for yellow hydrogen in 2100 – which itself is very small compared to the impacts of other alternatives and years). Indeed, for the non-diesel alternatives, the contributions to water use seem to lie either directly or indirectly in the electricity grid. An inspection of the grid mix reveals hydroelectricity in the European grid mix to be the main contributor, due to the evaporation of water in reservoirs (which is present in either implementation of the water use impact category discussed in Section 8.3.2). It must be mentioned that the quantification of water use is subject to discussion (Sonderegger & Stoikou, 2023). In this case, the water use used locally as an input in the hydrogen production process cannot be directly compared to water evaporated from a hydroelectricity reservoir elsewhere, even if they both contribute to this impact category.

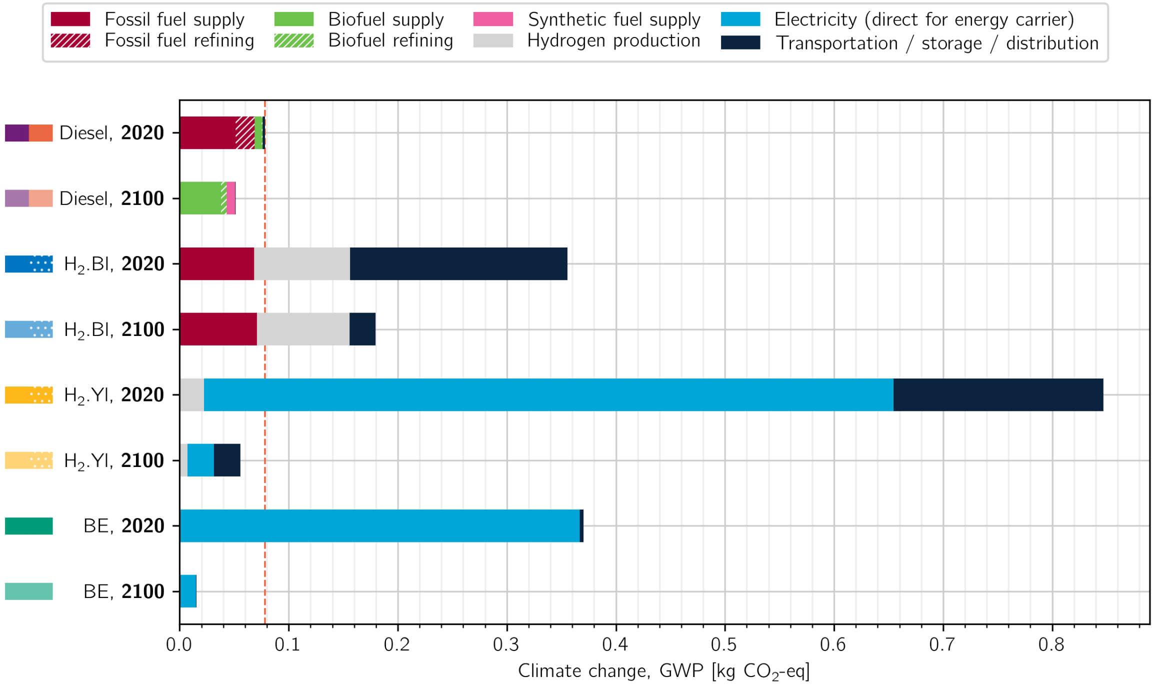


Figure 9.7: Contribution analysis of the fuel supply, per kWh produced, in the impact category climate change (updated to include characterisation factors for hydrogen gas emissions). In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

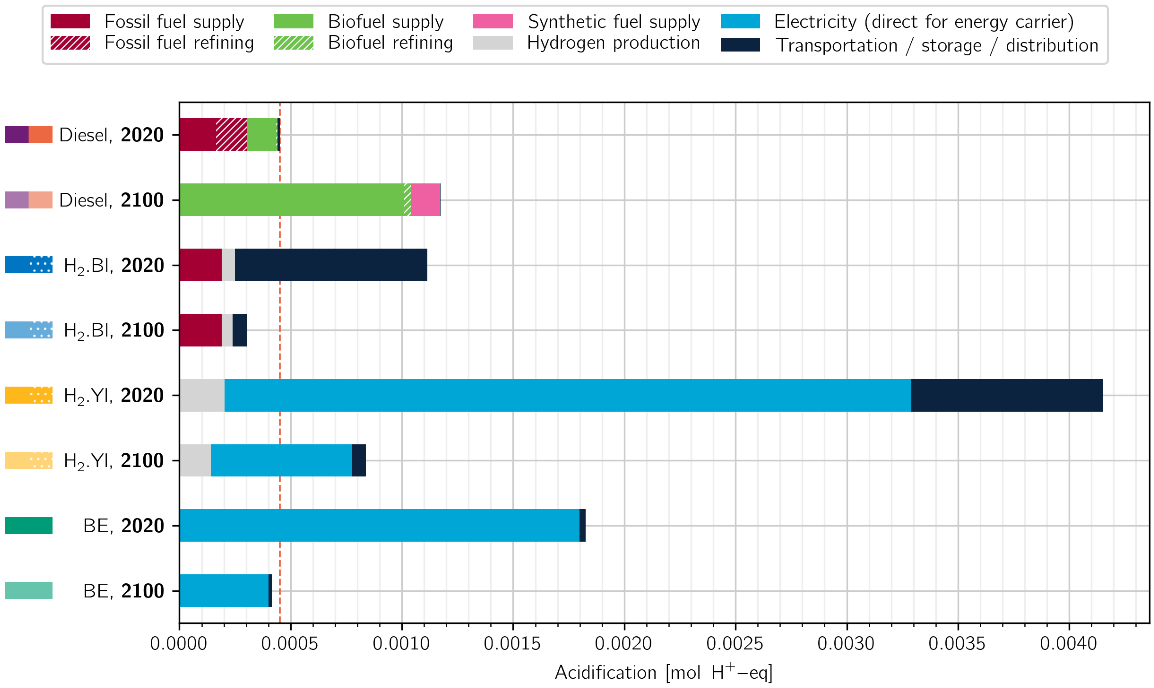


Figure 9.8: Contribution analysis of the fuel supply, per kWh produced, in the impact category acidification. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

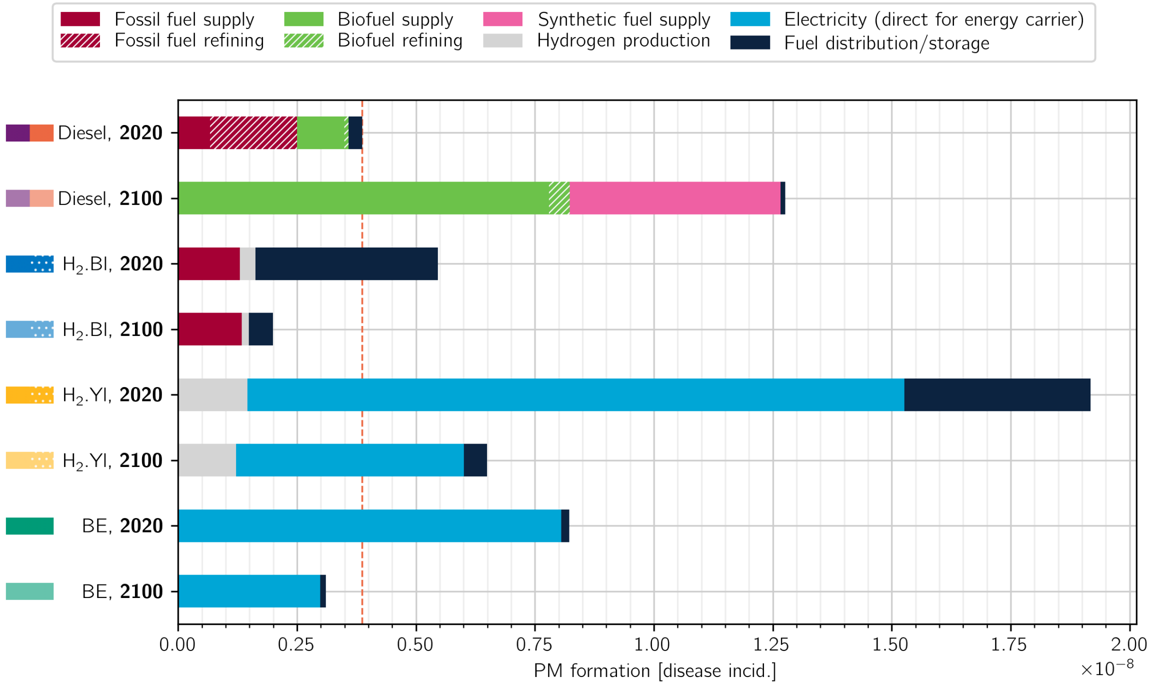


Figure 9.9: Contribution analysis of the fuel supply, per kWh produced, in the impact category particulate matter formation. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

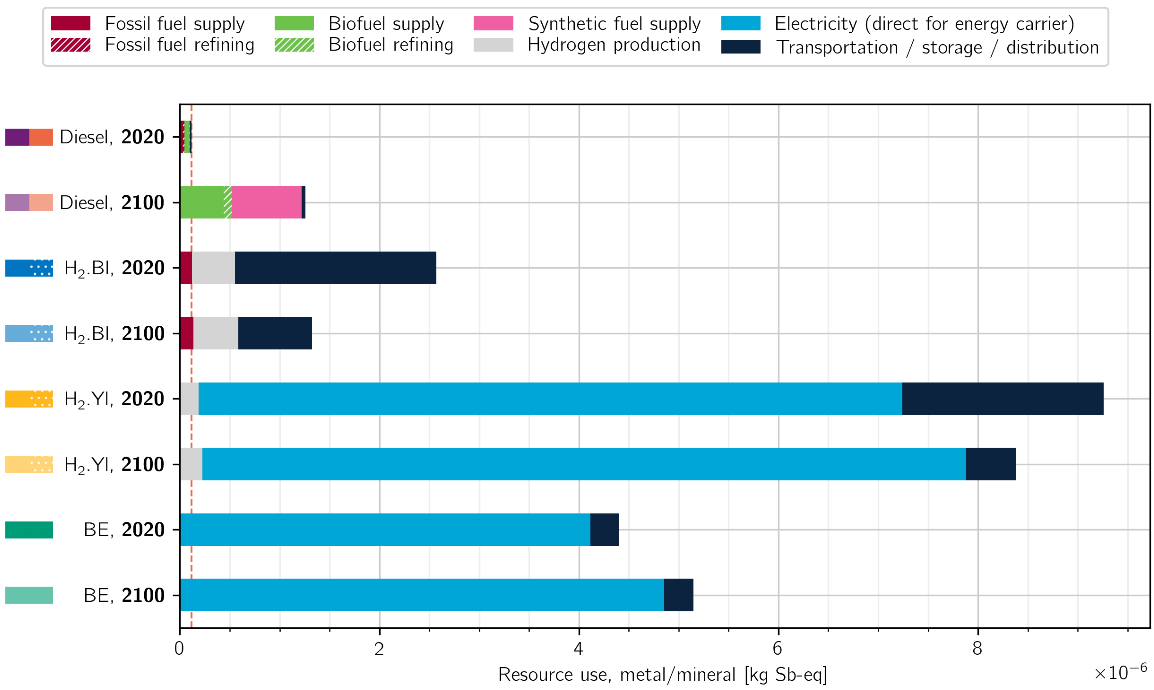


Figure 9.10: Contribution analysis of the fuel supply, per kWh produced, in the impact category material resources, metals/minerals. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

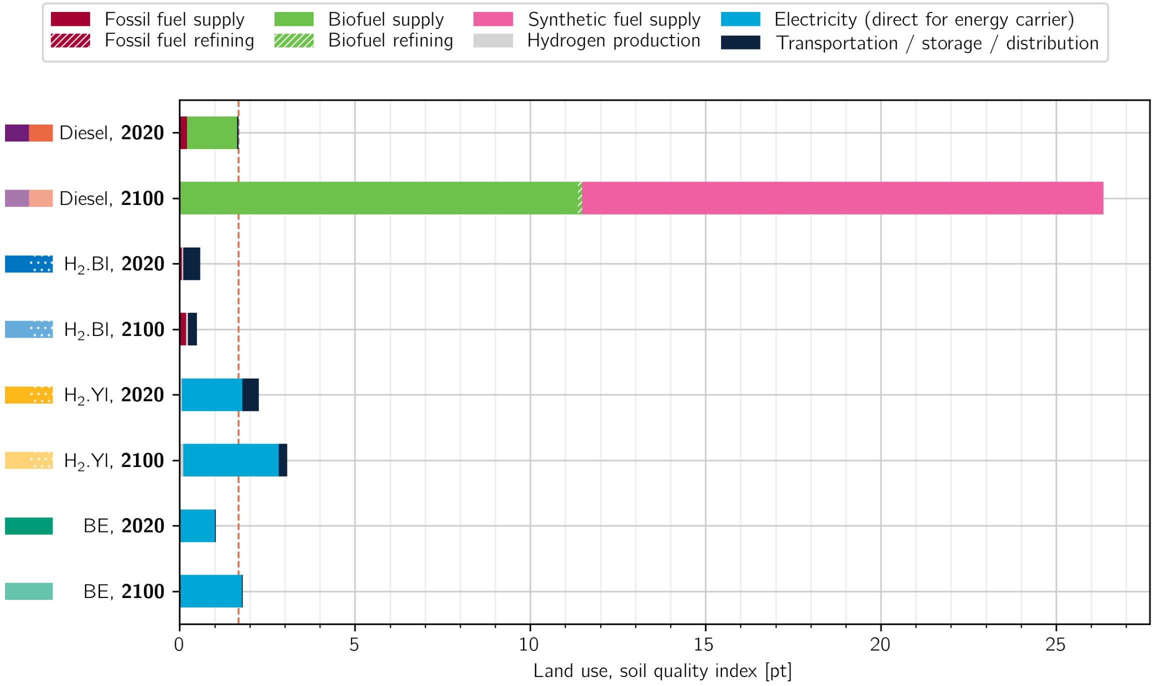


Figure 9.11: Contribution analysis of the fuel supply, per kWh produced, in the impact category land use. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

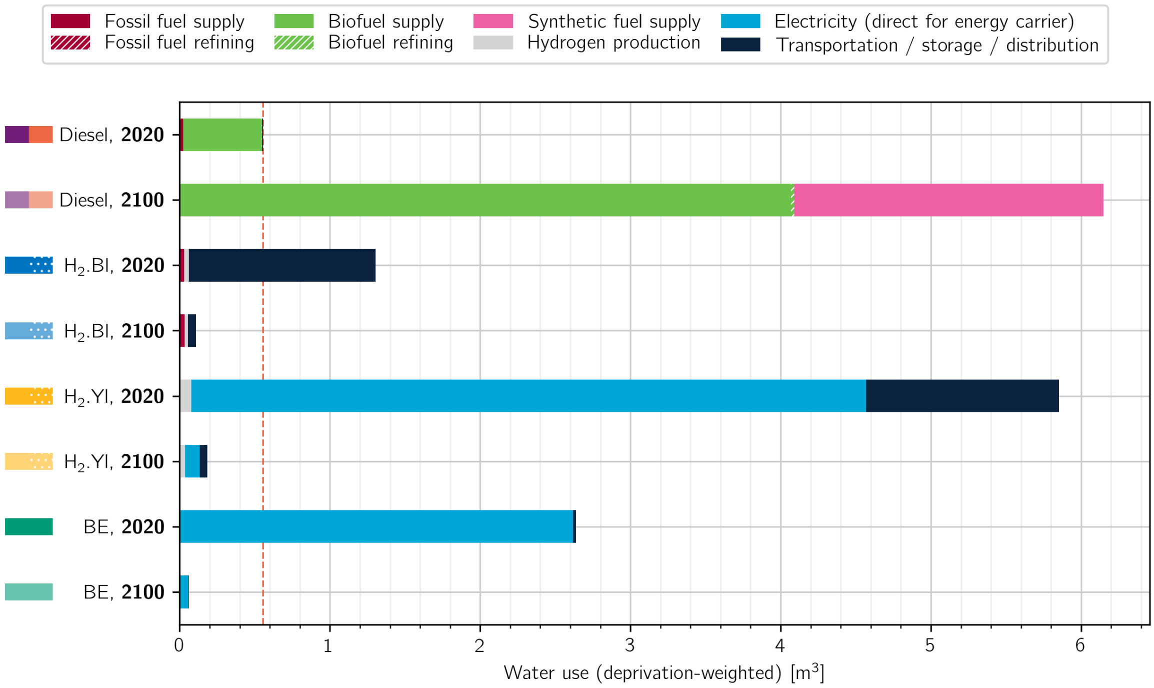


Figure 9.12: Contribution analysis of the fuel supply, per kWh produced, in the impact category water use (updated to characterise water extraction and emissions instead of evaporation). In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

9.3.3. Contributions by environmental flow

Another contribution analysis, per environmental flow involved, is depicted in Figures 9.13 to 9.16, for the impact categories of climate change, acidification, PM formation, and resource use.

Inclusion of biogenic emissions

In the contribution analyses by environmental flow (Sections 9.3.3 and 9.3.4), non-fossil CO_2 emissions are also included, marked in a striped pattern. This represents the part of CO_2 emissions – mainly in the operational phase – offset by the production of biofuel and synthetic fuel. This is an important difference, included with the purpose of showing how the CO_2 emissions shift from fossil to biogenic. The contribution of biogenic CO_2 can be neglected, as it is in all other visualisations, due to the uptake of CO_2 elsewhere in the fuel production chain.

The main contributor by far to climate change is CO_2 emissions, even without considering the non-fossil part. This is followed by a small contribution of methane, which is a stronger yet shorter-lived greenhouse gas. A contribution of hydrogen gas is also present for the hydrogen alternatives, which is small in absolute terms, even if it ends up accounting for 25% of the HFC.H_2.YI (2100) climate change impacts, where the emissions of CO_2 and methane are strongly reduced.

The acidification impacts are dominated by sulphur oxides (SO_x; mainly SO_2) and nitrogen oxides (NO_x). A contribution from ammonia (NH_3) is also present, but only plays a major role in the emissions for ICE.V.Diesel (2100). These three emissions are also main contributors to PM formation impacts, although the impacts from the emission of generic particulate matter is approximately as large as the SO_x, NO_x and NH_3 impacts combined, for all alternatives.

The main materials impacting the metals/minerals use impact category are tellurium, copper, and gold, as well as other scarce metals. Most of these have applications in electronics, electricity transmission, and renewable energy. Although lithium extraction is a concern when discussing battery-electric transportation (Greim et al., 2020), it does not appear among the most impactful resource extractions even for the BE alternative. An inspection of the impact category reveals that the characterisation factor of lithium is several orders of magnitude smaller than that of e.g. tellurium. As these factors are determined based on the depletion of available resource stocks, this appears to support reports indicating that the availability of lithium is not a principal constraint for the global energy transition, if its supply chain and recycling is managed properly (Kushnir & Sandén, 2012; Yaksic & Tilton, 2009).

