Sustainable transport by use of alternative marine and aviation fuels—a well-to-tank analysis to assess interactions with Singapore's energy system

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Contents

Abstract

Sustainable economic development and renewable energy carriers are challenges facing hub cities that will influence their future role in trade and transport. The objective of this paper is to discuss the interactions between alternative transport fuels for international applications and Singapore's energy system as a central hub of global transport.

The process chains for the supply of conventional fuels, liquefied natural gas, biofuels, and liquid hydrogen in Singapore are analysed by applying a well-to-tank analysis, following which the energy demand and the associated greenhouse gas emissions are calculated. A sensitivity analysis is performed to assess the individual impacts of various processes.

A comparison of process chains for the supply of fuels for marine and aviation purposes shows that conventional energy carriers and liquefied natural gas achieve higher energy efficiencies than biofuels and liquid hydrogen. Alternative fuels reduce greenhouse gas emissions by varying degrees depending on the fuel type. An analysis of interactions with Singapore's energy system identifies emerging opportunities and challenges for the city-state's economic system associated with future development of international transport. Although alternative fuels offer the possibility of diversifying Singapore's energy supply, creating new business opportunities, and increasing Singapore's impact on fighting climate change, limited resource potentials and higher energy prices set new challenges to secure Singapore's role as an international trade and transport hub.

Keywords (6):

Transport, Fuels, Bioenergy, Hydrogen, Environmental Impact, Economic Aspects

1 Introduction

This paper aims to determine future opportunities and challenges for Singapore that might arise out of interactions between its unique energy system and the supply of sustainable fuels for international transport.

Climate change, pollution, and resource dependencies are raising awareness towards the need for a more sustainable global economy. Development of unconventional energy resources, such as tight oil and shale gas, and the increasing economic efficiency of renewable energy sources have had a strong impact on energy supply of developed countries and have led to decarbonisation of economic activity. Environmental regulations will shape the future development of energy production in many countries. However, while alternative fuels and drive trains are being implemented for road transport in order to achieve a more sustainable transport system, maritime transport and aviation lag behind.

Current trends in global transport show that environmental and economic drivers might cause shifts in the type of fuel used for international transport. In marine transport, emission control areas limit emissions and set new environmental standards [1]. With low gas prices and higher petroleum prices, liquefied natural gas (LNG) is becoming an interesting alternative to the fossil fuels generally used for maritime transport (e.g. fuel oil) from an economic point of view. Ship engine manufacturers have started producing dual-fuel gas engines to allow the use of both natural gas and conventional fuels [2–4]. Ship owners see LNG-fuelled engines as a promising option for mitigating emissions [5]. Biogenic fuels and hydrogen are other possible substitutes to conventional fuels that have been discussed in scientific articles [6–9].

Singapore is a crucial spot in the introduction of alternative fuels for international transport on a global scale. Over 42 million tonnes of the world's fuel supply for shipping is bunkered in the port of Singapore [10], and 30 % of world trade is shipped through the Strait of Malacca [11]. Situated at this key position, the city-state of Singapore is more than just a large and highly developed city. Its population has grown rapidly to around 5.5 million people in 2014 [10], and it is the world's most important bunkering port [5], a leading container port [1], one of the largest exporting refinery centres [12], South Asia's leading financial centre [13], and a major airport hub [14]. These specialisations make Singapore a typical hub city. Most of its energy demand is determined by the above mentioned specialisations. The use of fuels for international aviation and marine shipping exceed demand for domestic primary energy use [15]. In order to create a sustainable energy supply for Singapore, not only domestic but also international energy use has to be taken into account. Singapore's energy system is highly dependent on technological and market developments with respect to fuels used for international transport. However, because of its role as one of the most important transport hubs, decisions taken in Singapore could have significant impact on the sustainability of international transport. These interactions make Singapore a key country in the future development of international transport.

Various life cycle assessments (LCA) have been carried out for the automotive sector. The Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context [6] and Argonne's GREET life cycle analysis [16] studied the effects of alternative fuels for passenger vehicles. In recent years, further studies have been done to investigate the environmental impact of alternative marine fuels [7,8,17–19] and alternative aviation fuels [20–23]. These studies, however, were based on data from Europe or the US.

Singapore and its surrounding region, which are situated in the centre of international trade flows, offer different framework conditions in terms of energy availability, renewable energy potential, and political constraints. As a hub for international transport, Singapore's energy system offers unique interactions with fuel supply for ships and aircraft and is therefore of high importance for the sustainable development of the world economy.

In Chapter 2, a methodology is developed on the basis of a detailed literature review to discuss process chains for the supply of bunker fuels for ships and aircraft in Singapore. Conclusive input data are derived from literature sources, and an overview of the selected scenarios is given. Conventional and alternative process chains for the supply of fuels for international transport demand are assessed in Chapter 3. Typical energetic factors, GHG emission factors, and costs are derived for each fuel type. Indicators derived from related literature are compared. Chapter 4 discusses prospects and challenges to Singapore in the enabling of a sustainable energy supply for international transport based on Singapore's unique position as the world's leading bunkering port.

2 Material and Methodology

In order to discuss interactions between Singapore's unique energy system and the supply of sustainable fuels for international transport, the characteristics of conventional and alternative fuels in terms of energy efficiency, GHG emissions, and costs have to be assessed. The investigation of process chains to supply such fuels, also known as bunker fuels, is an essential part of this paper. Bunker fuels are used in airplanes and ships to fire engines and generate propulsion.

2.1 Review of Related Literature

Various well-to-tank (WTT) studies have investigated the energy efficiency and GHG emissions of fuel supply chains. Most such research has been performed to investigate fuels for automotive applications. As many upstream processes for the production of automotive fuels are similar or identical to processes for the production of marine or aviation fuels, these studies are highly relevant to other more specialised literature. Accordingly, studies that investigate marine or aviation fuels often refer to studies of pathways for the evolution of road technologies. This review gives an overview of selected WTT and well-to-wheels (WTW) studies and methods that are related to the research objective of this paper.