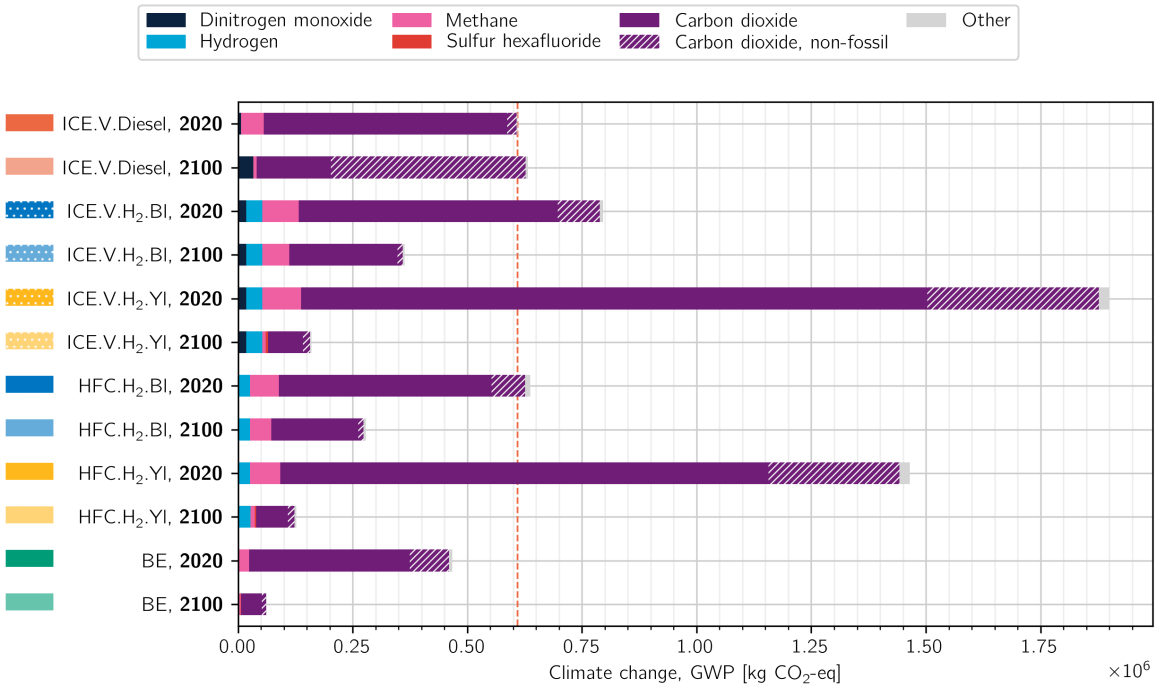


Figure 9.13: Contribution analysis per environmental flow in the impact category climate change (updated to include characterisation factors for hydrogen gas emissions). In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

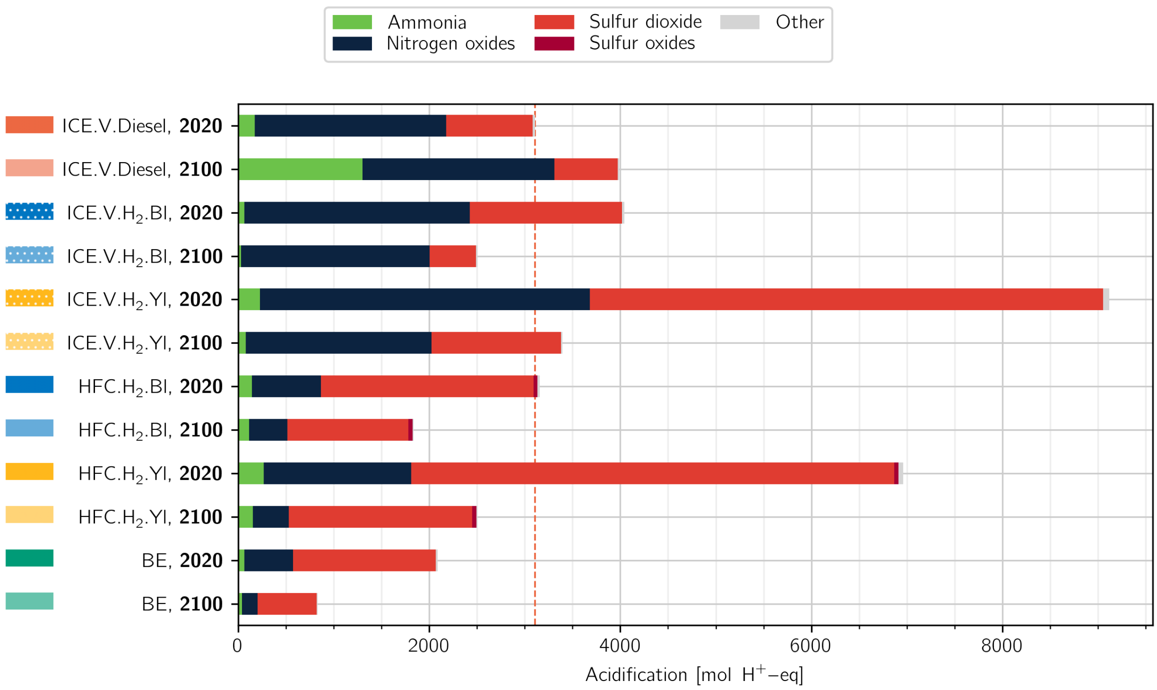


Figure 9.14: Contribution analysis per environmental flow in the impact category acidification. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

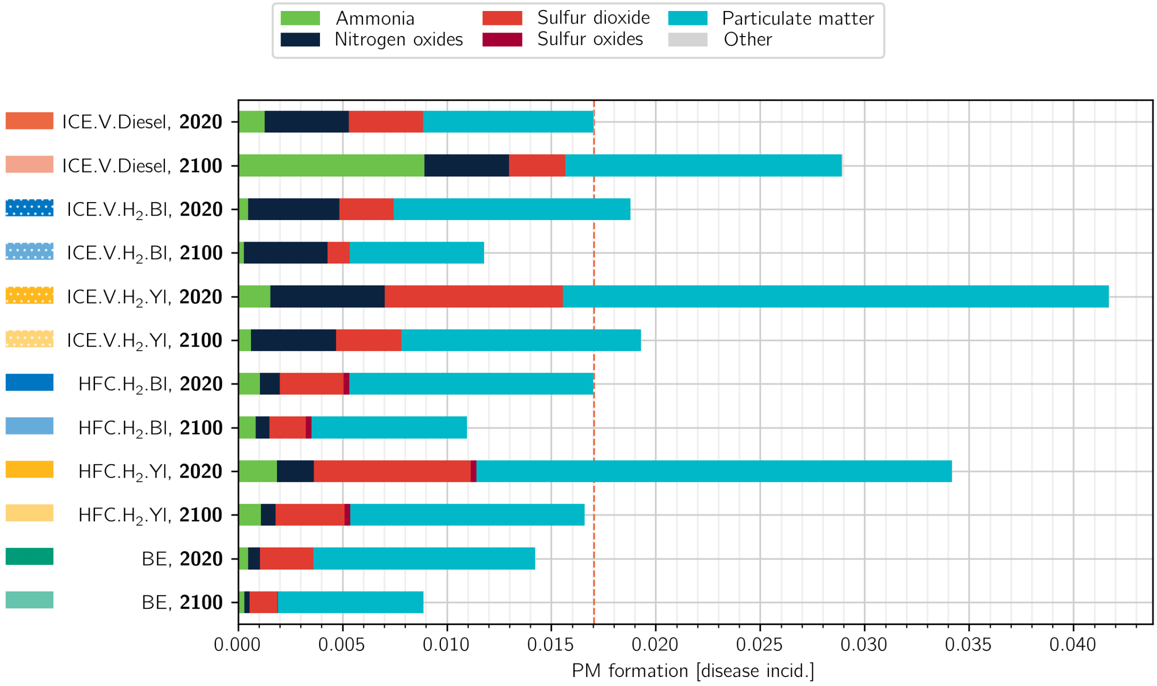


Figure 9.15: Contribution analysis per environmental flow in the impact category particulate matter formation. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

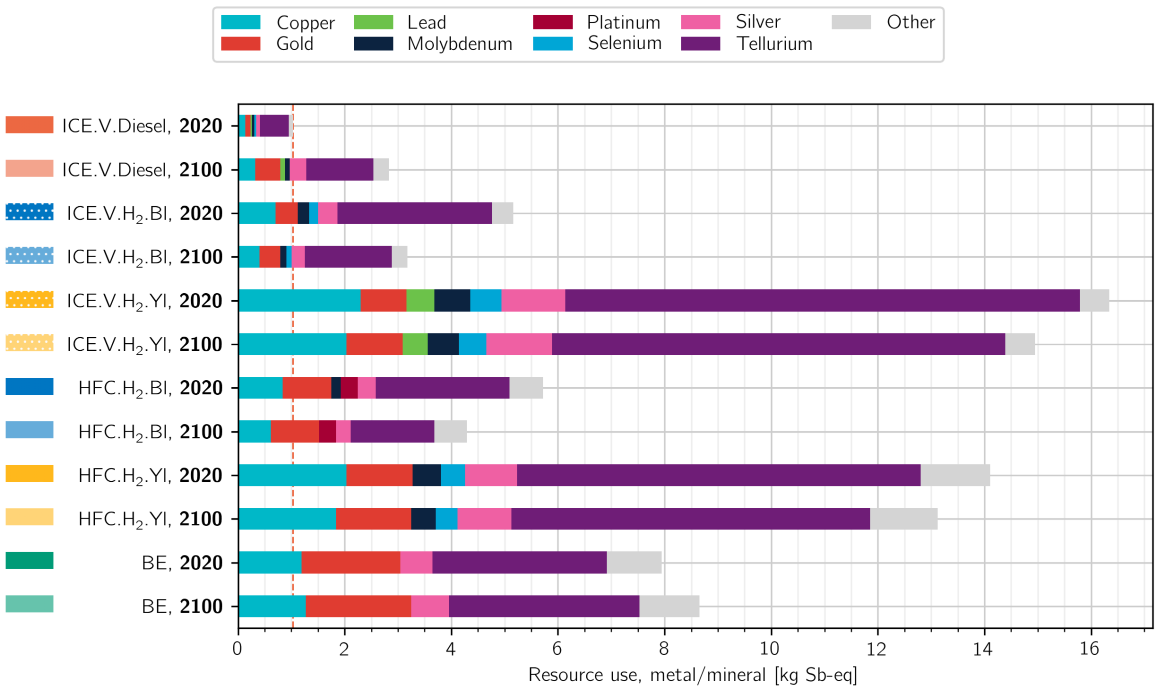


Figure 9.16: Contribution analysis per environmental flow in the impact category material resources, metals/minerals. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

9.3.4. Contributions to operations by environmental flow

The operational emissions of the inland shipping lifecycle are of special relevance, as these take place in a decentralised way, on the provincial waterways, often close to population centres. Figures 9.17 to 9.19 display a contribution analysis of only this part of the system, in the three impact categories most relevant to emissions of greenhouse gases or local environmental pollution in this phase (climate change, acidification, PM formation). As before, non-fossil CO_2 emissions are included in the visualisation for reference, although these should not count towards the total environmental impacts.

The climate change impact of diesel combustion is dominated by CO_2. Hydrogen does not contain any carbon; the climate change impact of its combustion, much smaller than that of diesel combustion, consists principally of nitrous oxide (dinitrogen monoxide; N_2O), which is a greenhouse gas that is produced in the combustion of some gaseous fuels (Colorado et al., 2017).

The combustion of diesel and hydrogen both produce a similar amount of NO_x (marginally higher for diesel), which impacts and dominates both acidification and PM formation. The combustion of diesel produces additional impacts to acidification and PM formation due to emissions of SO_2, due to the presence of trace sulphur – even in fuels classified as "low-sulphur".[1] The emissions of generic particulate matter is also higher for the combustion of diesel than for that of hydrogen.

It should be kept in mind that these results, where the local environmental pollution (acidification, PM formation) of diesel combustion are not significantly larger than that of hydrogen combustion, are based on a modern Stage V combustion engine. As the characterisation results (Section 8.1) have shown, the impact in these categories can be 3 to 4 times higher for older engines, due to the additional NO_x and PM emissions of these.

[1] Even biodiesel contains trace amounts of sulphur, albeit even lower than conventional "low-sulphur" diesel. As such, the SO_x emissions and impacts of the diesel mix in 2100 may lie lower than depicted in these results. As no concrete data on biofuels or synthetic fuels in inland shipping is available, this is not looked into further at present.

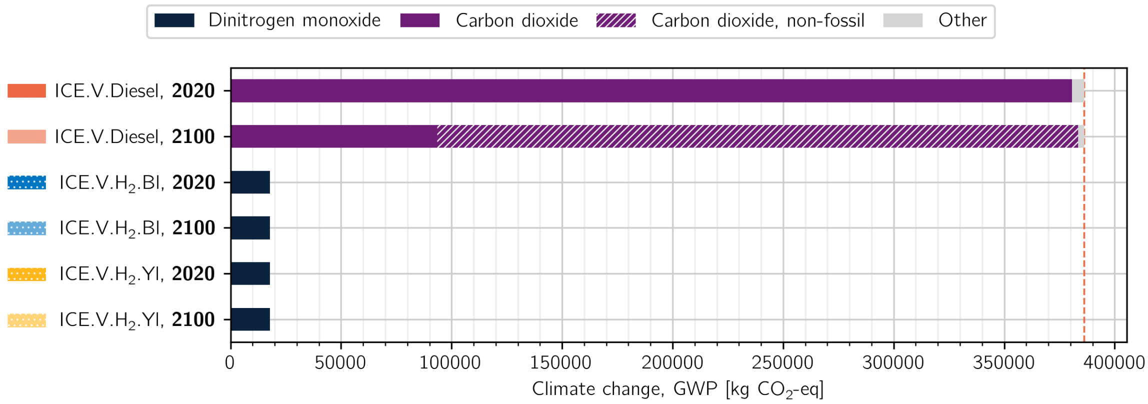


Figure 9.17: Contribution analysis per environmental flow in the impact category climate change (updated to include characterisation factors for hydrogen gas emissions). In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

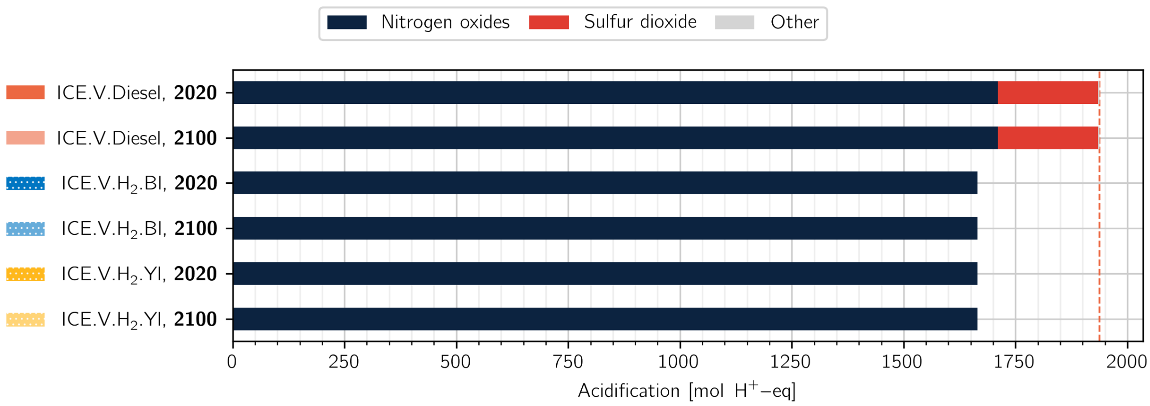


Figure 9.18: Contribution analysis per environmental flow in the impact category acidification. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

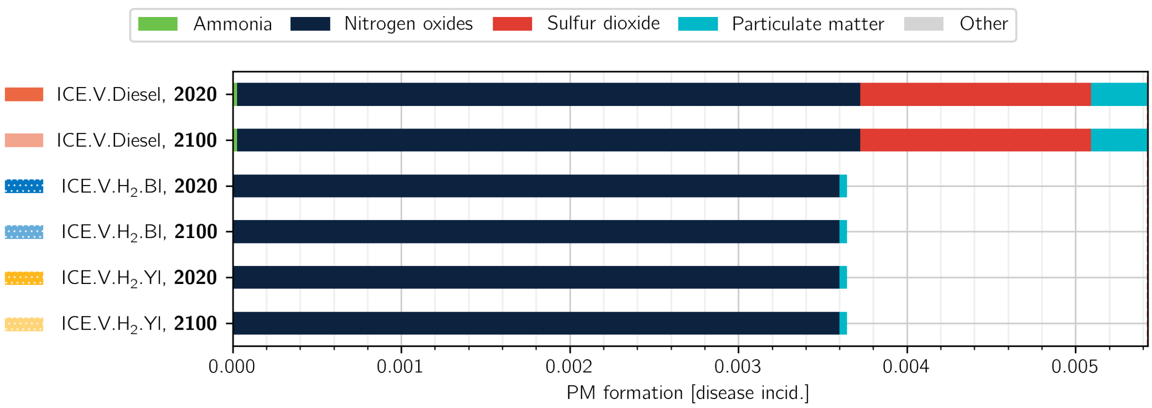


Figure 9.19: Contribution analysis per environmental flow in the impact category particulate matter formation. In orange, the baseline of ICE.V.Diesel (2020) for quick comparison.

9.4. Sensitivity analysis

The following modelling choices are considered to have a large potential impact on the nature of the results, and as such a sensitivity analysis is carried out for each of these.

1. Power system efficiency
2. Barge power and energy capacity
3. Scenario selection
4. Gradual replacement of fossil diesel by biodiesel and synthetic diesel

9.4.1. Power system efficiency

The contribution results have shown that the main contributors to inland shipping emissions (impact categories climate change, acidification, and PM formation) of the modelled system are the fuel supply and operations. These two system components are inversely proportional to the efficiency of the modelled power system (Table 7.2): at half efficiency, two times the energy input will be needed and two times the operational emissions will be emitted. And while all operational efficiencies depend on shipping routes and behaviour, the battery-electric and HFC efficiencies are especially uncertain, as no measurements or models corresponding to (inland) shipping appear to be available.

Concretely, the following efficiency ranges are to be considered:

- For the ICE power system, Boersema et al. (2023) indicate that 38%, which corresponds to the model value sourced from Abma and Verbeek (2017), is a commonly used theoretical efficiency. The actual efficiency may be as low as 30% when taking into account shipping behaviour and common loads.[2]
- Similarly, for the HFC system described by Boersema et al. (2023), the average efficiency is 44%, but the possibilities for efficiency range from 33% to 58%.
- For the battery-electric power system, Albatayneh et al. (2020) give a possible efficiency range, sourced from literature, for each system element. These combine to the average of 75% used in this study, but have a combined range of approximately 60% to 85%.

Figures 9.20 to 9.25 contain a simplified version of the contribution analysis shown in Section 9.3.1, including error bars for the possible results based on these efficiency ranges.

> **How to interpret power system efficiency results**
>
> The charts in these figures are a simplified version of the contribution analysis, divided only into two shares: fuel supply and operations, and all other contributions (barge life cycle, power system life cycle, infrastructure, etc.). The black error bars (whiskers) in each plot indicate the range within which each bar could lie based on the efficiency range of the power system.