In the following, the results of the basic literature are summarised in Chapter 2.1.1. The results of selected WTT and WTW studies focusing on marine transport or aviation technologies are summarised in Chapters 2.1.2 and 2.1.3.

As shown in this Chapter, the regional scope of related literature is mainly Europe and the United States. Therefore, a bespoke methodology to calculate key indicators for WTT pathways adapted to Singapore is developed in Chapter 2.2. In Chapter 3.4, specific results presented in related literature sources are compared to the results derived in this paper.

2.1.1 Basic and General Literature

Edwards et al. investigated processes and technologies for road transportation in the context of the JEC well-to-wheels analysis. JEC is a collaboration of European Commission's Joint Research Centre (JRC), EUCAR, and CONCAWE. The publication is a technical report published by the JRC with the goal of calculating energy efficiency, GHG emissions, and costs for all possible future automotive fuels and vehicle drive trains. The regional scope of the study is Europe and the selected technological data represents the time period after 2010. The JEC report is not a LCA-analysis as it does not take production and disposal processes into account (compare Chapter 2.2). It is split up into a WTT and a tank-to-wheel (TTW) analysis. In the context of our research, the WTT report is of special interest. Energy demand and emissions for a variety of pathways to supply fuels for road transport are calculated and grouped into conventional fuels, compressed natural gas, compressed biogas and synthetic methane, ethanol, ethers, biodiesel, hydrotreated plant oil, synthetic diesel, methanol, electricity, heat, combined heat and power, and hydrogen. For each pathway, an extensive description of processes, underlying methodology, and literature sources is presented. The resulting fundamental database makes the JRC WTT report a very valuable source for other WTT studies in various fields. Edwards et al. concluded that alternatives to conventional fuels are more expensive with current costs and technologies. Even if some alternatives offer significant GHG reduction potentials, their availability is limited and their energy consumption is often higher than that of conventional fuels. A mix of various fuels is expected to power road transport in the future, and this report highlights that the maximum GHG reduction potentials can only be exploited if not only transport technologies but also the energy system as a whole is investigated. [6,24]

While the JEC WTW analysis is an often cited reference in the European context, Argonne's 'Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET)' model is of similar importance in North America. Unlike the JEC study, the GREET model is an on-going project that provides software to researchers and analysts. This enables study of the well-to-wheels fuel cycle and the vehicle cycle, including material use and recovery, on an LCA basis. The GREET model calculates energy and water consumption, GHG emissions, and emissions of other pollutants for more than 100 different configurations of fuel pathways, including conventional fuels, natural gas, biofuels, electricity, and hydrogen. Furthermore, it does so for different vehicle types and drive train technologies. [16]

Other LCA models and providers of databases that offer valuable data and information but are not discussed in detail in this review include the Global Emission Model for integrated Systems (GEMIS), ProBas, and ecoinvent. [25–27]

Other process specific literature sources used to adapt the investigated pathways to Singapore's energy systems and related upstream processes are presented in Chapter 2.4

2.1.2 Literature with a Focus on Marine Transport

While sustainable fuels have been investigated for decades, studies on sustainable fuels for international marine transport are comparably new. Such research is motivated by stricter environmental regulations and the resulting rising costs of conventional fuels and associated drive trains, which result in the increased attractiveness of alternative fuels [7,8,17–19]. Methodological differences and main findings of selected studies are presented as follows:

Bengtsson et al. conducted a life cycle assessment of marine fuels. Their technical report aimed at assessing the environmental impact of bunker fuels from a life cycle perspective. The model comprises the North and Baltic Seas over a time period from 2015 to 2020. It should be emphasised that production and maintenance of capital goods are not included in the LCA. Aside from conventional fuels with and without exhaust cleaning technologies, both LNG and gas-to-liquid (GTL) are assessed in terms of total primary energy use, global warming potential, acidification, eutrophication, photo-oxidant formation, and human health. For the investigated fossil fuels, combustion of the fuels in the ship engines has the biggest environmental impact, and emissions can be slightly reduced by using LNG for marine transport. Findings on acidification and eutrophication are not elements of the current paper and are therefore not further discussed. [17]

A second publication based on a similar methodology was published by Bengtsson et al. to study the environmental impacts of biodiesel and biogas. These impacts were discussed on the basis of individual years of ferry service between the Swedish mainland and Gotland over a model period covering the years 2015 to 2025. An LCA methodology and investigated impact categories were applied as described above. Conventional fuels and LNG completed the scope of the investigation, which concluded that biofuels have the potential to significantly reduce GHG emissions compared to fossil fuels but can also lead to negative effects, such as increased primary energy consumption or increasing eutrophication potential. [7]

Verbeek at al. investigated the environmental and economic feasibility of using LNG as a marine bunker fuel. Their report studied three different types of ships based in the port of Rotterdam. Outcomes were evaluated by assessing future developments of environmental regulations through 2016. Different pathways to supplying LNG were discussed and compared with pathways to supplying conventional bunker fuels and automotive diesel fuel. Impacts were assessed on basis of emissions of GHGs and other air pollutants. It was concluded that the well-to-propeller (WTP) GHG emissions of LNG are lower than those of conventional fuels when an efficient supply chain is selected. Other air pollutants could be reduced significantly by the use of LNG. Further reductions of WTP GHG emissions could be achieved if biofuels are used. [18]

Chryssakis published a WTP analysis of alternative fuels for maritime applications. The aim of this publication was to provide a preliminary overview of the sustainability of a number of possible alternatives for marine bunker fuels. This was done by assessing GHG emissions based on a WTP basis. Sixteen pathways for conventional and alternative fuels for supplying Europe using current technologies were selected. Furthermore, the availability of potential biofuels was discussed. Chryssakis identified LNG as the most promising fuel owing to its competitive costs, lower GHG emissions, and reduction of other air emissions. LPG and sustainable biofuels at lower costs are other promising alternatives to conventional bunker fuels. The high costs of hydrogen and social animosity toward nuclear power are barriers to exploiting their significant GHG reduction potentials as substitutes for conventional fuels. The study concluded that further research should therefore focus on LNG, LPG, and selected biofuels. [8]