Analysing these figures makes some of the previous observations less certain, although the overall trends still hold. Where previously a slight but consistent benefit of hydrogen in an HFC solution over an ICE solution was observed, it can now be seen that the corresponding error bars overlap, and that a different real-life efficiency could favour the ICE solution instead.

[2] Other factors affecting the ICE efficiency range, such as the introduction of hybrid systems – which are less efficient in theory but may yield better total results due to improved flexibility and optimised load levels – are not considered, as no accurate data on these is available.

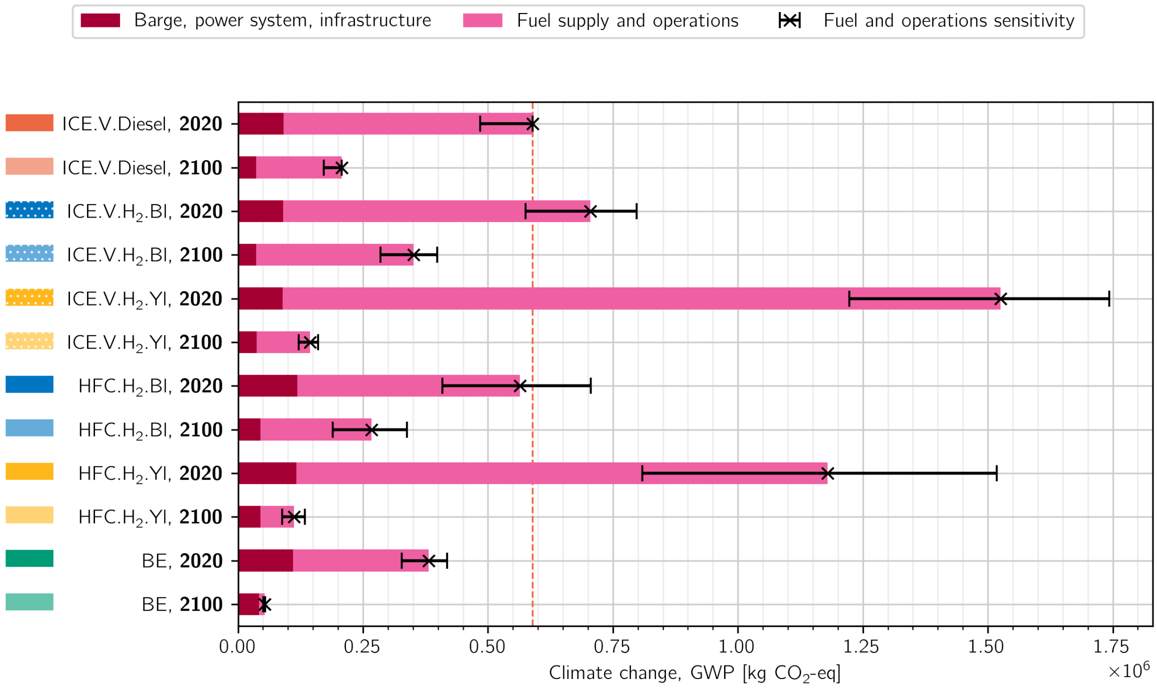


Figure 9.20: Characterisation results in the impact category climate change (updated to include characterisation factors for hydrogen gas emissions), including error bars for sensitivity to power system efficiency.

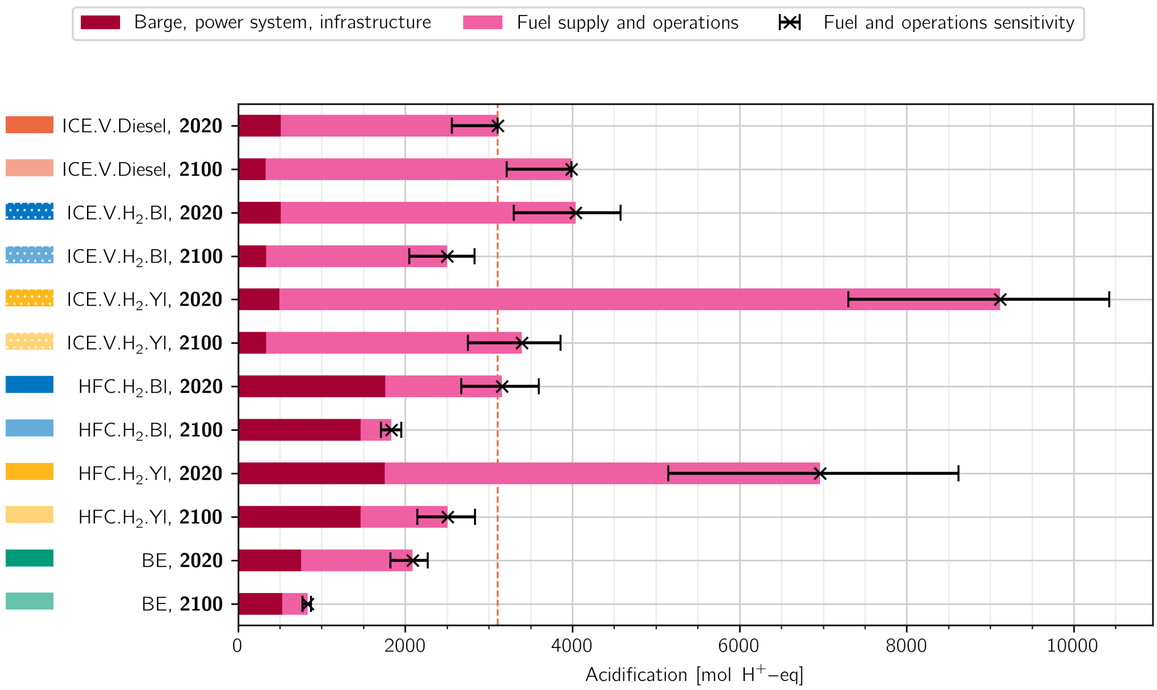


Figure 9.21: Characterisation results in the impact category acidification, including error bars for sensitivity to power system efficiency.

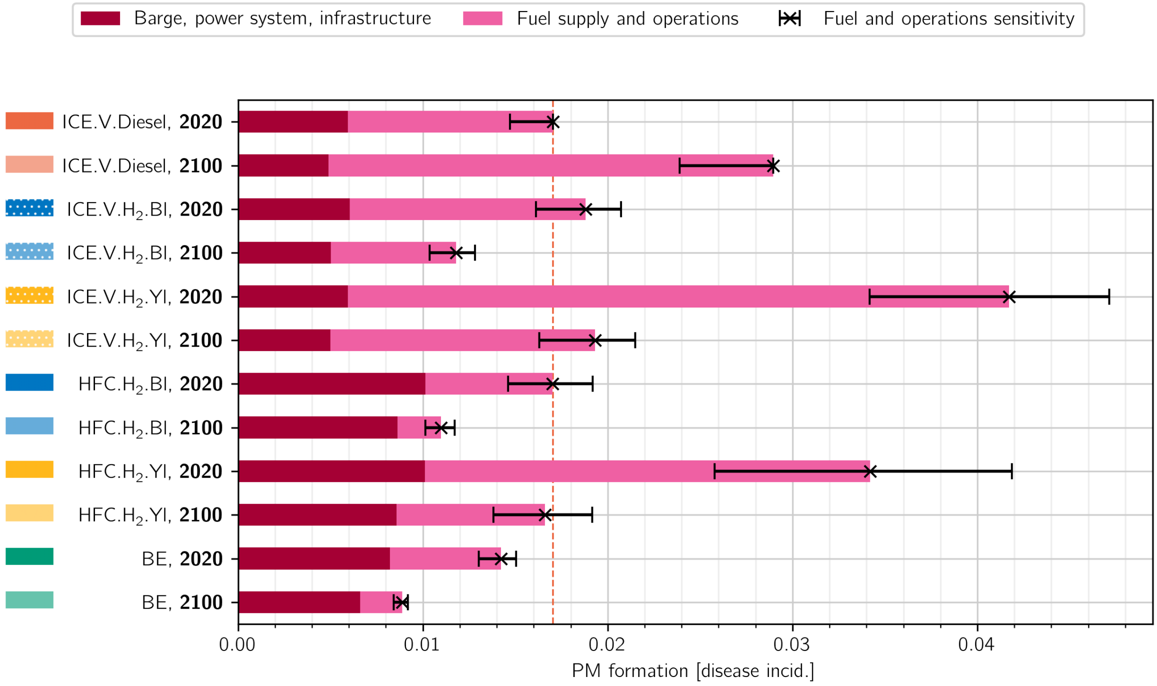


Figure 9.22: Characterisation results in the impact category particulate matter formation, including error bars for sensitivity to power system efficiency.

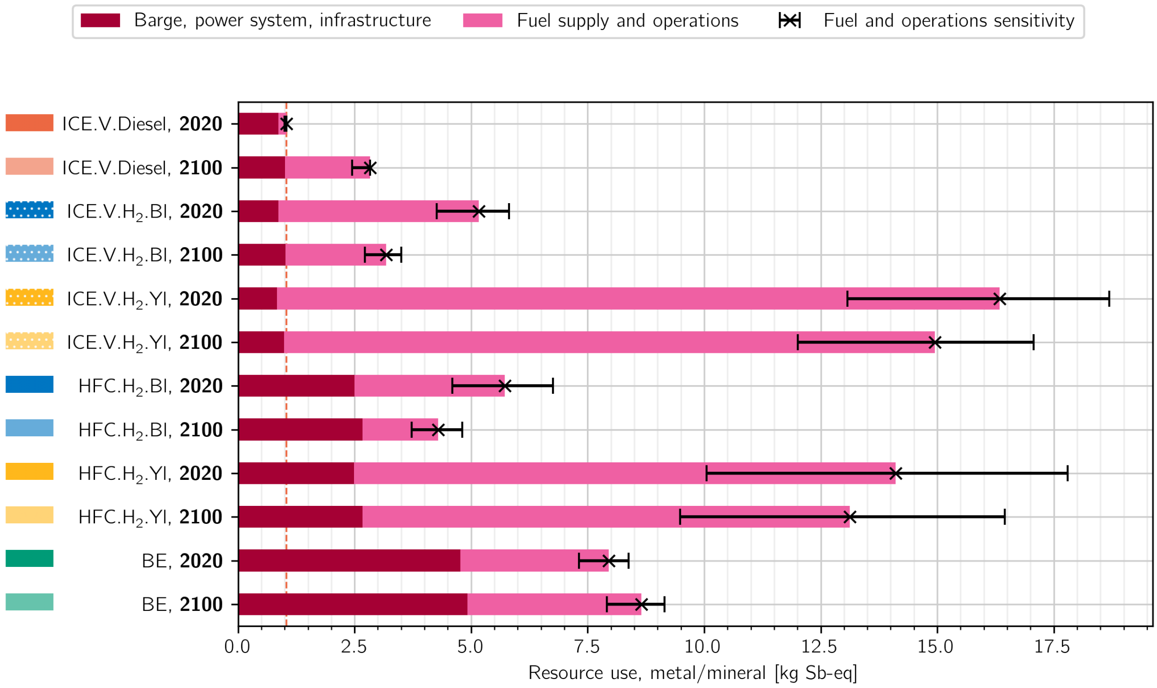


Figure 9.23: Characterisation results in the impact category material resources, metals/minerals, including error bars for sensitivity to power system efficiency.

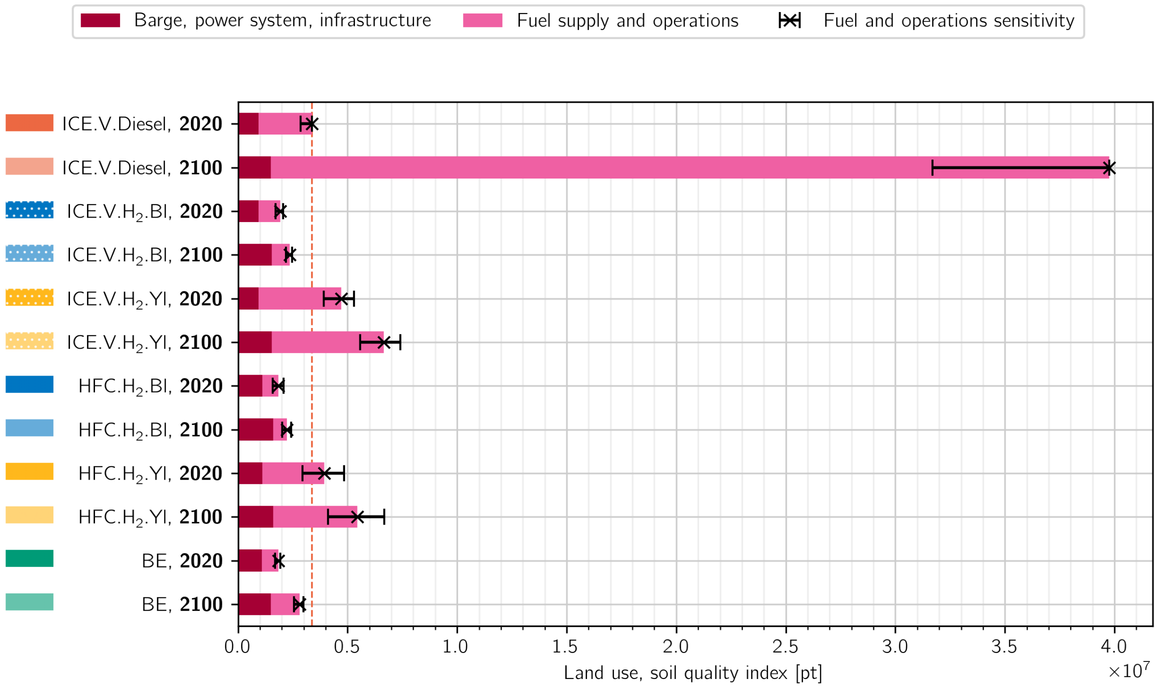


Figure 9.24: Characterisation results in the impact category land use, including error bars for sensitivity to power system efficiency.

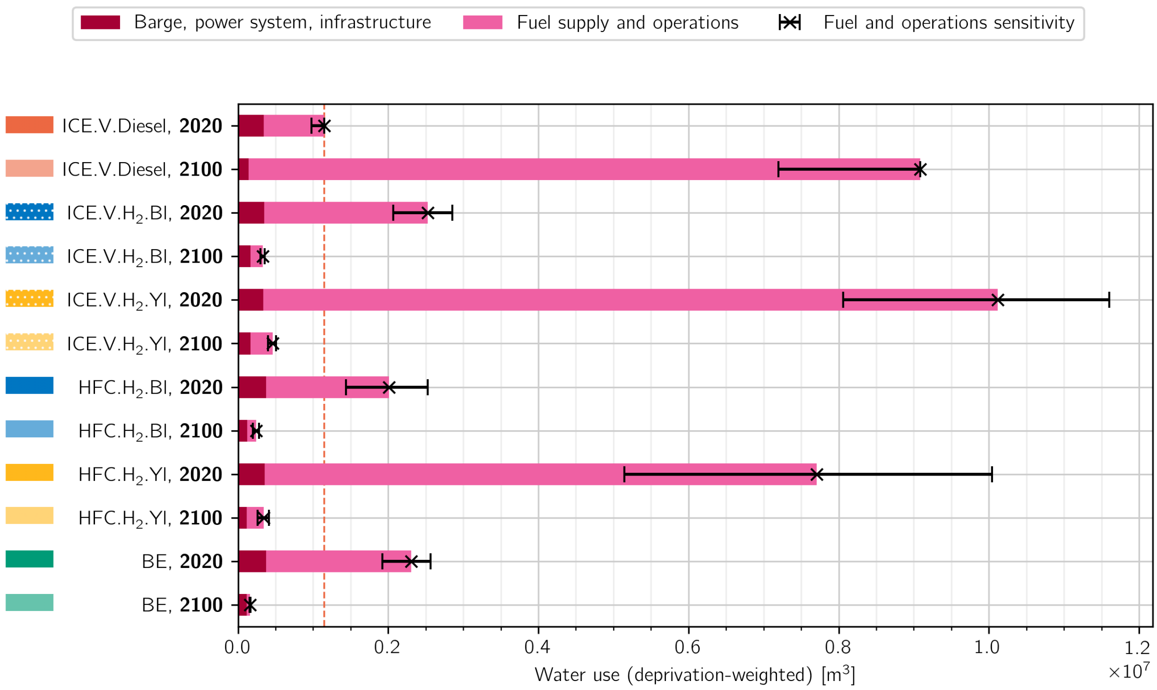


Figure 9.25: Characterisation results in the impact category water use (updated to characterise water extraction and emissions instead of evaporation), including error bars for sensitivity to power system efficiency.

9.4.2. Barge engine power and energy capacity

Leendert-Angelina, the barge used for the case study, was selected based on representativeness for the entire inland shipping sector, as well as criteria for barge refitting drafted by van der Geest et al. (2023). This barge is of a medium size and power, and generally travels short routes for which a low energy capacity is needed.

The characterisation results show that, in the 2100 scenario, the battery-electric alternative has the lowest overall emissions (impact categories climate change, acidification, and PM formation). However, the contribution analysis has shown that, especially for the this alternative, the battery production is responsible for a significant portion of the total impact. For a barge travelling longer distances or larger loads, this conclusion would likely not hold. Similarly, while the results show that a HFC solution has lower emissions than a hydrogen ICE solution, this may not be the case for a barge that requires more engine power, as the production of the fuel cell system also has a large contribution to the overall impacts of the HFC alternatives.

In Figures 9.26, 9.27, and 9.28 (climate change, acidification, and PM formation), the sensitivity of the 2100 results to the required energy capacity is shown, displaying the environmental impact of each alternative as a function of energy capacity/transportation required per trip. The contribution to impacts of hydrogen storage tanks is considered to scale linearly with this demand, while the contribution of battery containers increases in steps (each corresponding to an additional 2563 kWh container). The contribution of increasing diesel storage is considered negligible.

How to interpret Figures 9.26, 9.27 and 9.28

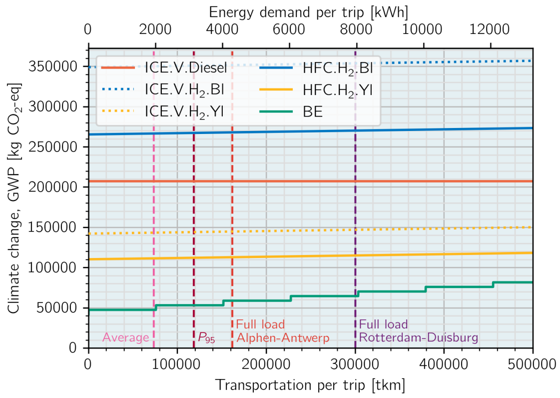
These figures, each corresponding to a different impact category, indicate the environmental impact of a selection of alternatives, as a function of the transportation demand per trip, which is assumed to scale linearly with the energy capacity (batteries or hydrogen tanks) required on board. In each chart, each coloured line corresponds to an alternative, and generally each alternative's impact increases with increasing transportation demand. In terms of environmental impact, the lowest-scoring alternative is the most desirable.
A selection of reference barges are included in these charts, as vertical dashed lines located at the position of their energy / transportation demand.