Brynolf assessed the environmental impact of future marine fuels in her PhD Thesis. In her approach, she combined an LCA analysis with a global energy system model in order to investigate cost effective marine bunker fuels in the context of stabilisation of CO_2 emissions and competition amongst energy carriers. The regional scope of the study was Northern Europe. As in the work done by Bengtsson, materials used for the production of capital goods were not included in the LCA. The investigated time period was 2010 to 2025. In total, ten types of fuels were investigated, including conventional fuels, LNG, and various types of biofuels. GHG and other air emissions were investigated. The thesis concluded that alternative fuels and technologies can contribute significantly to reducing GHG emissions, with LNG representing the most promising substitute for heavy fuel oil. Biofuels are also an interesting option to reduce the environmental impact of international marine transport, but its availability and costs were identified as major obstacles. [19]

An inspection of the literature related in this Chapter makes it clear that current research is mainly focussed on Europe [7,8,17–19]. Furthermore, it is important to highlight that different methodologies are often used, making it difficult to compare results. Aside from LNG, biofuels are identified as a possible substitute for conventional fuels if costs and fuel availability are sufficient [7,8,17–19]. Hydrogen may become an energy carrier in the long term if costs can be reduced significantly [8]. In order to assess alternative fuels for marine transport in Singapore, it is not sufficient to directly transfer pathways and methods developed for Europe. Therefore, we will develop our own methodology and collect suitable input data in order to produce a model adapted to Singapore and its surrounding region's geographical position and unique fuel supply chain characteristics.

2.1.3 Literature with a Focus on Aviation Technologies

Research on alternative aviation fuels is motivated by environmental concerns, rising costs of conventional fuels, and the increasing competitiveness of alternative fuels. A selection of studies investigating supply chains for alternative aviation fuels are summarised in this Chapter.

Elgowainy et al. conducted an LCA on basis of the GREET model presented in Chapter 2.1.1. Their report documented the key processes within the pathways for supplying alternative aviation fuels. Well-to-wake (WTW) energy use and GHG emissions were reported for different pathways of petroleum-based jet fuels, Fisher-Tropsch (FT) jet fuels, and biofuels. The study was conducted for ten different types of aircraft. They concluded that biofuels have the potential to significantly reduce GHG emissions compared to conventional jet fuels, with results dependent on feedstock, applied processes, and treatment of co-products. On the contrary, production of FT jet fuels from fossil energy carriers can increase the amount of GHG emissions. [20]

Stratton et al. published a comprehensive study of life cycle GHG emissions from alternative jet fuels, which was funded by the US Federal Aviation Administration Office of Environment and Energy and the US Air Force Research Lab. The aim of this study was to compare the WTW GHG emissions of different pathways for supplying alternative drop-in fuels in the United States for model year 2015. Their data and methodologies were based on the GREET model and were extended using additional literature. In addition to petroleum-based jet fuel pathways, different pathways were investigated for FT jet fuels and hydroprocessed renewable jet fuels from renewable oils. They summarise that selected biofuels and FT fuels from renewable feedstocks could contribute to potential carbon neutral growth of the aviation industry, and they highlight that selected feedstock type and processes as well as selected methodologies to allocate co-products and the allocation of emissions from land use change have a severe impact on the results. [21]

Saynor et al. investigated the potential for renewable energy sources in aviation (PRESAV). The aim of the PRESAV project was to identify the most promising renewable alternatives to petroleum-based jet fuel in terms of reducing non-renewable energy use and GHG emissions. Their analysis focused on activities and results both within the United Kingdom and internationally. A bespoke methodology was used to calculate the efficiency and costs of various fuel pathways, although their energy requirements and gains took only the utilisation phase of each process into account and did not include process construction and disposal. From a wide selection of energy sources, FT jet fuel produced from biomass, biodiesel, and hydrogen were suggested for additional research. However, the costs of alternative fuels are much higher than those of conventional jet fuel, and the effective use of hydrogen would require new aviation technologies and aircraft concepts.[22]

Pereira et al. studied LNG and liquid hydrogen (LH_2) as alternative fuels for aviation. Their objective was to evaluate if the WTW energy, GHG emissions, and other pollutants could be reduced by the use of these fuels. A model was developed based on evaluation of flights with different travel distances to study the overall life cycle from raw materials to transport services. The model combined the methods and data of other models previously discussed in this study, such as the GREET and GEMIS models, in order to study WTT energy and emissions. Pereira et al. used current technologies and adapted data on Portugal for their calculations. They concluded that LNG is not a feasible solution in terms of energy use and environmental impact when current technologies are used. However, LH_2 produced by steam methane reforming could reduce environmental and social impacts in comparison to jet fuel, and hydrogen produced by renewable energy sources was determined to be the optimal solution for reducing the environmental impact of aviation. [23]

Summarising the results of the above literature, it is clear that drop-in biofuels are seen as the most promising options [20–22]. Hydrogen might become a possible alternative fuel for aviation in the long term [22,23]. The pathways examined for supplying these fuels, however, focus on Europe and North America [20–23], and the respective studies use differing methodologies, assumptions and input data. As with marine fuels, a direct transfer of these pathways to Singapore is not a valid approach. In order to reflect Singapore's special characteristics in terms of its geographical position and surrounding region and its unique fuel supply chain situation, a bespoke methodology must be developed and suitable input data must be collected.

2.2 Definition of Methodology

The developed methodology identifies key indicators that describe energy efficiency, GHG emissions, and costs of the investigated fuels. Figure 1 visualises the applied terms and definitions.