In Figures 9.29, 9.30, and 9.31 (climate change, acidification, and PM formation), the sensitivity of the 2100 results to both the energy capacity and the engine power is shown, with a 2D surface coloured according to the alternative with the lowest impact in that impact category for a given combination of engine power and energy capacity/transportation required per trip. For energy capacity/transportation the same considerations as before apply; for engine power only the contribution of fuel cells is considered to scale linearly, with the contribution of increasing ICE and electric motor power considered negligible.

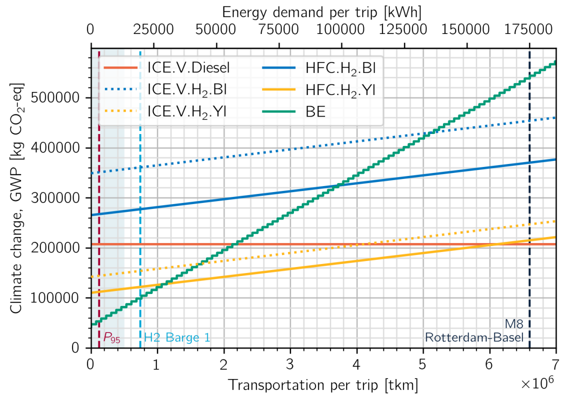
How to interpret Figures 9.29, 9.30 and 9.31

These figures, each corresponding to a different impact category, indicate the most desirable alternative (lowest impact) as a function of a barge's energy/transportation demand per trip (x axis) and its engine power (y axis). The chart areas are coloured according to the alternative that scores lowest for every combination of engine power and energy/transportation deman63.
A selection of reference barges are included in these charts, marked with a white + and labelled.
As a concrete example: a barge with the properties of the *H2 Barge 1*, which has an engine that is slightly less powerful than that of the *Leendert-Angelina* but has a higher energy capacity than the *Leendert-Angelina* as modelled in the case study, would have the lowest climate change impacts and lowest acidification impacts when operating with a battery-electric power system, but its PM formation impacts would be lowest if operating using blue hydrogen in an ICE.

In these figures, various operational profiles for the *Leendert-Angelina* and other barges are marked as references (Table 9.1).

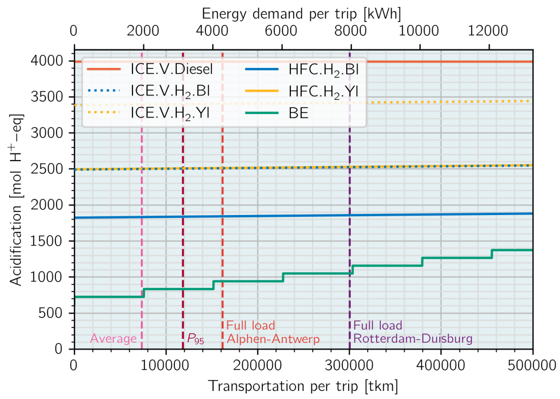


(a) For low energy capacity/transportation demand.

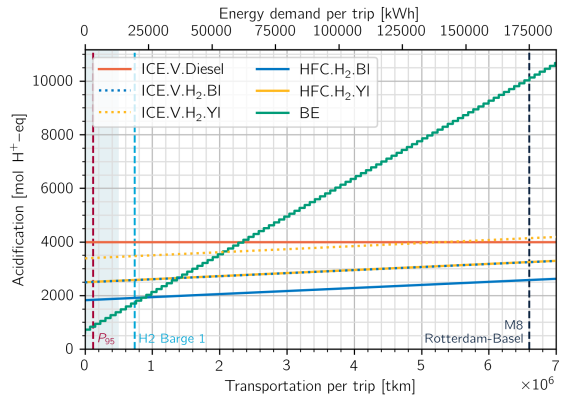


(b) For larger energy capacity/transportation demand.

Figure 9.26: Sensitivity analysis of the impact category climate change to changing energy capacity/transportation demand (2100).

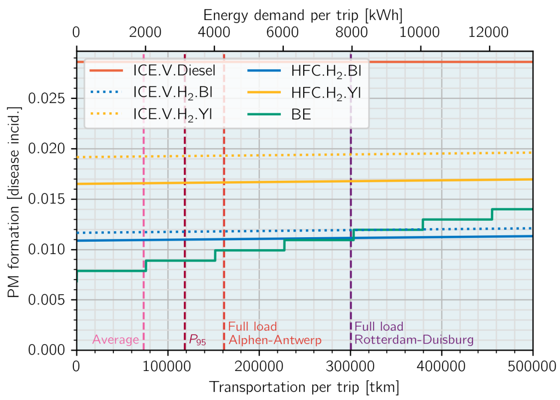


(a) For low energy capacity/transportation demand.

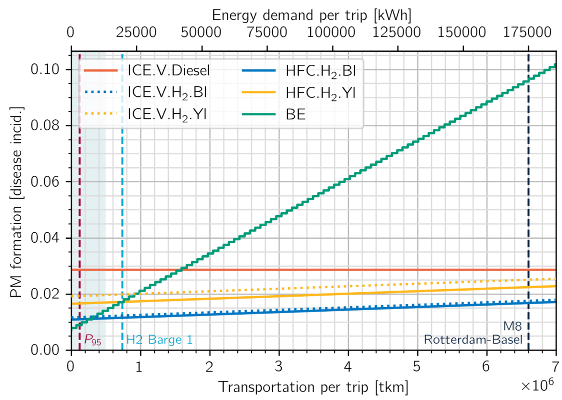


(b) For larger energy capacity/transportation demand.

Figure 9.27: Sensitivity analysis of the impact category acidification to changing energy capacity/transportation demand (2100).



(a) For low energy capacity/transportation demand.



(b) For larger energy capacity/transportation demand.

Figure 9.28: Sensitivity analysis of the impact category PM formation to changing energy capacity/transportation demand (2100).

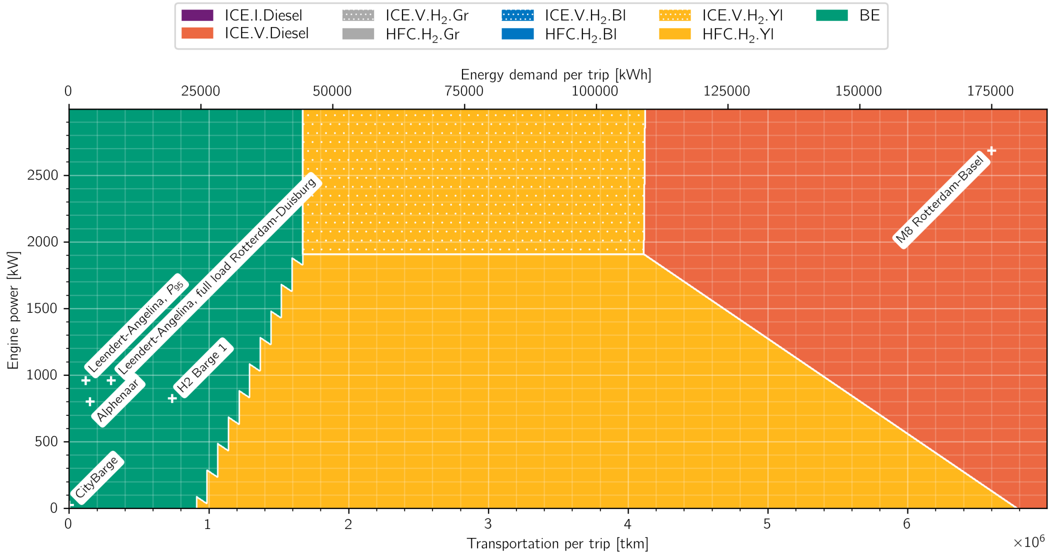


Figure 9.29: Sensitivity analysis of the impact category climate change to changing energy capacity/transportation demand and engine power (2100).

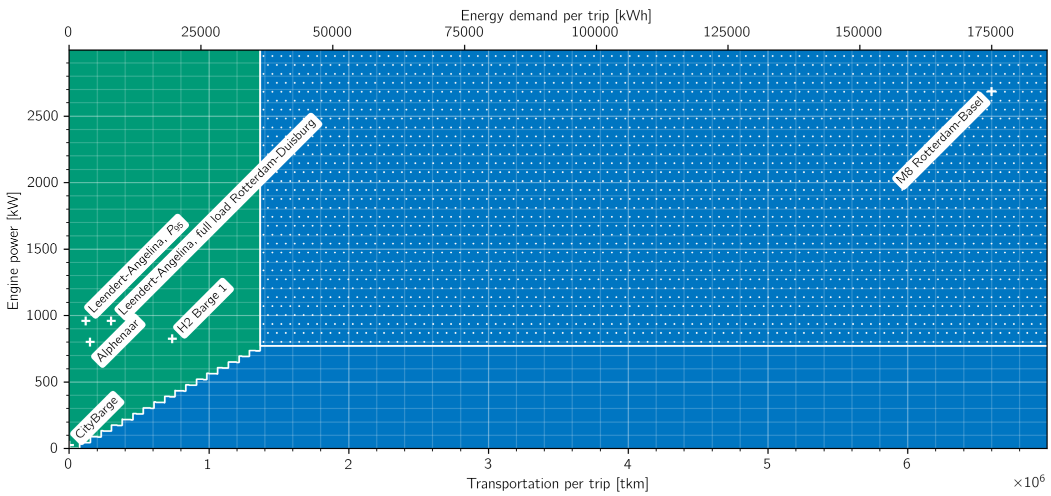


Figure 9.30: Sensitivity analysis of the impact category acidification to changing energy capacity/transportation demand and engine power (2100).

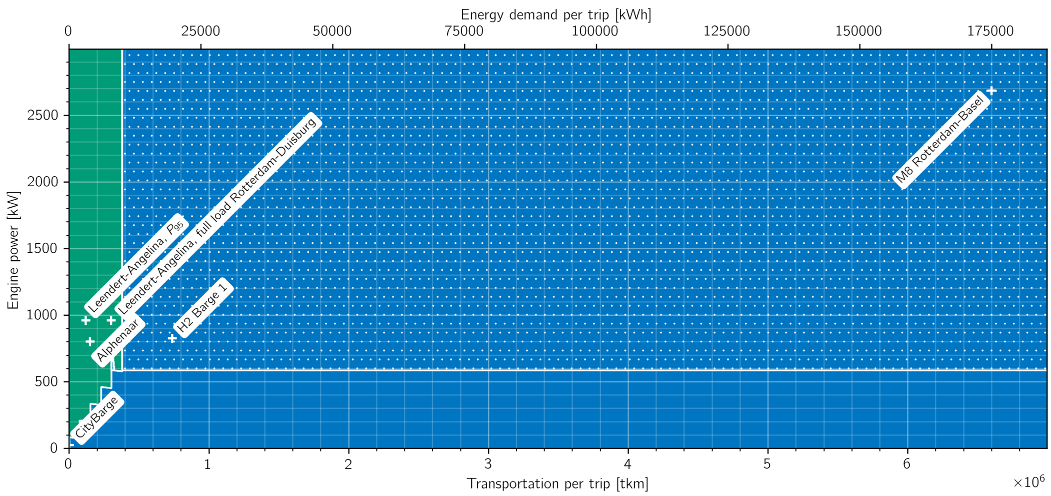


Figure 9.31: Sensitivity analysis of the impact category PM formation to changing energy capacity/transportation demand and engine power (2100).

Table 9.1: List of reference barges indicated in the figure of the "engine power and energy capacity" sensitivity analysis, alongside their engine power and an estimate for energy capacity for the stated operational profile, based on efficiencies for the *Leendert-Angelina*.

Label	Power	Capacity	Description
Average	960 kW	1945 kWh	*Leendert-Angelina*, with the average transportation required for an average shipping movement.
P_{95}	960 kW	3140 kWh	*Leendert-Angelina* in the case study situation, based on the 95th percentile (P_{95}) of its shipping movements.
Full load Alphen-Antwerp	960 kW	4284 kWh	*Leendert-Angelina*, on its most energy-intensive shipping movement recorded in South Holland, from Alphen aan de Rijn to Antwerp.
Full load Rotterdam-Duisburg	960 kW	7963 kWh	*Leendert-Angelina*, on a common international inland shipping route, from Rotterdam to Duisburg, with a full load.
CityBarge	24 kW	40 kWh	A KOTUG CityBarge, as operated by Circle Line Logistics, with a total of 24 kW propulsion power and 40 kWh battery capacity.
H2 Barge 1	825 kW	19 553 kWh	*H2 Barge 1* (formerly *FPS Maas*), an M8-class inland barge operating with a HFC system, with a capacity for 1000 kg of hydrogen.
Alphenaar	800 kW	4000 kWh	*Alphenaar*, a M8-class inland barge currently operating with two 2000 kWh battery containers.
M8 Rotterdam-Basel	1684 kW	175 000 kWh	Generic M8-class inland barge on a long international route, from Rotterdam to Basel.

These results indicate that, regarding these three impact categories, the BE alternative is the most favourable only when energy capacity/transportation demand is comparatively low. When a higher capacity is needed, a hydrogen solution becomes more effective (yellow, when considering climate change; blue, when considering acidification and PM formation). And for hydrogen, a HFC system has lower overall emissions for low engine power, while at higher engine power, an ICE solution is more effective. Counterintuitively, at high engine power and energy capacity/transportation, sailing on diesel appears to remain the alternative giving the least contribution to global warming. However, it is important to keep in mind that this is based on a scenario where the diesel supply is based entirely on biodiesel and synthetic diesel, and would not be true for fossil-based diesel.

All these results are based on the *Leendert-Angelina*'s average energy-to-transportation ratio, which is assumed to be fixed and to hold for the other barges included as well – even if this is unlikely to be true for barges much larger or smaller. Furthermore, practical matters such as reduction in cargo space for placing battery containers (making the BE alternative impractical as required battery capacity increases) are also not taken into account. For instance, the *H2 Barge 1*'s position in Figure 9.26 and Figure 9.29 indicates that this barge would have low climate change impact if powered by battery containers – however, for a battery capacity equivalent to its 1000 kg of hydrogen (stored in 2 containers), an impractical total of 10 battery containers would be needed. The very longest routes, such as Rotterdam-Basel, would require more battery containers than container spaces available on board.

All these considerations change if it is possible to introduce additional stops along a route. If occasional stops are possible for refuelling on very long routes, hydrogen fuel remains an option instead of having to resort to (bio-/synthetic) diesel. And if even more frequent stops can be planned in, battery containers can be swapped on-route, making it viable to cover long distances on battery containers with low environmental impacts and without the mentioned practical and economical disadvantages. The practicality and indirect changes in environmental impacts of such changes (e.g. lower average speed due to extra stops) are not covered in the scope of this study.

9.4.3. Scenario selection

For the analysis of results throughout the 21st century, the SSP2 pathway (extrapolated development trends) was selected, and within this pathway, the SSP2 - RCP2.6 scenario for moderate climate policies in line with the Paris Agreement. However, as discussed in Section 6.2.2, the SSP2 - Base (no significant climate policies) and SSP2 - RCP1.9 (more ambitious climate policies in line with the Paris Agreement), are also of interest to this study. The difference in assumptions for changes to the electricity and diesel sector have been displayed previously in Figure 6.1 and Figure 6.3.

The analysis is repeated with Premise databases for this other databases, so that the following characterisation results can be compared, from less to more ambitious climate policies:

SSP2 - Base Figure 9.32 (page 94) and Figure 9.33 (page 95)

SSP2 - RCP2.6 Figure 8.1 (page 54) and Figure 8.2 (page 55), the default scenario in this analysis

SSP2 - RCP1.9 Figure 9.34 (page 96) and Figure 9.35 (page 97)

In the long run, especially in 2100, the characterisation results between the three scenarios are very similar. The main differences between the three scenarios lie in 2030 and 2050, where the decrease in emissions across all alternatives depends on the climate policy ambition level in the scenario. It can be observed how for the more ambitious SSP2 - RCP1.9 scenario most non-diesel alternatives have much lower CO_2 emissions than the diesel alternatives starting in 2030, while for the SSP2 - Base scenario this remains more ambiguous until 2050.

Conversely, the additional environmental impact in PM emissions, land use, and water use caused by the introduction of biofuel and synthetic fuel in the diesel mix are also delayed in the less ambitious scenario, and strengthened in the more ambitious scenario. The effects of this fuel mix on the results will be discussed in more detail in the following section.

9.4.4. Gradual replacement of fossil diesel by biodiesel and synthetic diesel

In all three scenarios, a majority of the diesel supply is projected to be substituted by biodiesel or synthetic diesel, both hailing from biomass. This is in line with reducing CO_2 emissions to net zero, as such biogenic CO_2 emissions can be excluded from emission totals. However, the required production chain for these fuels has significant environmental impact in other impact categories, such as the strong increase in land and water use for the two diesel alternatives when approaching 2100 discussed in the contribution analysis.

Figure 9.36 (page 98) and Figure 9.37 (page 99) contain the characterisation results for a scenario in which the diesel mix does not vary, and diesel remains fully fossil-based even in 2100. The following differences can be observed:

1. Greenhouse gas emissions of diesel decrease only slightly between 2020 and 2100, as use-phase emissions of CO_2 do not vary.
2. Acidification impacts of diesel does not increase, but slightly drop.
3. Photochemical oxidant formation impacts of diesel drop only slightly.
4. Particulate matter formation impacts of diesel does not increase, but slightly drop.
5. Fossil resource use of diesel drops only slightly, as fossil fuels stay in use.
6. Metal/mineral resource use of diesel increases only slightly, as more resource-intensive fuel production processes are not needed.
7. The extreme increases in land use and water use of diesel disappear, so that the diesel alternatives have the lower impacts of all alternatives in these categories.

Overall, it can be seen that, without the aid of biofuels or synthetic fuels, using diesel as energy carrier for inland shipping results in continued high greenhouse gas emissions and moderate-to-high local emissions (acidification, photochemical oxidant formation, PM formation) from barge operations.

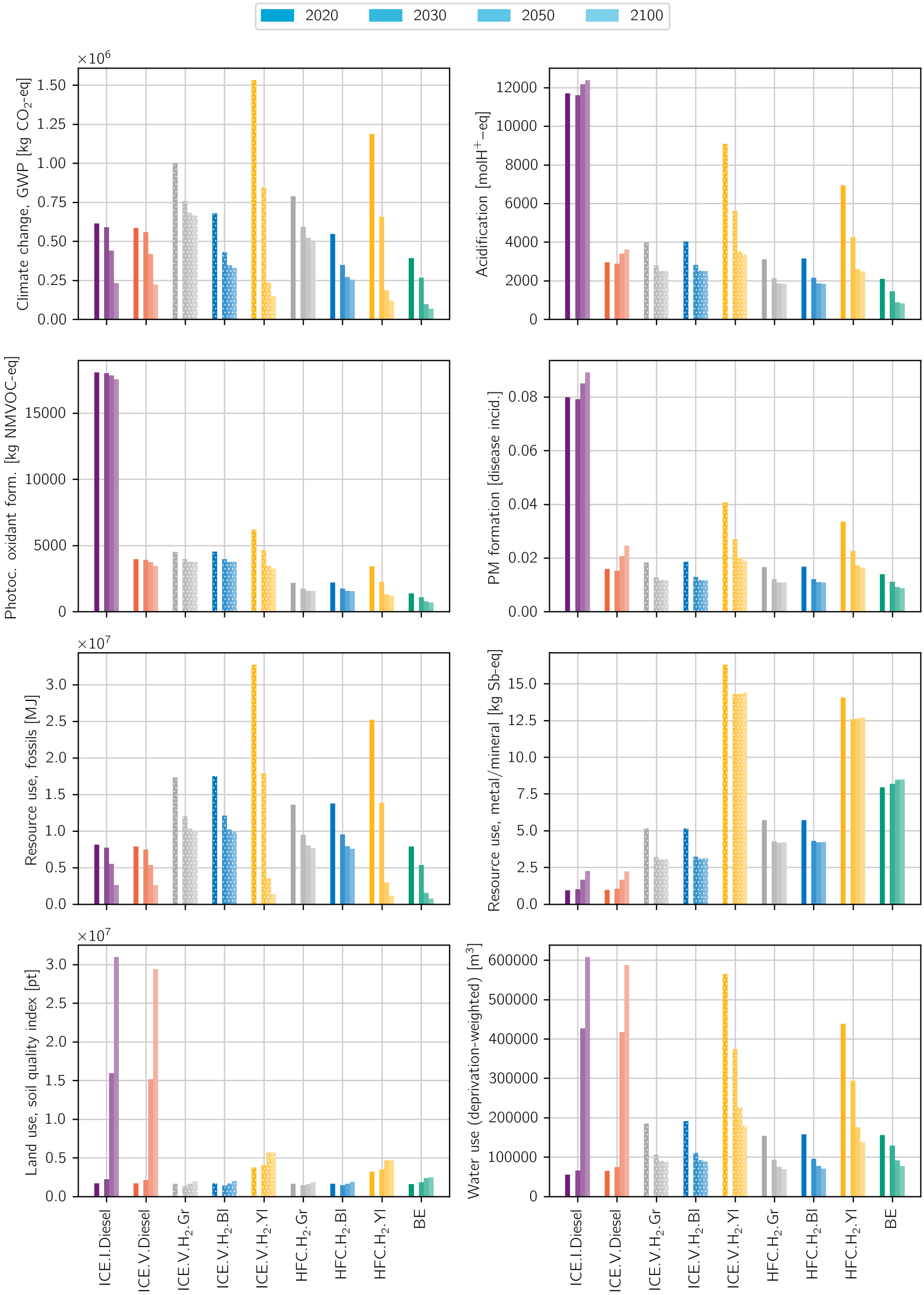


Figure 9.32: Characterisation results in the SSP2-Base scenario, each graph representing a different impact category. Results grouped by alternative. Compare to Figure 8.1 and Figure 9.34.

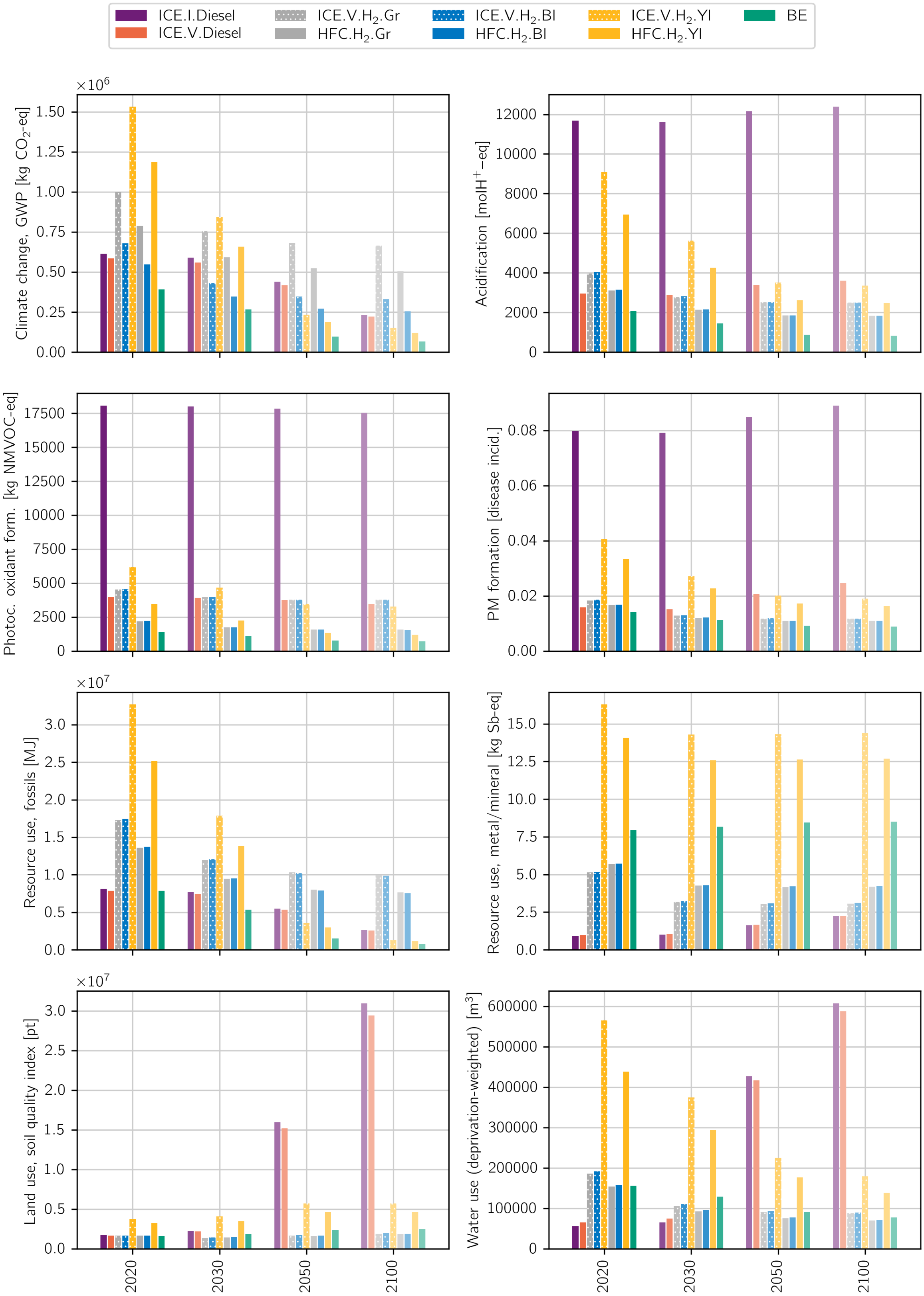


Figure 9.33: Characterisation results in the SSP2-Base scenario, each graph representing a different impact category. Results grouped by year. Compare to Figure 8.2 and Figure 9.35.

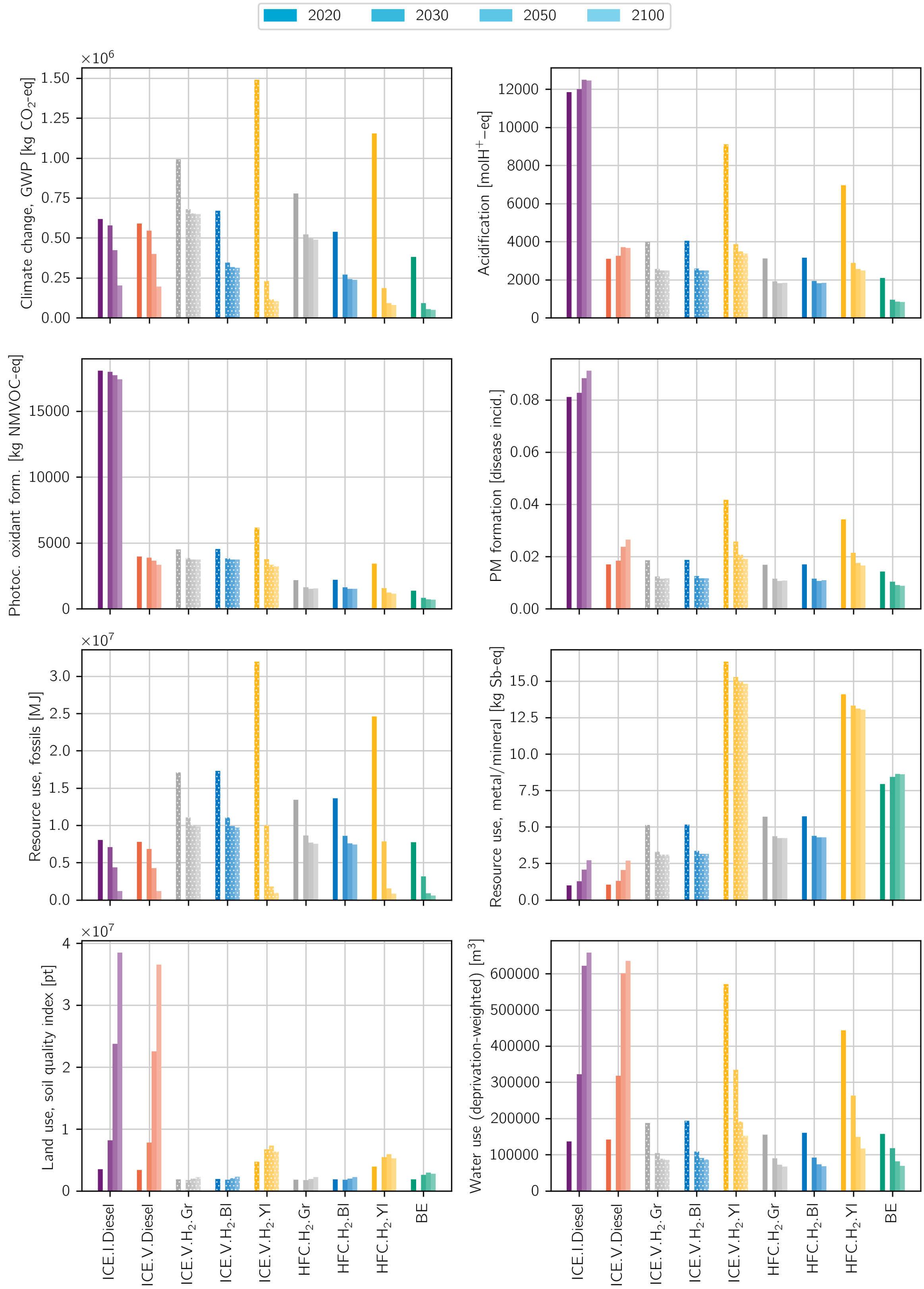


Figure 9.34: Characterisation results in the SSP2-RCP1.9 scenario, each graph representing a different impact category. Results grouped by alternative. Compare to Figure 9.32 and Figure 8.1.

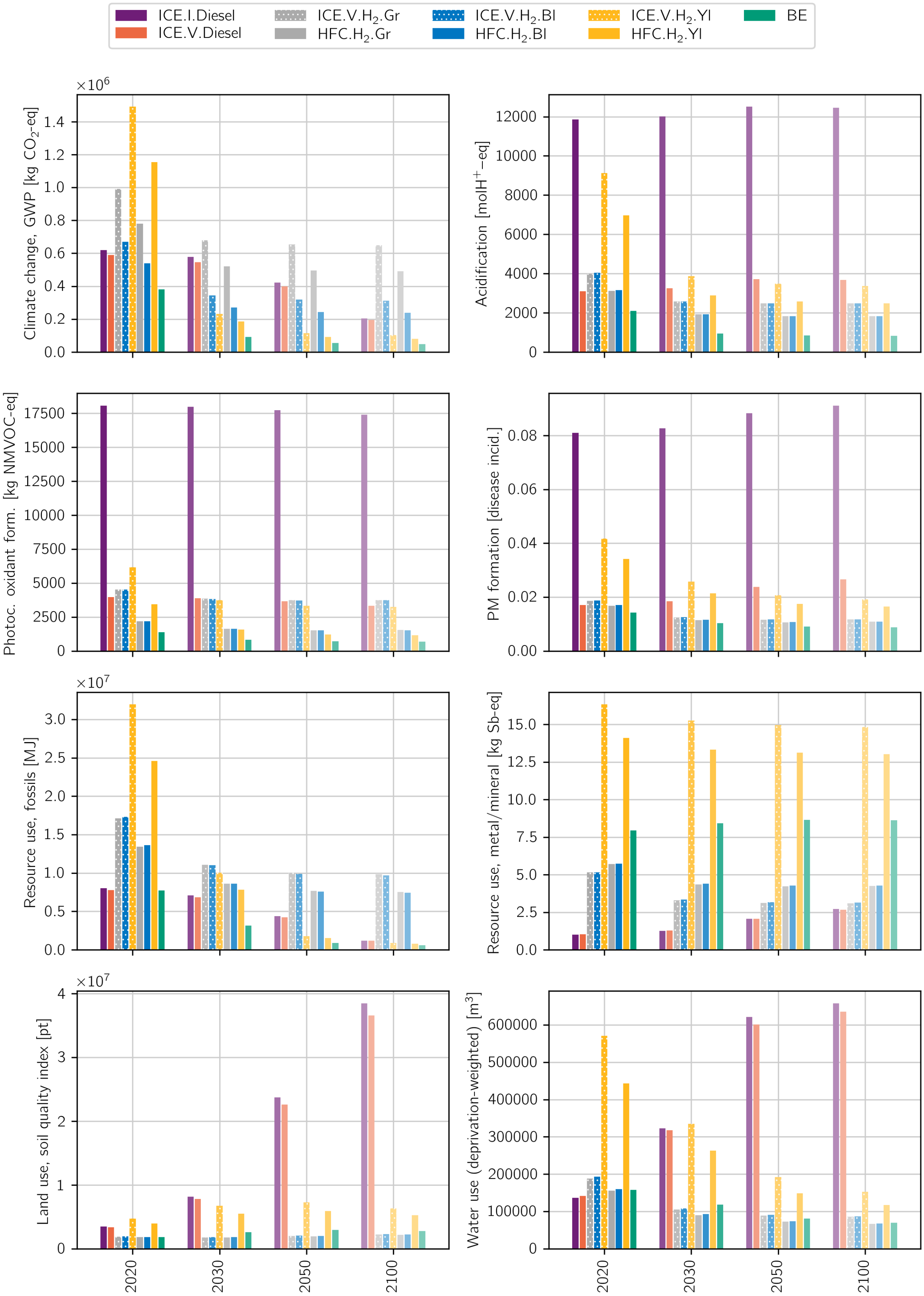


Figure 9.35: Characterisation results in the SSP2-RCP1.9 scenario, each graph representing a different impact category. Results grouped by year. Compare to Figure 9.33 and Figure 8.2.

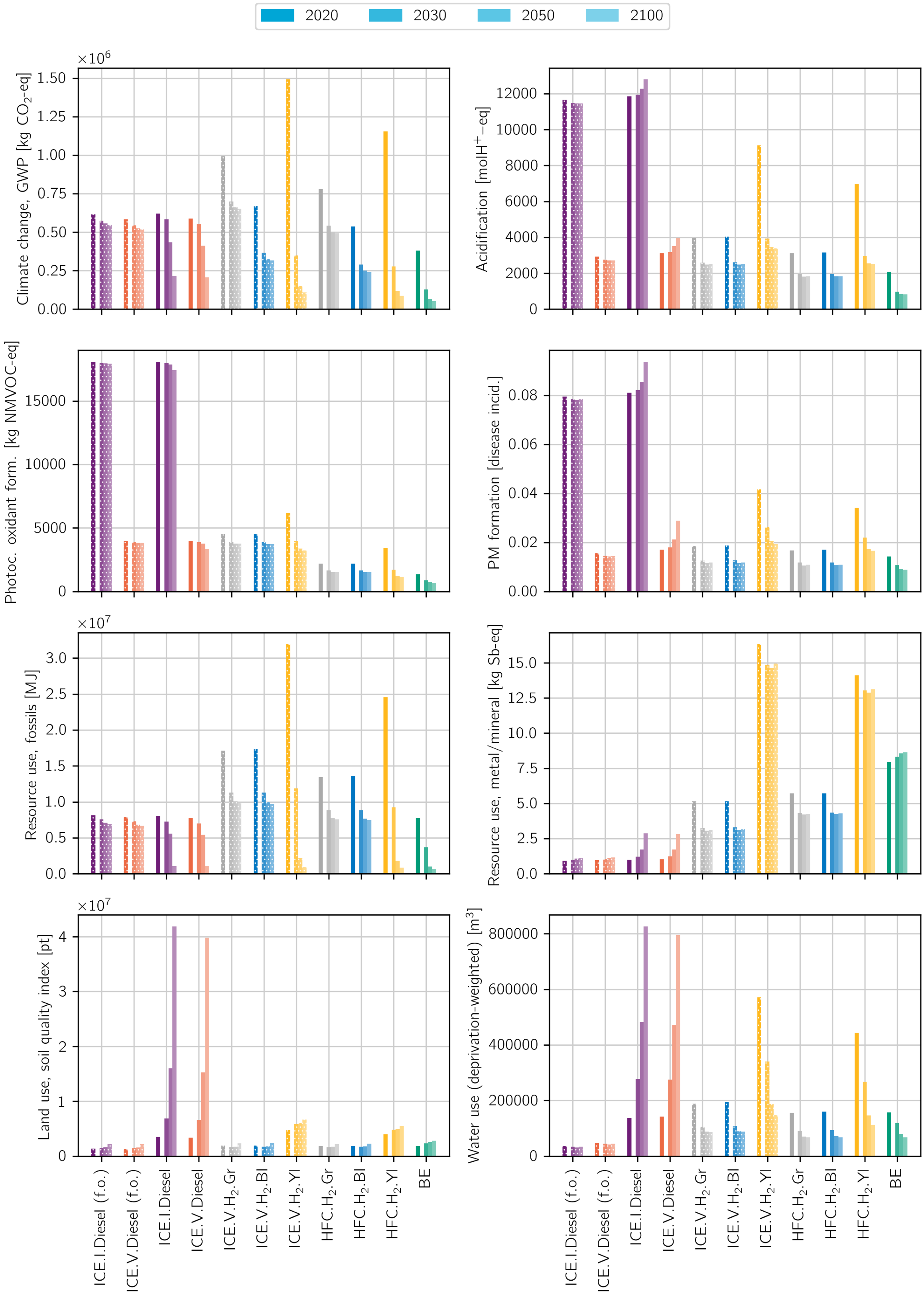


Figure 9.36: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category. Results grouped by alternative. Including comparison with diesel without non-fossil substitutes.