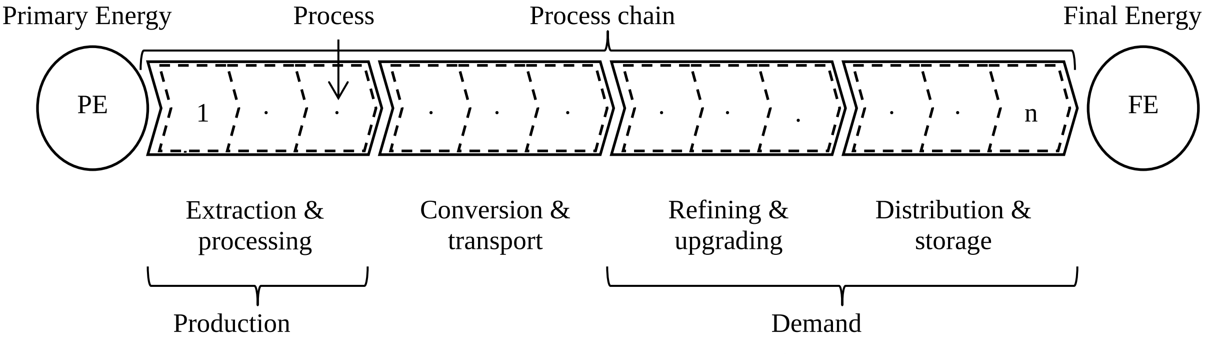


Figure 1: Conversion of primary energy to final energy–Applied terms and definitions

Bunker fuels are defined as final energy (FE), which is available to the energy consumer. In this investigation, bunker fuels comprise energy supplied to the fuel tanks of ships and airplanes. Fossil energy carriers in their original form occur as primary energy (PE), e.g. crude oil. Transformation from primary energy to final energy includes different processes depending on the expected product. Different processes $i \in \{1 \ldots n\}$ are combined to process chains or pathways in order to transform a primary energy resource to a final energy product.

Processes are assigned to four groups, which subdivide process chains:

- Extraction and processing (production site);
- Conversion (production site) and transport;
- Refining and upgrading (demand site);
- Distribution and storage (demand site).

In this study, each process $\boldsymbol{i}$ is described by an energy balance in which energy inputs $\boldsymbol{E_{In,i}}$ equal energy outputs $\boldsymbol{E_{Out,i}}$ plus energy losses $\boldsymbol{E_{L,i}}$.

$$\boldsymbol{E_{In,i}} = \boldsymbol{E_{Out,i}} + \boldsymbol{E_{L,i}} \tag{1}$$

Energy inputs for each process $\boldsymbol{E_{In,i}}$ cover:

- Energy demand for construction or production $\boldsymbol{E_{Prod,i}}$;
- Energy demand for utilisation $\boldsymbol{E_{Uti,i}}$;
- Energy demand for disposal $\boldsymbol{E_{Disp,i}}$.

$$E_{In,i} = E_{Prod,i} + E_{Uti,i} + E_{Disp,i} \quad (2)$$

$E_{Uti,i}$ is composed of two components: energy input $E_{Main,i}$, which is transformed into the target product; and additional energy required in the process $E_{Aux,i}$, which has to be supplied by other energy carriers, e.g., electricity, diesel, and heating oil.

$$E_{Uti,i} = E_{Main,i} + E_{Aux,i}. \quad (3)$$

Figure 2 displays the energy balance for process i and defines the relevant terms.

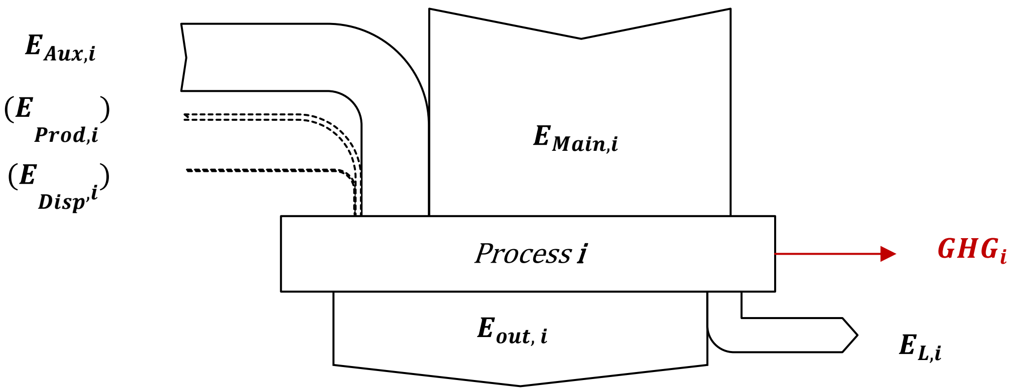


Figure 2: Energy balance of a single process

In accordance with other studies investigating well-to-tank (WTT) pathways presented in Chapter 2.1, the energy demands for production ($E_{Prod,i}$) and disposal ($E_{Disp,i}$) are not taken into account. Hence, the scope of this investigation is focussed on energy use and emissions occurring during utilisation. As data about used materials for production or at disposal is often not available for Singapore or subject to large uncertainties, this approach limits inaccuracies. $E_{Main,i}$ and $E_{Aux,i}$ and their individual compositions differ depending on the methodology applied, characteristics of processes, and data quality.

The energy output $E_{Out,i}$ of each process describes the energy of the target product. Energy losses $E_{L,i}$ are the difference between $E_{In,i}$ and $E_{Out,i}$ that occurs in transformation from inputs to outputs.

$$E_{L,i} = E_{In,i} - E_{Out,i} = E_{Main,i} + E_{Aux,i} - E_{Out,i} \quad (4)$$

Sometimes processes do not only have one primary output (target product) but also co-products and remnants. The treatment of these products influences the overall energy efficiency and GHG emissions. In the literature, different methods are applied. [6,28,29]:

- *Focus on target product*: Co-products and remnants are considered losses. All emissions and energy expenditure are attributed to the target product, which is required in the specific process chain.
- *Allocation method*: This method expands the method *Focus on target product* by crediting the energy contents of the co-products and remnants to the cumulative energy demand (CED) of the target product.
- *Substitution method*: In contrast to the allocation method, the energy content of the co-products or remnants are not credited to the cumulative energy demand (CED) of the target product; instead, the energy savings for not producing possible substitutes are credited to the CED of the target product.
- *Quantitative method*: Whenever by-products and remnants occur within the process chain, additional energy balances are added to take these products into account. Physical, energetic, economic or ecologic parameters are used as couplers to calculate the energy demand of the target product.