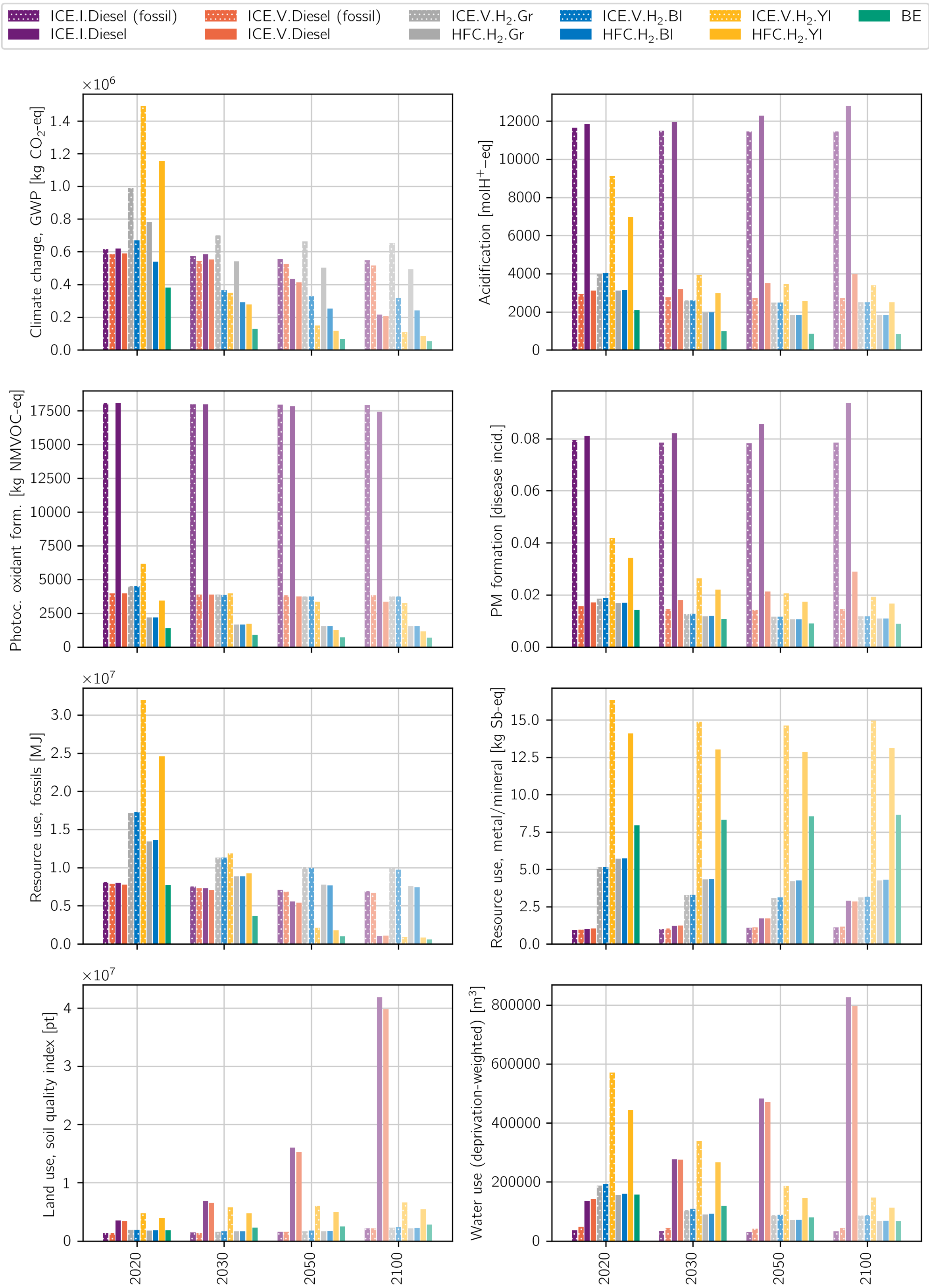


Figure 9.37: Characterisation results in the SSP2-RCP2.6 scenario, each graph representing a different impact category. Results grouped by year. Including comparison with diesel without non-fossil substitutes.

IV

Discussion & conclusions

Image: Binnenvaart Erasmusbrug, by Nextlogic

10

Discussion

10.1. Implications of the obtained results

The LCA results and their interpretation lead to an extensive series of observations regarding different potential energy carriers and engine technologies for inland shipping. None of these is "best" overall: the most preferable solution depends on which environmental impact categories are prioritised, whether priority is given to benefits and drawbacks on the short or long term, and what type of barge and route is assessed.

10.1.1. On zero-emission shipping

A goal that is often strived for is "zero-emission shipping". If this is a mandatory boundary condition, and if this is interpreted as meaning "no emissions whatsoever in the operational phase", any ICE solution must be discarded. Of the studied alternatives, only a hydrogen fuel cell or battery-electric solution is zero-emission. As has been seen, and as will be discussed further below, these alternatives are the ones with the most significant practical challenges.

Besides practical considerations, it can also not be stated that these options are truly zero-emission. Emissions elsewhere in the life cycle remain, and are often higher than they would be for a conventional diesel ICE solution. This is an example of *burden shifting*, and should not be neglected. In the short term, climate change and some local impacts to health and the environment from a hydrogen solution may lie higher than they are for a diesel solution. But where diesel emissions happen mainly during ship operations, the hydrogen emissions happen in the industrial fuel production chain, further away from population centres and where future point-source emission capture can have more potential.

10.1.2. On the viability of electric batteries

When considering the entire life cycle, and looking at projected development for 2030 and beyond, a battery-electric solution appears to be the most favourable one for the studied barge and route. It has the lowest impact for climate change, acidification, photochemical oxidant formation, PM formation, and fossil resource use impact. Conversely, metal/mineral resource use is relatively high, and land and water use also increases moderately when compared to the present (fossil diesel) case.

As seen in Section 9.4.2, the environmental advantage of electric batteries decreases as more energy capacity is required, due to the large contribution of battery production to this alternative's environmental impact. Regarding climate change and acidification, electric batteries lose their advantage for energy capacity requirements of more than approximately 25 000 kWh, and regarding PM formation, above 8000 kWh. Above these demands, a hydrogen solution has lower life-cycle impacts. These limits may be increased depending on future developments in battery technology, whether batteries' lifespans end up longer than the 10 years considered in this model, or whether batteries can be usefully repurposed for e.g. grid balancing.

In practice, these environmental constraints to battery usage may not even be encountered: there are also economical and practical limitations to consider. A battery-electric solution may be less expensive over the lifetime of a barge, but requires much higher upfront investment costs than a diesel ICE (EICB & TNO, 2021) mainly due to the production of batteries. And there are practical limitations to how many batteries a barge can carry. At about 2500 kWh per battery container (with present battery technology), carrying sufficient battery containers for a long route becomes impractical or even impossible. This could be mitigated by planning in extra stops for switching or recharging batteries on-route, with the viability of this depending on the frequency of stops needed, which in turn depends on battery capacity and ship load.

For short routes and light loads, such as the local-level transportation offered by the city barges mentioned in Chapter 3, a battery-electric solution remains the best contender overall.

10.1.3. On hydrogen fuel and types of hydrogen

Three types of hydrogen have been assessed: grey hydrogen (produced from natural gas via steam methane reforming), blue hydrogen (grey hydrogen, with carbon capture and storage (CCS) at its production), and yellow hydrogen (produced from grid electricity via electrolysis). In the long term, with projections for grid electricity to become fully decarbonised in the second half of the century, yellow hydrogen becomes equivalent to green hydrogen.

In terms of decarbonisation and reducing dependence on fossil fuels, yellow/green hydrogen is the only viable long-term solution. Indeed, after electric batteries, yellow hydrogen (be it in a HFC or ICE solution) is the energy carrier with the lowest global warming and fossil resource extraction impact beyond 2050. It should be noted that, as the characterisation results confirm, the production of yellow hydrogen is less than half as efficient as using electricity directly via batteries due to inefficiencies and losses in conversion, transportation and storage.

However, looking at local environmental pollution (acidification, PM formation), yellow hydrogen is not the least impactful of the hydrogen fuels. For these two impact categories, yellow hydrogen impacts are 25% to 50% higher than those of grey or blue hydrogen, remaining comparable to those of diesel in a Stage V ICE. It bears repeating that these impacts take place in a different part of the assessed system (fuel production for hydrogen, barge operations for diesel) and thus in a different geographical location; for the Province of South Holland, the emissions from hydrogen production may be less urgent to address due to them occurring at industrial sites, away from population centres and potentially easier to capture or mitigate, as opposed to on waterways throughout the province.

In comparing grey or blue hydrogen, the results indicate a decrease of up to 50% of climate change impacts with negligible increases in other impact categories. This observation, based on the hydrogen production datasets from Premise and sourced from Antonini et al. (2020), indicates that blue hydrogen should be preferred to grey hydrogen in terms of environmental impact. However, as of present, CCS technology is still in initial phases of development, and pathways for its implementation are uncertain and cannot be relied upon (EICB & TNO, 2021).

In any case, for the success of hydrogen fuel (yellow/green, if climate change impact reduction is prioritised), it is important for hydrogen production and distribution infrastructure to be scaled up significantly beyond what is available now, and research to be carried out into improving efficiency and point-source CO_2 capture technology in the necessary hydrogen/electricity production processes. Existing projects and collaborations in South Holland and the rest of the Netherlands provide a starting point for this.

10.1.4. On hydrogen fuel cells versus hydrogen combustion

Two main methods of energy production from hydrogen have been assessed. Combustion in an ICE, similar to those already in use for diesel, or electricity production in a hydrogen fuel cell (HFC). The former is more practical and economical to apply – as discussed in Section 4.1 – but also emits some NO_x and PM originating in the combustion process. This is confirmed in the LCA results, with a small but consistent advantage in acidification, photochemical oxidant formation, and PM formation impacts for a HFC solution. Climate change impacts are also lower, as well as land and water use, due to the more efficient use of hydrogen fuel in HFCs. A sensitivity analysis has shown that this advantage disappears at the lower end of the range of possible HFC efficiencies, although real-life ICE efficiencies are also expected to be lower than in theory.

Besides these environmental concerns and the mentioned practical differences, compatibility with other technologies can also be a factor to take into consideration. A hydrogen ICE solution has a technological overlap with the present-day power systems for diesel, and can count on the existent expertise of the South Holland shipping industry. On the other hand, a HFC solution would require an electric power system and auxiliary batteries, making it more similar to a battery-electric solution. Some[1] have already envisioned a future wherein these two technologies do not compete but instead complement each other: by putting hydrogen storage tanks and HFCs in swappable containers, a barge with an electric power system could be switched from hydrogen fuel to electric batteries and back depending on changing requirements.

10.1.5. On land and water use for biofuel and synthetic fuels

An diesel solution has many environmental drawbacks, as has been discussed previously. Regarding climate change impacts only, a significant reduction can be achieved by the gradual replacement of fossil diesel by biodiesel or synthetic diesel alternatives. The assessed future pathway envisions that, by 2100, fossil diesel will be fully phased out and replaced by synthetic diesel ($\sim 75\%$) and biodiesel ($\sim 25\%$). The results have also shown that this would entail a significant increase in land and water use, eclipsing all other alternatives including hydrogen production.

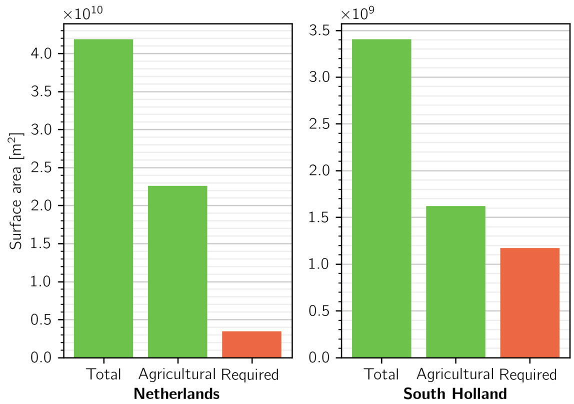


Figure 10.1: Land area required for meeting the biodiesel and synthetic diesel production demand for the entire inland shipping sector in the Netherlands or South Holland, compared to total surface area and agricultural land area.

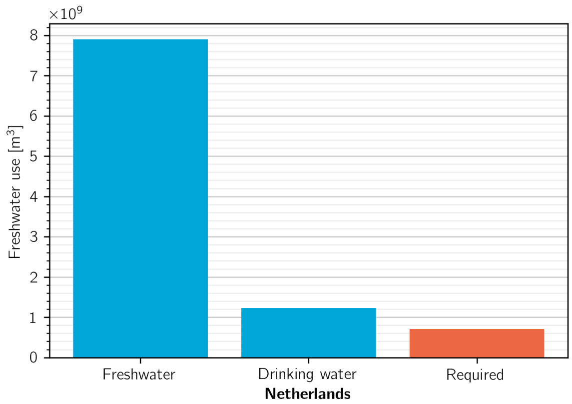


Figure 10.2: Non-weighted water volume required for meeting the biodiesel and synthetic diesel production demand for the entire inland shipping sector in the Netherlands, compared to total freshwater consumption and drinking water consumption.

Figure 10.1 and Figure 10.2 contain a simplified assessment of the land and water use required[2] for the production of the amount biodiesel and synthetic diesel to meet the fuel demand of the inland shipping sectors in the Netherlands (land and water) and South Holland (land only),[3] compared to the amount of land and water available in these regions.[4] This comparison is not entirely fair, as a country or region does not need to be self-sufficient in its energy supply, but nevertheless provides a useful contextualisation of the land and water use that a transition to these fuels would entail.

[1] Discussed at the RH_2INE conference in 2023.

[2] Land use based on the ReCiPe 2016 v1.03, midpoint impact category "land use, agricultural land occupation". Due to the characterisation factors (< 1 on average), the shown results are actually a conservative estimate of the actual land area required. Water use based on the customised EF v3.1 impact category for "water use, deprivation-weighted" with a characterisation factor of 1, thus removing the weighting.

[3] Total transport demand for the Netherlands estimated based on sector fuel demand (Rijkswaterstaat, 2017) and transportation statistics (CCNR, 2021). Share corresponding to South Holland based on mass transported in trips that (partially) take place in the province (van der Geest & De Leeuw van Weenen, 2016), making this a generous estimate due to the inclusion of trips that go beyond the provincial borders.

[4] Land totals based on land use statistics (CBS, 2020). Water totals based on freshwater and drinking water statistics (Contenture, 2022). Note that this refers to the annual consumption of freshwater and drinking water, not the much larger potential available water from rain and rivers.

These charts indicate that the land use for the production of these alternative fuels in a volume enough to meet the demands of the entire sector is prohibitively high. In the case of South Holland, two thirds of agricultural land would be need to destined to agriculture and forestry for fuel production to meet local demand. Even the statistic for the entire Netherlands, more conservative and possibly more accurate, would destine over 8% of the national land area (more than the size of South Holland) to this purpose – competing with food production in a country where most land is agricultural already and unused land is scarce (CBS, 2020) – before considering other sectors also looking to biofuels and synthetic fuels for their energy transition.

Regarding water use, this scenario is more plausible: the required water is over half the available drinking water, but only 9% of the annual consumption of freshwater, which in itself is only a small fraction of the potential freshwater sources (rivers, rain). However, this does not take into account the seasonal nature of water supply and the difficulty to retain large amounts of water, an issue that will worsen as risk of droughts increases in the Netherlands (NOS, 2022a, 2022b).

10.1.6. On energy carriers and technologies not assessed

The list of potential energy carriers and barge power system technologies that could aid in the energy transition of the inland shipping sector is extensive. A few notable ones that have not been assessed in this report will be discussed in this section, as well as their potential advantages and disadvantages.

Combustion engines and fuels

Other novel **fuels** that could be used include (bio- or synthetic) methane, methanol, or ammonia (EICB & TNO, 2021) or e-fuels, as discussed in Section 4.1. Biofuel production would be similar that of the assessed diesel substitutes. These can have practical or environmental benefits, but the land and water use considerations would remain. E-fuels produced from hydrogen (such as green ammonia) would be similar in production to hydrogen, while being more practical to store and transport. The advantages of these fuels would lie principally on this practical side, while environmental impacts can be expected to be comparable to those of hydrogen. Data on their application for (inland) shipping is scarce at present.

Cleaner and more efficient **combustion engines**, such as ones meeting the EURO VI standard (Dekker, 2020), have the potential to further reduce local environmental pollution, from e.g. NO_x and PM, in the operations phase (see Section 9.3.1). Such engines could be used for the diesel (fossil or bio-based/synthetic) or hydrogen fuels assessed, as well as the other fuels mentioned in the previous paragraph. More efficient combustion engines would not, however, significantly reduce the CO_2 emissions inherent from the combustion of the selected fuel, nor could they be cleaner (in the operations phase) than the emission-free battery-electric or HFC alternatives.

Another solution not discussed is a **hybrid** solution, where a diesel generator would be combined with a battery-electric power system (van Huizen, 2022). This would allow barges to sail without emissions on short routes or near to population centres, while being able to rely on energy-dense fossil fuels such as diesel for longer distance. This would be an effective and practical way to reduce local environmental and health impacts in the short term, but does not align with long-term goals of fully phasing out fossil fuels and greenhouse gas emissions (unless the combustion component is in turn powered by one of the bio-based or synthetic fuels mentioned above). Actual emissions would be difficult to generalise, as these depend on real-life conditions and behaviour, such as in what proportion the electric and fuel-based power supply would be used. Furthermore, inefficiencies extra energy conversion steps can be expected to lead to higher emissions from fuel combustion (EICB & TNO, 2021).

Fuel cells

The HFC alternatives are based on polymer electrolyte membrane (PEM) fuel cells, which as of present have the greatest potential for commercially viable vehicle applications (US Department of Energy, 2023). Other **fuel cell technologies** exist, which can have advantages over PEM fuel cells, such as lower costs, environmental impacts from their production, or higher efficiency, but they are impractical to implement or rely upon at present. As an example, direct methanol or ammonia fuel cells are simpler to manufacture and their fuel is easier to transport and store; however, they are suitable mainly for low power applications and have relatively low efficiencies (EICB & TNO, 2021).

Alternative (bio- or synthetic) **fuels** discussed previously, such as ammonia or methanol, can also be used to power fuel cells, with similar advantages and disadvantages as discussed before: a fuel such as methanol is more efficiently stored and transported, but its production from hydrogen incurs additional energy losses and complexity.

Batteries

In this study, NMC-622 lithium-ion batteries have been used, but other **battery technologies** exist. Advantages of such types of batteries lie mainly in lower environmental impacts for their manufacturing, less use of scarce materials, and practical advantages in e.g. weight or volume. Examples can include $LiFePO_4$ lithium-ion batteries (EICB & TNO, 2021) or flow batteries (Bajic, 2023). However, technological maturity of such technologies is too low, or available data too scarce, to determine whether they would be practical to apply in inland shipping. In the case study, environmental impacts for the NMC-622 batteries were already very low, although they were found to not scale well (both in terms of environmental impact and practicality) to longer distances and larger loads transported. Such alternate batteries may prove to be better in this regard.

In this study, the modelled battery-electric alternative was based on swappable battery containers. Especially for lower-capacity applications, non-swappable, rechargeable batteries can also be considered. The environmental impact contribution of battery swapping and charging was found to be minor, while the contribution of battery production can be high. This indicates that the differences between swappable and non-swappable batteries would be mainly practical, and not environmental.

10.1.7. On inland shipping and other transport modalities

The transportation portfolio of the Province of South Holland reaches beyond inland shipping. Road (lorry) and rail (train) transport are other contenders for freight transportation within the same approximate geographical scope. The performed assessment in which the characterisation results for inland shipping were compared with database data for these other modalities give some insights into how these compare to each other. Overall, transport by lorry (either powered by diesel or electric batteries) has higher environmental impact than inland shipping of any kind, while rail transport (especially electrified) can be compared to the cleanest scenarios and technologies for inland shipping, and scales more efficiently than inland shipping powered by batteries or fuel cells. Economically, road transport is also the most expensive, while rail transport is comparable to inland shipping on a medium-sized barge, and large barges have even lower costs (Visser, 2020).

These environmental and economical advantages for rail and inland waterway transport are hampered by the fact that road transportation is the most flexible by far, while inland shipping is limited to waterways and rail transportation requires expensive and extensive railway infrastructure. On the other hand, the inland waterways that do exist tend to have unexploited transportation capacity, allowing for growth of the inland shipping sector, while road and rail capacity are more constrained (van der Geest & De Leeuw van Weenen, 2016; Visser, 2020).

10.2. Course of action

As the previous discussion points indicate, electric batteries are the ideal energy carrier for an inland barge regarding overall environmental impacts, as long as the required on-board energy capacity is low. If more energy capacity is needed, a ship could use hydrogen (from electrolysis using renewable electricity, for minimal climate change impact). A liquid fuel such as bio-/synthetic diesel can still be considered, but only for very high energy capacities, and if one of other energy carriers mentioned are not viable, even considering the possibility of extra stops for refuelling or battery switching. All of these fuels are suited for an electric power system (even diesel, in a hybrid electric system if necessary), although hydrogen could be better purposed in a combustion engine instead of a fuel cell if the required power output is very high. All these considerations can be summarised in a decision tree, shown in Figure 10.3, although this diagram necessarily simplifies the more nuanced discussion given in this chapter, by only considering the climate change impact category and giving hard limits for fuel/technology preference based on the *Leendert-Angelina*'s operational profile (based on Figure 9.29).

This decision tree, and the overall results of this study, can aid the Province of South Holland in stimulating an energy transition in the inland shipping sector. It provides a quantitative basis for comparing alternative fuels and energy systems under equal circumstances. Overall, the results do not conflict with existing intentions (such as the policy trends discussed in Section 4.2, which already include stimulating cleaner combustion engines in the short term, and long-term support for electric and hydrogen-based sailing), while allowing for more informed decision-making in future. As opposed to previously available knowledge for South Holland, the present study does take into account the entire barge lifecycle or additional system components such as infrastructure, and it allows to contrast the tradeoffs among different environmental impact categories between the studied alternatives side-to-side, making it concrete where the strengths and weaknesses of the different alternatives lie.

At the same time, the results in this study raise further questions and highlight opportunities for further research, which will be mentioned in the next section.

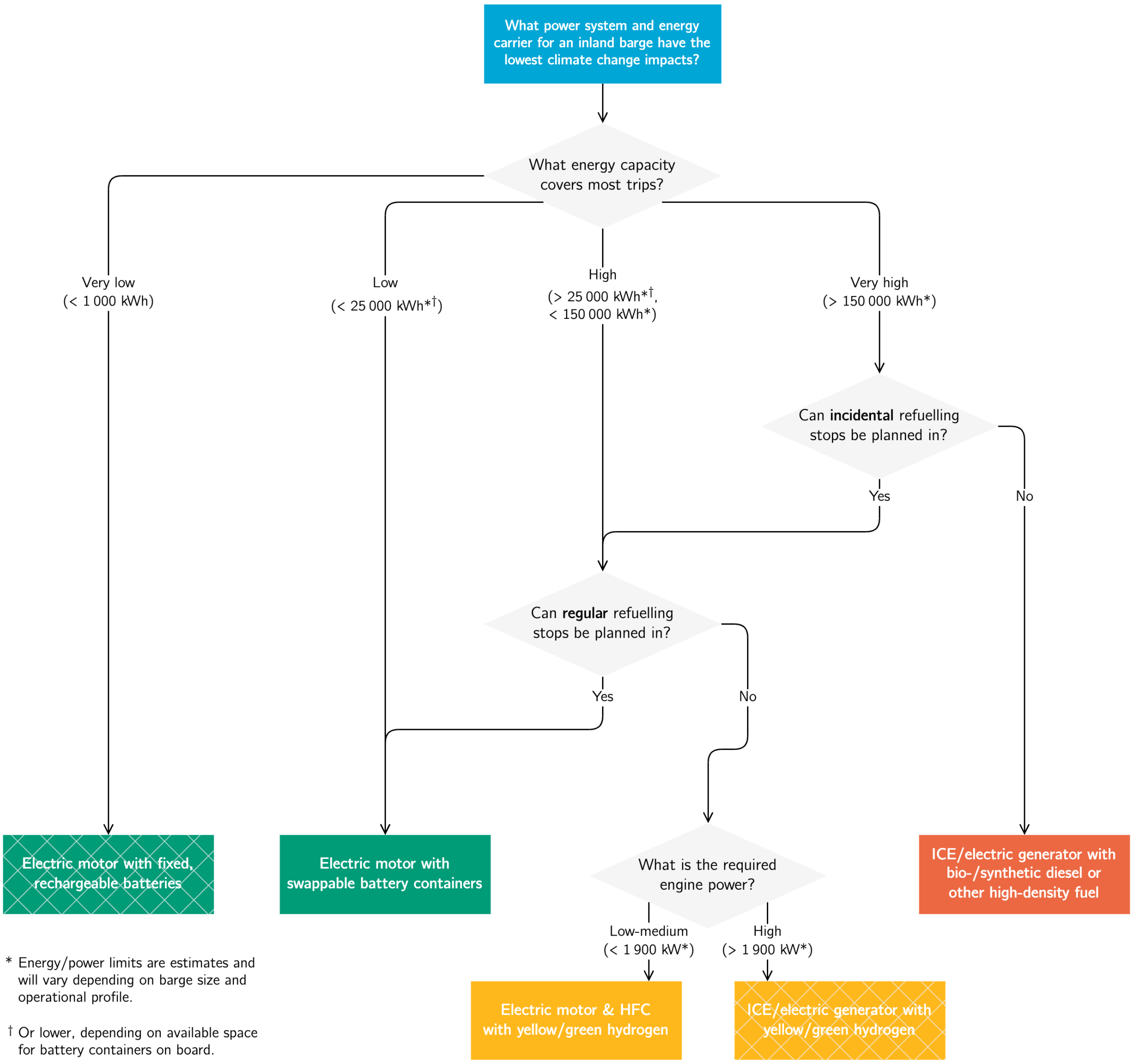


Figure 10.3: Decision tree indicating the optimal power system and energy carrier for an inland barge, regarding climate change impacts in 2100, based on the operational profile of the case study barge, *Leendert-Angelina*. See the main text for a more nuanced discussion.

10.3. Assumptions, limitations, and future research

The life cycle assessment carried out in this study is based on a series of assumptions and modelling choices which condition the results. The main one of these is relating the model function to the operational profile of a specific barge. The results in Section 9.4.2 have shown the significant variations that are possible depending on a barge's power and energy capacity. Other factors, such as a ship's size and hull shape can be expected to have similarly large impact on the results. Like the power and energy capacity, these are impossible to generalise to arrive at a conclusion valid and accurate for the both the very largest and smallest of inland barges – even if the case study barge has been selected to represent an average-sized ship.

The allocation choice made in selecting the *allocation, cut-off by classification* version of the Ecoinvent database likewise impacts the results for material extraction and recycling, although this would not affect the significant emissions from barge operations or fuel production. Another important modelling choice is the use of the SSP2 pathway for future socio-technical development. The sensitivity analysis for different scenarios within this pathway has shown minimal differences in the long term, but a radically different pathway could lead to entirely different long-term conclusions. A final, non-negligible assumption is that the choice of energy carrier does not directly impact the barge's freight capacity or power demand. This is true by approximation for the case study barge (where the required batteries or hydrogen tanks represent a comparatively small fraction of the barge's total mass and capacity), but does not hold for barges with a larger energy capacity relative to their size.

Some further limitations of the performed study include not distinguishing between the differing origins of emissions or their proximity to population centres. As has been addressed in the discussion, this makes characterisation results for local environmental and health impacts not fully comparable between alternatives with a large operation. A more detailed geographical analysis is also lacking, as many background processes used in the model have a national or European scope.

In this discussion, various knowledge gaps and other possibilities for future research have come to light. A deeper analysis of the current topic could address the assumptions and limitations described, by analysing more alternative energy carriers and technologies, over more varied future pathways, expanding the model with compartmentalised emissions and regional adjustment on the province level, and performing sensitivity analyses to barge size and operational profile. A combined sensitivity analysis with a Monte Carlo simulation could be useful in discovering the full range of possibilities for various types of inland barges. Such an analysis would be aided by actual operational measurements of fuel consumption and emissions from inland barge operations, which are scarce even for conventional diesel fuel and as of yet unavailable for other potential fuels mentioned in Section 4.1 such as methanol. Another element to consider in a more detailed LCA (or other quantitative assessment) is the effects of introducing en-route stops for refuelling, recharging, or swapping battery containers, which would make the alternatives with lower operational impacts more viable at the expense of decreased average speed.

On the other hand, a broader study could look beyond the environmental impacts by relating the obtained LCA results to an economic analysis of the different alternatives, or even the viability of business cases involving specific alternatives. Life cycle cost analysis (LCCA) may be a useful framework for an economic analysis to complement the LCA, giving a life-cycle perspective of both environmental and economic aspects, giving a more complete overview than the studies on the costs of specific fuels or technologies that have been cited in this report. This could fit in with a future inclusion of the inland shipping sector in the EU Emissions Trading System (ETS), which would put a price and cap on emissions of CO_2, CH_4, and NO_2. Finally, a study based on industrial ecology tools for analysing social processes, such as the multi-level perspective (MLP), could provide more thorough insight into the energy transition of the sector, the actors involved in it and their roles, and opportunities and challenges in the transition.

11 Conclusions

The inland shipping sector in the Province of South Holland faces a series of challenges and opportunities in reducing environmental impacts. In this study, these have been assessed, and an LCA has been performed to answer the following research question:

> **Research question**
>
> What are the life-cycle environmental impacts, and processes that most contribute to these, of inland shipping in South Holland, considering a future energy transition, comparing combustion engines and electric motors as power systems, as well as comparing bio-based or synthetic fuels, hydrogen, or lithium-ion batteries as energy carriers?

The LCA considered various different alternative power systems and energy carriers for the annual operations of a barge of medium size operating on short routes within the Province of South Holland: (fossil or bio-/synthetic) diesel in an older Stage I ICE, (fossil or bio-/synthetic) diesel in a modern Stage V ICE, hydrogen (grey, blue, or yellow) in a modern Stage V ICE, hydrogen (grey, blue or yellow) in an electric HFC system, and a lithium-ion battery-electric power system. The results of this LCA lead to insights helpful in answering this research question.

For the selected case study barge, a battery-electric system has the lowest climate change, acidification, photochemical oxidant formation, and particulate matter formation impacts. This advantage increases further in the future, according to the used scenario for the decarbonisation of the energy system. Hydrogen as an energy carrier is also promising, although its advantages become apparent mainly beyond 2030, according to the used scenario, and its impacts remain above that of batteries. Of the hydrogen types assessed, yellow hydrogen (leading to green hydrogen with a decarbonised electricity grid mix) has the lowest climate change impacts, while for local environmental impacts blue hydrogen performs slightly better. For hydrogen, a HFC system has slightly lower emissions and higher efficiency than a combustion engine. The gradual replacement of fossil-based diesel with biodiesel and synthetic diesel can potentially reduce climate change impacts by more than half (a smaller reduction than for yellow hydrogen or lithium-ion batteries), at the expense at increasing life-cycle impacts to acidification and PM formation, as well as requiring a disproportionately high use of land and water. Finally, a comparison with database data for road and rail transport indicate that inland shipping has significantly lower environmental impacts overall than transportation by (diesel or battery-electric) lorry, although only a battery-electric barge can have impacts as low as those of an electric train.

In the case of diesel, the source of impacts in climate change, acidification, and PM formation lies mainly in the operational emissions, while in most other cases, the fuel supply chain is the main contributor to environmental impacts. A Stage V ICE is seen to strongly reduce local environmental effects (acidification, photochemical oxidant formation, PM formation) compared to an older engine, but does not significantly reduce climate change impacts, which are inherent to the combustion reaction. In the battery-electric alternative, the production of batteries also contributes a distinct factor, as does the production of fuel cells in the HFC alternative. Other factors assessed, such as production of the rest of the barge and the life cycle of infrastructure play a relatively minor role. A further analysis extrapolating some of these contribution results indicates that, beyond a certain energy capacity required (related to trip length and freight capacity), a battery-electric system quickly ceases to be the most favourable alternative, with hydrogen being preferable. And while a HFC system tends to have lower impacts than hydrogen in an ICE, this is not the case for barges which require a large amount of engine power, as the decrease in operational emissions is offset by extra emissions for the production of batteries and fuel cells. For barges with the very largest requirements of power and capacity, bio- and synthetic diesel may prove to be the solution with the least climate change impacts. Alternatively, additional stops for switching battery containers or refuelling hydrogen can be a way to make battery-electric or hydrogen-powered sailing. These conclusions have been summarised in the decision tree given in the previous chapter.

These observations fit in with observed national and provincial policies, including the encouragement of inland shipping over road transport. In the short term, phasing out the oldest generation of combustion engines, for which subsidies are available, is an effective way of strongly reducing, but not eliminating, local effects to the environment and human health. In the long term this is not sufficient to reach climate and environmental targets, and the shipping sector must look towards engine technologies and fuels that have no operational emissions whatsoever. Based on the obtained results, a battery-electric system is optimal for shipping routes on a small-scale regional level, within South Holland or between South Holland and its neighbouring provinces. For national and international shipping movements, a HFC system powered by hydrogen appears favourable, especially if a surplus of renewable energy becomes available for the production of green hydrogen. This is also in line with existing policies, which includes subsidies for electrification of barges, and existing projects for international collaboration on the proliferation of hydrogen fuel. In the long term, the combustion of diesel (which in a fossil fuel phaseout scenario can only be bio-based or synthetic) should be reserved only for the very longest routes and heaviest transports where both batteries and hydrogen are impractical, as bio- and synthetic diesel cannot be realistically produced on the level required to fuel the entire sector due to the aforementioned land and water constraints. For any of these technologies, technological development, investments, and infrastructure are necessary, requiring the involvement and collaboration with many parties. From this point of view, existing collaborations such as RH_2INE and the Refit Alliantie should be lauded, but as the data collection process for this study has shown, the existence and accessibility on data (e.g. real-life emissions) remains a barrier.

These conclusions are subject to the selected future scenario, in which ambitious progress is made in decarbonising the energy sector and the development of new technologies such as industrial-scale hydrogen production and carbon capture and storage. Such developments are a necessary condition for the environmental success of the studied alternatives. Furthermore, the conclusions are based near-entirely on the environmental considerations that result from the performed LCA. Economical and practical concerns (such as the investment costs for fuel cell and battery technologies, and the mass and volume that batteries occupy on board) may lead to different priorities. Mixed solutions may come to mind to facilitate the transition, such as a hybrid diesel-electric system which can sail electrically for short stretches to reduce local environmental and health effects near population centres or sensitive nature areas while still being able to use diesel for long distances, or a barge with a modular electric power system which can use either battery containers or containerised hydrogen tanks and HFC systems depending on trip distance, although these solutions have not been assessed in detail.

Future research could expand on the environmental assessment by involving more alternative energy carriers (e.g. methanol), a deeper analysis of environmental compartments and regional emissions, more varied future development scenarios, a wider array of case study barges, and the obtention of real-life emission measurements for inland barges. Alternately, a broader scope could be focused on, including economical or social analyses of the energy transition in the inland shipping sector.

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A

Selection of case study barge

A report commissioned by the Province of South Holland contains an inventory of barges that sail primarily on South Holland's provincial waters, as well as a list of criteria that make a ship a likely candidate to be refitted with a more environmentally friendly power source (van der Geest et al., 2023).

The shipping sector is inventoried based on the following barge properties (given as an overall overview as well as divided among various principal waterways and ports):

- Barge name
- Barge owner, company type, Chamber of Commerce (KvK) number, and age of youngest owner
- Barge type (CEMT class, indicating dimensions)
- Barge construction year
- Barge engine type (emission standard, assumed based on engine age)
- 95th-percentile energy consumption (energy consumption covering 95% of shipping movements)
- Number of annual shipping movements within South Holland.

Figure A.1 displays the distribution of some of these relevant properties.

According to van der Geest et al., the criteria for determining the usefulness and likelihood of a barge being refitted with a cleaner power system include engine age, ownership by a larger shipping company (*rederij*) or sailing for a specific shipper, being built after 1995, and the owner being younger than 45 years of age. To select a case study barge, it must be roughly representative of this inventory of barges, i.e., it must not strongly contradict the mentioned criteria for refitting, nor strongly diverge from the average physical properties of these barges.

For this purpose, a Python script is used to perform the following steps:

1. Set numerical proxies for the quantitative variables of engine type (NO_x emissions based on the associated emission standards) and barge type (barge length and beam).
2. Calculate z-scores (indicating how strongly each barge's value diverges from the average) for the distributions of: number of shipping movements, year of construction, energy consumption, length, beam, and NO_x emissions. The z-score of a property value x in the distribution X, z_X, is calculated as:

$$z_X = \frac{x - \mu_X}{\sigma_X}$$

   where μ_X is the distribution's mean and σ_X is the distribution's standard deviation, with X corresponding to each of the assessed property distributions.

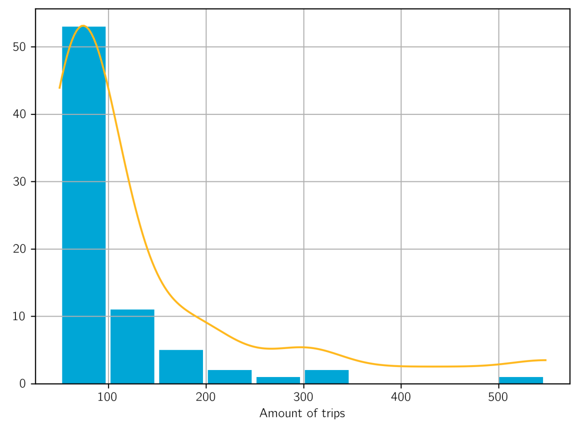
3. The different properties' z-scores are combined into a single weighted z-score Z by performing a weighted sum of the individual z-scores, then dividing the resulting distribution by its standard deviation.

$$Z = \frac{\sum_X \left(\left(\sum_{X'} \frac{w_{X'}}{\sum_{X''} w_{X''}} \right) * z_X \right)}{\sqrt{\sum_X \left(\frac{w_X}{\sum_{X'} w_{X'}} \right)^2}}$$

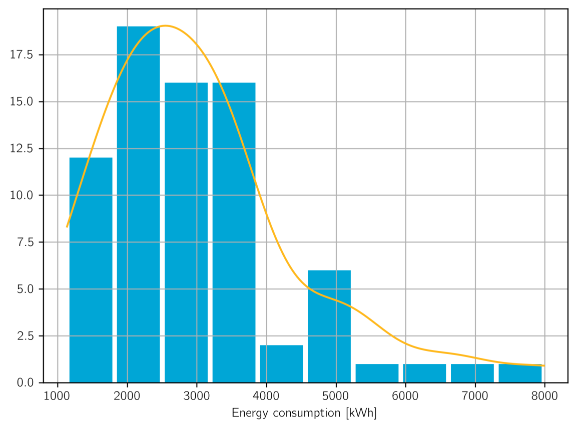
No specific weights w are determined (all set to 1), except for a weight of $2^{\frac{-1}{2}}$ for the length and beam, as these are indicative of the same property, CEMT class.