This study attempts to avoid co-products wherever possible by splitting up processes into sub-processes that produce only the desired product, e.g., instead of including the refinery process with multiple outputs, a specialised process for jet fuel production is used to calculate specific energy use and GHG emissions. In the biofuel process chain, energy and GHG reductions of co-products are credited using the substitution method.

Within the process chain, the main energy input of process i ($\boldsymbol{E_{Main,i}}$) is equal to the energy output of process $i-1$ ($\boldsymbol{E_{Out,i-1}}$):

$$\boldsymbol{E_{Main,i} = E_{Out,i-1}} \tag{5}$$

The cumulative energy demand (CED) is a common measurement used to determine the efficiency of a process chain. According to the definition used above, in this study, CED only includes energy demands of utilisation and does not account for the energy required for process production or disposal:

$$\boldsymbol{CED = E_{Main,1} + \sum_{1}^{n} E_{Aux,i}} \tag{6}$$

Whereas the energy of the final fuel is included in the $\boldsymbol{CED}$, WTT energy use (or upstream energy use) includes the energy content of the final fuel and accounts only for the energy that is expended to produce one unit of final energy.

Figure 3 visualises the simplified methodology we use to calculate primary energy and emissions.

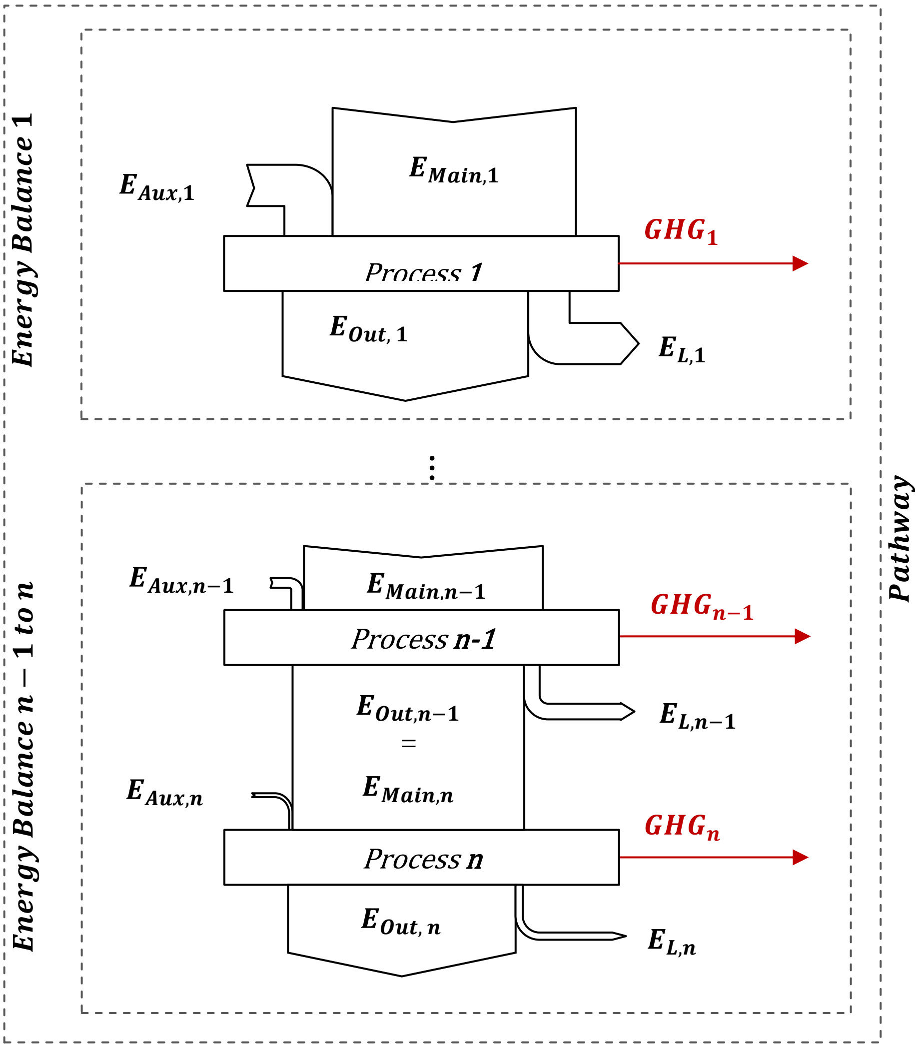


Figure 3: Methodology to set up process chains and calculate energy and GHG emissions

The overall efficiency of supply g_{PATH} of a WTT pathway is expressed by the energy output of the final process $E_{Out,n}$ divided by the CED:

$$g_{PATH} = \frac{E_{Out,n}}{CED} = \frac{E_{Out,n}}{E_{Main,1} + \sum_1^n E_{Aux,i}} \tag{7}$$

In addition, the concept of energy returned on energy invested (EROI) is used to set the amount of energy gain in relation to the amount of energy expended during energy production:

$$EROI = \frac{E_{Out,n}}{E_{Main,1} + \sum_1^n E_{aux,i} - E_{Out,n}} \quad (8)$$

GHG emissions GHG_i are calculated for each process by multiplying the energy output $E_{Out,i}$ with a specific emission factor $c_{GHG,i}$:

$$GHG_i = c_{GHG,i} \times E_{Out,i} \quad (9)$$

GHG_i includes those GHG emissions that occur in the transformation of inputs within a process. These are calculated from two types of GHG emissions: direct emissions, which are emitted within the process of converting the required inputs to the desired outputs; and upstream emissions, which are emitted in prior processes to produce the required inputs. Only direct emissions are taken into account for the consumption of $E_{Main,i}$ within a process. Upstream emissions caused by the consumption of $E_{Main,i}$ are allocated to previous processes through an increase of $E_{Main,i}$. As $E_{Aux,i}$ is expressed in terms of primary energy, upstream emissions have to be included for each process separately.

The upstream emissions GHG_{Path} of the total pathway, also referred to as WTT emissions, results from the sum of emissions emitted in every process i. Only emissions caused by production of the final fuel are included in this value. Direct emissions emitted by burning the final fuel have to be accounted additionally.

$$GHG_{PATH} = \sum_i^n GHG_i \quad (10)$$

Costs of fuels in Singapore are reflected by current market prices. As there are no market prices available for hydrogen, costs are calculated for every process step in its production. Specific costs $c_{Costs,i}$ per unit of process output are multiplied by $E_{Out,i}$ to calculate $C_{,i}$for every process:

$$C_i = c_{Costs,i} \times E_{Out,i} \quad (11)$$

The total fuel costs for a selected pathway are calculated by summing up all costs C_i occurring in the individual processes:

$$C_{PATH} = \sum_i^n C_i \quad (12)$$

2.3 Scenarios

Before chances and challenges caused by international bunker fuels in Singapore can be assessed in Chapter 4, key indicators must be derived for existing and alternative bunker fuels. Applying the methodology described in Chapter 2.2, these indicators provide information about energy efficiency, GHG emissions, and costs of fuels.

Current processes and technologies are used to define process chains and calculate input parameters. Input data are chosen in line with literature sources and reflect the particularities of Singapore, e.g., transport distance and characteristics of products and processes by export region. Literature may offer different values for some technologies owing to differences in methodology, technical parameters, timeframe, or regional specifics. In this paper, the basic process parameters $\boldsymbol{E_{Main,i}}$, $\boldsymbol{E_{Aux,i}}$, and $\boldsymbol{GHG_i}$ are described by average (**ave**) values. In some cases, the process parameters are extended to minimum (**min**) and maximum (**max**) values to allow a more robust assessment and cover uncertainties that may represent possible process specific developments.

Three scenarios are defined. The basic or **ave** scenario of a pathway uses only **ave** values for each process. Similarly, the **max** or **min** scenarios of a pathway use only **max** or **min** values for each process. In order to assess the effect of each process within a process chain, a sensitivity analysis is conducted in Chapter 3.2.

Based on the literature presented in Chapter 2.1 and our own considerations, the following fuels are investigated to assess their impact on Singapore's energy system. Conventional fuels are produced by the transformation of crude oil; these are divided into Jet fuel (Jet), Marine Gas Oil (MGO), and Marine Fuel Oil (MFO). By contrast, process chains for LNG, biofuels (HRD, HRJ), and hydrogen (LH_2) produced by renewable energy sources are analysed as substitutes to these fuels. An overview of the investigated pathways and scenarios is given in Table 1.

Table 1: Overview of investigated pathways and scenarios

Pathway	Scenarios	Category	Investigated fuel and its application(s)
MFO	min ave max	Conventional Fuels	Marine Fuel Oil for ships
MGO	min ave max	Conventional Fuels	Marine Gas Oil for ships
LNG	min ave max	Liquefied Natural Gas	Liquefied Natural Gas for ships
HRD	min ave max	Biofuels	Hydrogenated Renewable Diesel for ships
LH_2	min ave max	Liquid Hydrogen	Liquid Hydrogen for ships and airplanes
JET	min ave max	Conventional Fuels	Jet fuel for airplanes
HRJ	min ave max	Biofuels	Hydrogenated Renewable Jet fuel for airplanes

2.4 Inputs and Data

Assessment of the related literature shows that the characteristics of Singapore's energy system are not adequately covered by existing WTT studies. It is therefore necessary to select specific process data representing Singapore's energy system and its upstream energy supply.

Processes are organised into four major categories: Conventional fuels, LNG, Biofuels, and LH_2. For each process, $\boldsymbol{E_{Main,i}}$, $\boldsymbol{E_{Aux,i}}$, and $\boldsymbol{GHG_i}$ are introduced in units of MJ_{out}. A summarised description of input parameters is presented in the following discussion. For additional information, this Chapter is extended using specific data on applied models and assumptions published separately in the Supplementary Materials of this article (*'Annex C Detailed Description of Processes'*).

Table 2 summarises the input data of processes with regard to the methodology presented in this Chapter.

Table 2: Input data for energy consumption and emissions occurring in each process

	Input data processes	Main energy			Auxiliary energy			GHG emissions		
		MJ_{main}/MJ_{out}			*MJ_{Aux}/MJ_{out}*			*gCO_2eq/MJ_{out}*		
		min	*ave*	*max*	*min*	*ave*	*max*	*min*	*ave*	*max*
Conventional fuels	Crude oil extraction (SG mix)	1.017	1.024	1.080	0.000	0.000	0.000	1.56	1.81	6.01
	Crude oil extraction (Int.)	1.047	1.050	1.080	0.000	0.000	0.000	3.53	3.73	6.01
	Crude oil transport	1.000	1.000	1.000	0.008	0.009	0.022	0.63	0.70	1.68
	Product transport to SG	1.000	1.000	1.000	0.009	0.030	0.046	0.70	2.26	3.48
	Refining of MGO/Jet	1.050	1.085	1.120	0.000	0.000	0.000	3.68	6.22	8.82
	Refining of MFO	1.010	1.014	1.050	0.000	0.000	0.000	0.74	1.05	3.68
	Jet fuel distribution	1.000	1.000	1.000	0.004	0.004	0.004	0.23	0.23	0.23
	Marine fuel distribution	1.000	1.000	1.000	0.003	0.003	0.003	0.17	0.17	0.17
LNG	NG extraction and processing	1.010	1.020	1.050	0.000	0.000	0.000	2.00	4.00	7.00
	NG liquefaction and loading	1.065	1.079	1.114	0.000	0.000	0.000	4.08	5.26	7.23
	LNG sea-transport	1.016	1.048	1.053	0.004	0.013	0.015	1.22	3.70	4.08
	LNG receiving terminal	1.000	1.003	1.010	0.002	0.002	0.002	0.12	0.26	0.68
	LNG distribution	1.001	1.001	1.001	0.000	0.000	0.000	0.04	0.04	0.04
Biofuels	Cultivation of oil palms	1.000	1.000	1.000	0.070	0.090	0.110	5.40	10.40	15.40
	Extraction of CPO	1.818	2.000	2.381	-0.068	-0.005	-0.005	-6.76	24.95	24.95
	Transport of CPO to SG	1.000	1.000	1.000	0.013	0.013	0.013	0.91	0.91	0.91
	Production of HRJ/HRD	1.000	1.000	1.000	0.100	0.120	0.140	5.00	8.00	10.00
	Distribution of HRJ	1.000	1.000	1.000	0.004	0.004	0.004	0.22	0.22	0.22
	Distribution of HRD	1.000	1.000	1.000	0.003	0.003	0.003	0.17	0.17	0.17
LH_2	Electricity generation	1.000	1.000	1.000	0.000	0.000	0.000	0.00	0.00	0.00
	Hydrogen electrolysis	1.260	1.500	1.640	0.000	0.000	0.000	0.00	0.00	0.00
	Hydrogen liquefaction	1.000	1.000	1.000	0.210	0.280	0.300	0.00	0.00	0.00
	Hydrogen ocean transport	1.049	1.085	1.100	0.000	0.000	0.000	0.00	0.00	0.00
	Hydrogen distribution	1.026	1.046	1.067	0.000	0.000	0.000	0.00	0.00	0.00