4. Barges with a construction year before 1990 are removed from the dataset (providing a bit more margin than the inventory's cut-off year of 1995), and the remainder are sorted by their value of Z.

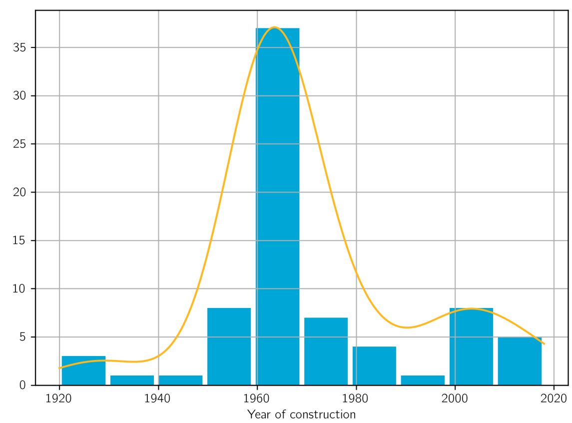
Of the resulting list of barges, the ones with Z closest to 0 will be the ones that are closest aligned to the average in each assessed property. The most representative barge is the *Leendert-Angelina*, which is used as case study target in this report. Its properties can be seen in Table 1.1.



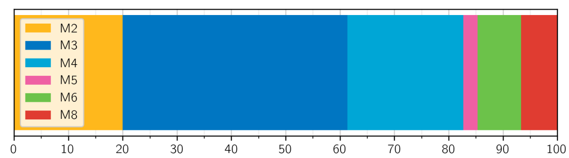
(a) Distribution and rough kernel density estimation of the barges' annual trip count within South Holland.



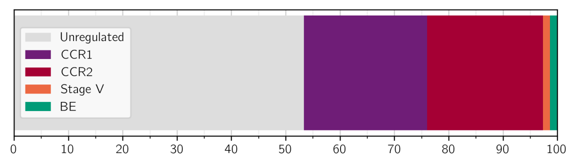
(b) Distribution and rough kernel density estimation of the barges' 95th-percentile energy consumption.



(c) Distribution and rough kernel density estimation of the barges' year of construction.



(d) Proportion of barge types (by CEMT class / barge dimensions; ascending).



(e) Proportion of barge engine types (by corresponding emission rate; descending).

Figure A.1: Some histograms and bar charts characterising the barge inventory.

B

Unit process and LCI data

Available online

Unit process and life cycle inventory data, exported from the LCA model, is available online at https://static.quan.cat/inlandshipping.

C

LCA Viewer

Over the course of this project, the need arose to explore a large array of different LCA results (comparing them across alternatives, different scenarios, and impact categories), and share selected LCA results with interested parties, such as policymakers at the Province of South Holland and industry contacts. This led to the creation of the *LCA Viewer*, an online tool for visualising LCA characterisation and normalisation results. This tool has been adapted to be independent of this study, being able to visualise results exported from any Activity Browser project.

> **Access the LCA Viewer**
>
> LCA results for the study into inland shipping in South Holland can be viewed in the LCA Viewer at https://qlcav.quan.cat?project=inlandshipping. A generic sample project, comparing a selection of processes from the Premise databases, can be viewed at https://qlcav.quan.cat?project=sample.

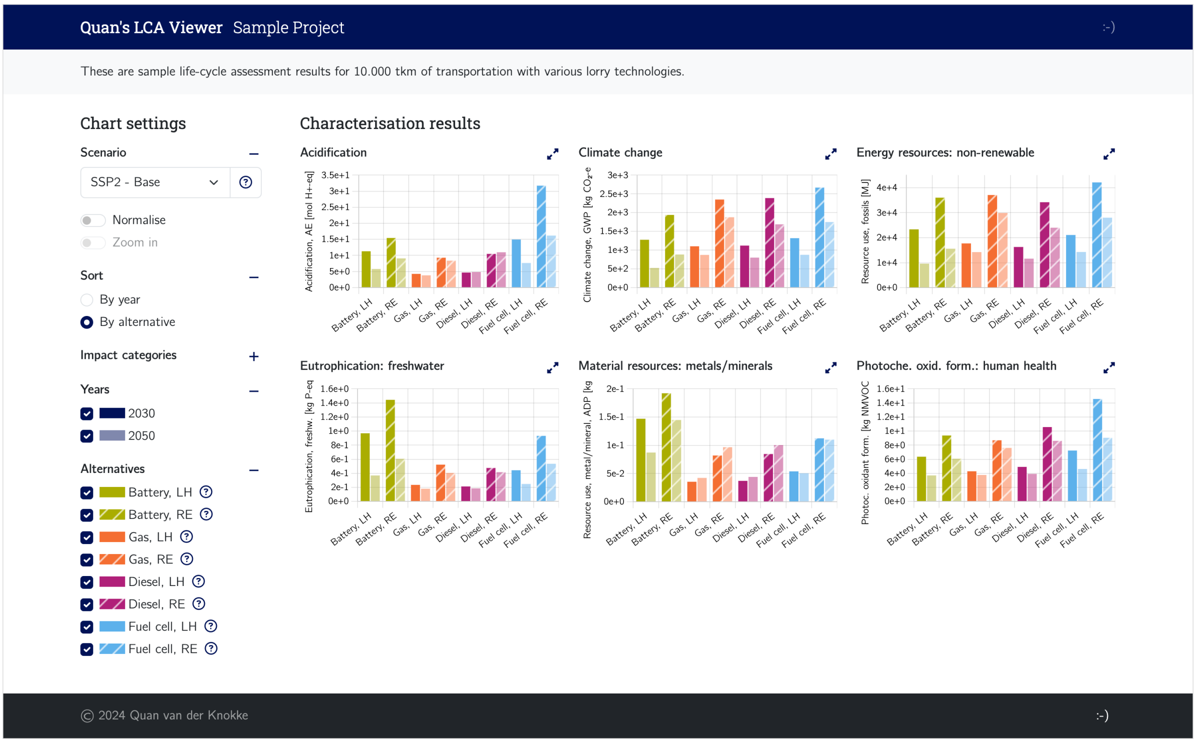
Use-case and advantages

For LCA practitioners

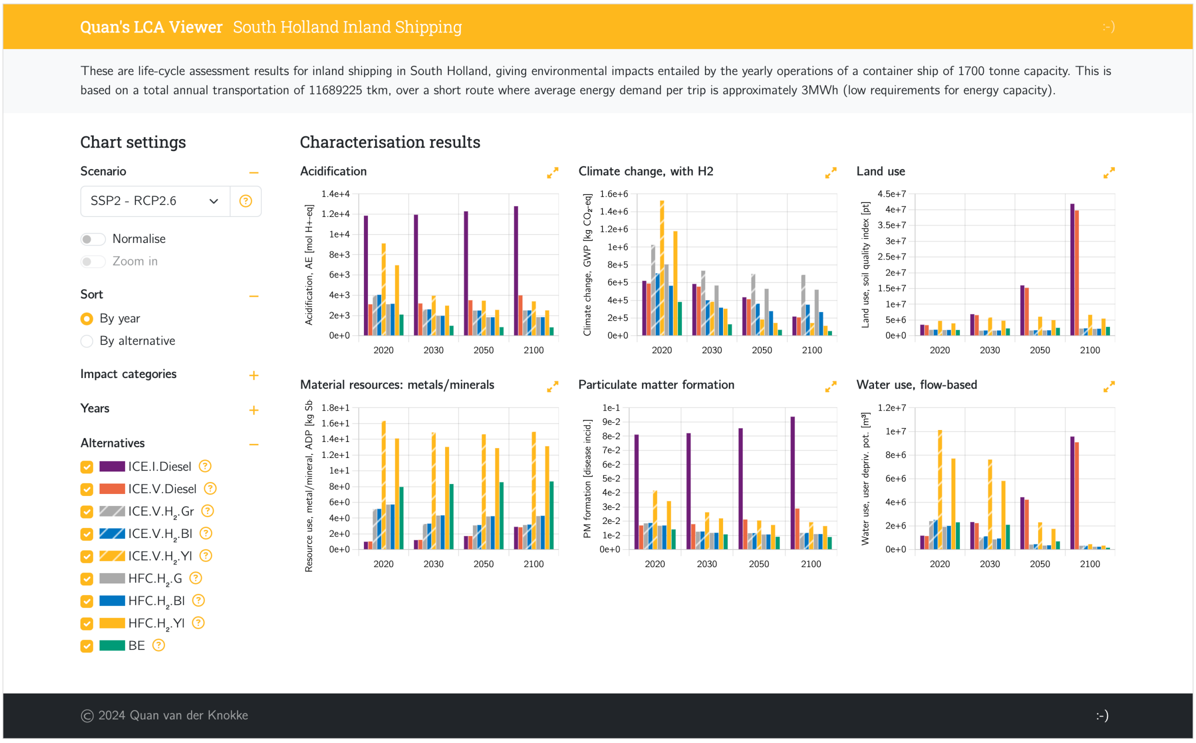
For LCA practitioners in need of exploring their initial results, working with LCA software can be cumbersome. Often, to visualise a different set of data, model results need to be recalculated and exported, then opened externally. For projects like the inland shipping case study, with nine alternatives, at four points in time and in three scenarios (108 different sets of characterisation results), this requires a significant investment of time and repeated work. The LCA viewer makes it possible to not only visualise all these results from a single CSV export, but also to filter through data and toggle the visibility of individual data sets and impact categories, allowing a practitioner to find and display the most relevant data for their study. Finally, it allows normalisation of the results, a feature lacking in the Activity Browser, if category totals are provided.

For commissioners and other external parties

Results he LCA viewer can complement an LCA report such as the current one. This is especially relevant for projects with parties interested not only in conclusions but also in the underlying data, even if they are not familiar with LCA software. With the LCA viewer, characterisation and normalisation results can be hosted on a website and viewed, filtered, and compared from any device (including on mobile devices and tablets), making it easy for any stakeholder to access and interpret the data. User-friendly labels and description tooltips can aid to explain the data even for users who do not have experience in LCA.



A sample project in the LCA Viewer.



The South Holland inland shipping study in the LCA Viewer.

Development

The LCA Viewer is a modern web application built with the Vue.js framework, selected for being lightweight and the capabilities of its reactivity system. This implicitly links the state of the user interface and available data and seamlessly re-renders content when data and settings change, allowing a robust implementation of filters and chart settings.

Project data is made available to the application via uploaded CSV files and a metadata file, which includes project-specific settings for file names, theming, labels/descriptions, and category totals for normalisation. On page load, the CSV file being loaded into memory as a JavaScript object, and then filtered and sorted via Vue computed properties.

All processing is done on the browser side, and the built application (excluding project data) is very lightweight ($\sim$ 800 kB), making the application easy to host.

> **Source code and releases**
>
> The source code for the LCA Viewer is open-source and can be accessed at https://github.com/Q-Quan/Quan.LCAViewer.

Glossary

LCA glossary

Terms and definitions adapted from Guinée et al. (2002).

Alternative one of a set of product systems studied in a particular LCA, e.g. for comparison (note: some LCA steps are carried out for all alternatives together (e.g. selection of impact categories), while others are repeated for each alternative (e.g. characterisation)

Attributional LCA/retrospective LCA a type of LCA focusing on the contribution of a particular way of fulfilling a certain function to the entire spectrum of environmental problems as they currently exist or are being created[1]

Background process a process for which secondary data, viz. databases, public references, estimated data based on input-output analysis, are used in an LCA

Category indicator a quantifiable representation of an impact category, e.g. infrared radiative forcing for climate change

Characterisation a step of Impact assessment, in which the environmental interventions assigned qualitatively to a particular impact category (in classification) are quantified in terms of a common unit for that category, allowing aggregation into a single score: the indicator result; these scores together constitute the environmental profile

Characterisation factor a factor derived from a characterisation model for expressing a particular environmental intervention in terms of the common unit of the category indicator

Completeness check a step of the Interpretation phase to verify whether the information yielded by the preceding phases is adequate for drawing conclusions in accordance with the Goal and scope definition

Consequential LCA/prospective LCA a type of LCA focusing on the environmental changes resulting from a switch to or from a particular product system or an extra functional unit of a particular product system[1]

Consistency check a step of the Interpretation phase to verify whether assumptions, methods and data have been applied consistently throughout the study and in accordance with the Goal and scope definition

Contribution analysis a step of the Interpretation phase to assess the contributions of individual life cycle stages, (groups of) processes, environmental interventions and indicator results to the overall LCA result (e.g. as a percentage)

Co-product any of two or more functional flows from a co-production process

Economic flow a flow of goods, materials, services, energy or waste from one unit process to another; with either a positive (e.g. steel, transportation) or zero/negative (e.g. waste) economic value

Emission a chemical or physical discharge (of a substance, heat, noise, etc.) into the environment, considered as an environmental intervention

Environmental impact a consequence of an environmental intervention in the environment system

Extraction withdrawal of a biotic or abiotic resource from the environment in a unit process, considered as an environmental intervention

Final product a product requiring no additional transformation prior to use

Flow diagram a graphic representation of the interlinked unit processes comprising the product system

[1] The glossary in Guinée et al. (2002) employs the same definition for prospective LCA as for consequential LCA, and the same definition for retrospective LCA as for attributional LCA. In this report, *prospective* LCA is used to contrast with a *retrospective* LCA, relating to the state of technology described (Weidema, 1998), while *consequential* LCA is used to contrast with an *attributional* LCA, relating to the use of average or marginal data to describe impacts to the economy (Ekvall, 2019).

Foreground process a process for which primary, site-specific data are used in an LCA, for whatever reason

Function a service provided by a product system or unit process

Functional flow any of the flows of a unit process that constitute its goal, viz. the product outflows of a production process and the waste inflows of a waste treatment process

Functional unit the quantified function provided by the product system(s) under study, for use as a reference basis in an LCA, e.g. 1000 hours of light

Goal and scope definition the first phase of an LCA, establishing the aim of the intended study, the functional unit, the reference flow, the product system(s) under study and the breadth and depth of the study in relation to this aim

Impact assessment the third phase of an LCA, concerned with understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study

Impact category a class representing environmental issues of concern to which environmental interventions are assigned, e.g. climate change, loss of biodiversity

Impact result/indicator score the numerical result of the characterisation step for a particular impact category

Input a product (goods, materials, energy and services), waste for treatment or environmental intervention (including resource extraction, land use, etc.) modeled as 'entering' a unit process

Intermediate product an input or output from a unit process which undergoes further transformation before consumptive use

Interpretation the fourth phase of an LCA, in which the results of the Inventory analysis and/or Impact assessment are interpreted in the light of the Goal and scope definition (e.g. by means of contribution, perturbation and uncertainty analysis, comparison with other studies) in order to draw up conclusions and recommendations

Inventory analysis the second phase of an LCA, in which the relevant inputs and outputs of the product system(s) under study throughout the life cycle are, as far as possible, compiled and quantified

Inventory table the result of the Inventory analysis phase: a table showing all the environmental interventions associated with a product system, supplemented by any other relevant information

Land occupation the unavailability of a given plot of land for alternative uses for a certain period of time

LCA study an environmental study in which LCA methodology is employed, performed by practitioners who may or may not be affiliated to the party or parties commissioning the study

Life cycle the consecutive, interlinked stages of a product system, from raw materials acquisition or natural resource extraction through to final waste disposal

Life-cycle assessment (LCA) compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle; the term may refer to either a procedural method or a specific study

Multifunctional process a unit process yielding more than one functional flow, e.g. co-production, combined waste processing, recycling

Multifunctionality and allocation a step of the Inventory analysis in which the inventory model is refined and the input and output flows of multifunctional processes are partitioned to the functional flows of those processes

Natural resource a biotic or abiotic resource that can be extracted from the environment in a unit process

Non-functional flow any of the flows of a unit process that are not the goal of that process, viz. product inflows, waste outflows and environmental interventions

Normalisation a step of Impact assessment in which the indicator results are expressed relative to well-defined reference information, e.g. relative to the indicator results for global interventions in 1995

Normalisation factor the reciprocal of the indicator result for a particular impact category and reference system; used in the normalisation step

Normalisation result the result of the normalisation step: a table showing the normalised indicator results for all the selected impact categories, supplemented by any other relevant information

Output an economic flow (e.g. energy, waste for treatment) or environmental intervention (e.g. pollutant or noise emission) modeled as 'leaving' a unit process

Phase any of the four basic elements of an LCA, viz. Goal and scope definition, Inventory analysis, Impact assessment and Interpretation

Pollution a change in the state of the environment due to emissions

Phase a change in the state of the environment due to emissions

Practitioner an individual group or organisation conducting an LCA

Product a positively valued economic flow of goods, materials, energy or services produced in a unit process and possibly serving as an input to another unit process

Product system a set of unit processes interlinked by material, energy, product, waste or service flows and performing one or more defined functions

Recycling a unit process, or set of processes, for collecting and/or treating waste from a unit process for useful application in the same or in a different product system (closed and open loop recycling, respectively)

Reference flow quantified flow generally connected to the use phase of a product system and representing one way (i.e. by a specific product alternative) of obtaining the functional unit

Sensitivity and uncertainty analysis a step of the Interpretation phase to assess the robustness of the overall LCA results with respect to variations and uncertainties in the methods and data used

Stakeholder an individual group or organisation concerned about or affected by the environmental performance of a product system or the outcome of an LCA (note: the LCA commissioner is also a stakeholder)

System boundary the interface between a product system and the environment system or other product systems

Unit process the smallest portion of a product system for which data are collected in an LCA

Waste (for treatment) an economic flow with a zero or negative value produced in a unit process and serving as an input to another unit process (note: materials such as waste paper and scrap metals with a positive economic, i.e. market value are thus not wastes but products)

Inland shipping & report-specific glossary

Barge flat-bottomed vessel generally intended for sailing on inland waterways

Biodiesel biofuel comparable to diesel, produced from plant-based oils or animal fats; in this study, produced from rapeseed oil transesterification

Blue hydrogen hydrogen produced from natural gas via steam methane reforming (like grey hydrogen), where CO_2 emissions are captured and stored

Diesel mix proportion of fossil-based diesel, biodiesel, and synthetic diesel supplied

Energy carrier substance or system that can be used to transport or store energy, such as a fuel or a battery

Energy density amount of energy contained with in a fuel, per unit mass or volume

Grey hydrogen hydrogen produced from natural gas via steam methane reforming

Grid mix proportion of electricity from different sources (e.g. coal power plants, gas plower plants, wind energy, solar energy, etc.) available from the electricity grid

Inland shipping transportation of freight over inland waterways

Local environmental impact environmental impact that has health or environmental effects on the local surroundings of the point of emission

Refitting/retrofitting replacing or repairing machinery in a vehicle or building; in this study, the replacement of an inland barge's power system with an alternative that is more environmentally friendly

Shore power electricity supplied to ships by plugging in to shore outlets at ports, docks, etc., which avoids running engines in port

Synthetic diesel diesel alternative produced from another hydrocarbon fuel; in this study, produced from wood chips via wood gasification and the Fischer-Tropsch process

Yellow hydrogen hydrogen produced from grid electricity via electrolysis

Zero-emission shipping inland shipping, by a barge that emits no direct pollutants in its operations