2.4.1 Conventional Fuels

Supply of MFO, MGO, and Jet in Singapore requires a complex supply chain. The essential processes are listed in Table 2 and described in the following paragraphs. A more detailed description of process data, sources, and applied assumptions is given in Annex C.1 in the Supplementary Materials of this article.

Crude oil extraction. Energy required to extract crude oil varies according to recovery method, global region of extraction, and deposit type. In this study, energy demand is set as 1.024 MJ_{main}/MJ_{out} and GHG emissions to 1.81 gCO_2eq/MJ_{out}. To increase robustness, a minimum energy demand of 1.017 MJ_{main}/MJ_{out} and GHG emissions of 1.56 gCO_2eq/MJ_{out} are chosen in line with IOGP data [30,31] and shares of crude oil and condensate imports from different world regions according to IE Singapore [32]. In addition, a very high energy demand of 1.080 MJ_{main}/MJ_{out} and GHG emissions of 6.01 gCO_2eq/MJ_{out} are set as **max** values to show possible impacts of significantly higher energy demand, which might be caused by the use of more energy intensive production methods in current export countries or a shift of the import mix to importers with higher energy demand for oil recovery, such as the US or South America.

Crude oil transport. Based on country of origin [32] and typical fuel consumption of crude oil transport [33], energy consumption of crude oil transport to Singapore is calculated to be 0.009 (MJ_{aux}/MJ_{out}). GHG emissions are 0.70 gCO_2/MJ_{out}. Transport efficiency depends on speed, ship size, capacity utilisation, weather, and other factors. Further reductions of the transport distance seem rather unlikely as the main source of crude oil is the Middle East. Therefore, energy demand in the **min** scenario is reduced by 10 % (0.008 MJ_{aux}/MJ_{out}, 0.63 gCO_2/MJ_{out}). For the **max** parameters, a higher transport distance is assumed. This would result from a shift of oil imports from mainly the Middle East to more distant regions such as the Americas or Africa. In the **max** scenario, energy demand increases to 0.022 MJ_{aux}/MJ_{out} and emissions increase to 1.68 g CO_2e/MJ_{out}.

Crude oil refining. The energy efficiency of refineries depends on the share of straight-run products and on upgrading processes, refinery complexity, crude oil quality, and yield of output products. To calculate efficiency of MFO and MGO/Jet production, the origins of Singapore's crude oil [32] and resulting average crude quality, complexity data of Singapore's refineries, and heavy product yield [34,35] are taken into account. Based on these data, a regression formula for calculating efficiencies of refineries [36] to estimate specific refinery efficiency of fuels in Singapore can be derived. Production of MGO/Jet in Singapore is set to an efficiency of 1.085 MJ_{main}/MJ_{out} and production of heavy fuel oils such as MFO to an efficiency of 1.014 MJ_{main}/MJ_{out}. The resulting emissions are 6.22 gCO_2eq/MJ_{out} for MGO/Jet and 1.05 gCO_2eq/MJ_{out} for MFO. To take into account high uncertainty, the ranges for energy demand and emissions are set for MFO (1.01 MJ_{main}/MJ_{out} to 1.05 MJ_{main}/MJ_{out} and 0.74 gCO_2eq/MJ_{out} to 3.68 gCO_2eq/MJ_{out}, respectively) and for MGO/Jet (1.05 MJ_{main}/MJ_{out} to 1.12 MJ_{main}/MJ_{out} and 3.68 gCO_2/MJ_{out} to 8.82 gCO_2eq/MJ_{out}, respectively).

Fuel distribution. The final step in conventional fuel pathways is the distribution of fuels. Most energy is consumed by pumping operations. Relatively long transport distances are assumed in order to avoid an underestimation of energy demand for distribution. Owing to limited data, these values include high uncertainties. Estimates show that fuel distribution is a very effective process within the process chain. Jet fuel is transported from the refinery to the airport, unloaded, stored, and distributed by trucks or a fuel hydrant system. Overall energy consumption in this step is 0.004 MJ_{aux}/MJ_{out} and GHG emissions are 0.23 gCO_2eq/MJ_{out}. Marine fuels are distributed by ship-to-ship (STS) distribution in ports, with a resulting energy consumption of 0.003 MJ_{aux}/MJ_{out} and GHG emissions of 0.17 gCO_2eq/MJ_{out}.

Fuel imports. It is important to emphasise that a large percentage of bunker fuels is imported and not produced in Singapore. According to ENI [34,35], fuel oil production in Singapore is highly volatile, covering 23 % of fuel oil consumption in 2012 and 9 % of fuel oil consumption in 2013. These figures do not necessarily constitute the fuel oil mix supplied to ships, as large quantities of fuel oil are exported [32]. It is further assumed that 15 % of MFO consumed in Singapore is produced locally, while MGO/Jet is assumed to be solely produced in Singapore. The pathways are combined accordingly.

To understand the oil import mix to Singapore, the efficiency of crude extraction and fuel transport must also be determined. World average data calculated on the basis of IOGP data [30,31] are used to denote the extraction efficiency of fuel oil produced outside of Singapore. To model the **max** scenario efficiency and emissions, the process parameters used for Singapore are assumed to be universal. In accordance with Table 2, energy use is set to 1.050 MJ_{main}/MJ_{out} (1.047 MJ_{main}/MJ_{out} to 1.080 MJ_{main}/MJ_{out}) and associated GHG emissions to 3.73 gCO_2eq/MJ_{out} (3.53 gCO_2eq/MJ_{out} to 6.01 gCO_2eq/MJ_{out}).

Previous crude oil transport into fuel oil exporting countries is not taken into account in this methodology, and refinery efficiencies and emission factors in other countries are assumed to be the same as those in Singapore and are not further distinguished.

In order to represent the high share of international bunker oil imports to Singapore, this investigation examines product transport of fuel oil. For exporting countries [32] and specific fuel consumption for product transport [33], energy use is and GHG emissions are calculated to be 0.030 MJ_{aux}/MJ_{out} and 2.26 gCO_2eq/MJ_{out}, respectively. Uncertainties are taken into account by assuming different transport distances, resulting in 0.009 MJ_{aux}/MJ_{out} and 0.70 gCO_2eq/MJ_{out} and 0.046 MJ_{aux}/MJ_{out} and 3.48 gCO_2eq/MJ_{out} in the **min** and **max** scenarios, respectively.

2.4.2 Liquefied Natural Gas

A description of input data for the LNG pathway shown in Table 2 is given in this Chapter. A more detailed assessment of process data, sources, and applied assumptions for the pathway is given in Annex C.2 in the Supplementary Materials of this article.

NG Extraction and processing. The energy required to supply the energy for the processes of extraction and processing is highly variable and dependant on deposit type, location, and technology. As natural gas imports from Malaysia and Indonesia are forecast to start diminishing in 2016, LNG imports will dominate Singapore's gas mix in the future [37].

Analyses of different studies show that energy consumption of extraction and processing ranges from less than 0.010 to 0.080 MJ/MJ_{out}. GHG emissions range from 1.00 to 11.00 gCO_2eq/MJ_{out}

[6,18,30,38–44]. In line with available literature, primary energy use is set to 1.020 MJ_{main}/MJ_{out} and specific GHG emissions to 4.00 gCO_2eq/MJ_{out}. In order to cover the broad range of available data in terms of location, technology, and methodology, a **min** value (1.010 MJ_{main}/MJ_{out}; 2.00 gCO_2eq/MJ_{out}) and a **max** value (1.050 MJ_{main}/MJ_{out}; 7.00 gCO_2eq/MJ_{out}) are defined.

NG Liquefaction and loading. Large scale liquefaction of natural gas often takes place directly in the vicinity of gas fields. For example, Qatargas, the world's largest LNG exporter, offers an integrated LNG value chain with offshore recovery, transport via wet-gas pipelines onshore, processing, liquefaction, storage, and loading of company-owned LNG tankers [45]. Other large LNG projects such as the Gorgon Gas Project in Australia unite recovery, production, liquefaction, and export processes in close proximity. Natural gas, which is transformed to LNG in liquefaction plants, has a higher density than compressed natural gas and is thus easier to transport. Natural gas is transformed into a liquid phase through cooling; owing to the required low temperatures, this process is highly energy intensive. Based on a modified model for LNG liquefaction and loading presented in the WTT analysis of JRC [6], energy use and GHG emissions for this process are calculated to 1.079 MJ_{main}/MJ_{out} and 5.26 gCO_2eq/MJ_{out}, respectively. The min scenario with higher efficiencies, less flaring, lower methane losses, and a more efficient terminal is associated with an energy demand of 1.065 MJ_{main}/MJ_{out} and emissions of 4.08 gCO_2eq/MJ_{out}. Lower efficiencies and increased flaring raise the methane and terminal losses in the **max** scenario and result in an energy demand of 1.114 MJ_{main}/MJ_{out} and GHG emissions of 7.23 gCO_2eq/MJ_{out}.

LNG transport. Long range LNG transport is most efficiently performed by ships. During transport, part of the LNG is gasified from heat input, producing boil-off gas (BOG) [6,46]. Usually, insulation in modern LNG carriers is designed so that the energy requirements at the ship's design speed equals BOG [47,48]. The energy consumption and emissions of LNG carriers can be estimated based on a simple model assuming ship size, transport distance, speed, boil-off rate, and share of BOG/MGO use. In the **ave** scenario, distances are set according to today's import mix, which is dominated by imports from Equatorial Guinea [32]. While a higher share of more distant imports increases transport distance in the **max** scenario, distance is significantly reduced in the **min** scenario, in which LNG is imported from Australia and the Middle East in equal shares. Energy consumption is calculated to 1.048 MJ_{main}/MJ_{out} (1.016 MJ_{main}/MJ_{out} to 1.053 MJ_{main}/MJ_{out}) and 0.013 MJ_{aux}/MJ_{out} (0.004 MJ_{aux}/MJ_{out} to 0.015 MJ_{aux}/MJ_{out}). GHG emissions are assumed to be 3.70 gCO_2eq/MJ_{out} (1.22 gCO_2eq/MJ_{out} to 4.08 gCO_2eq/MJ_{out}).

LNG receiving terminal. In order to calculate the parameters for LNG terminal operations, a model is developed to determine energy efficiency and emissions of LNG bunkering in Singapore's port. LNG imports are unloaded at the LNG import terminal at Jurong Island. Heat input to equipment and pipe network during normal operations causes vaporisation of small parts of the LNG. The terminal is equipped with boil-off-gas recovery. The receiving terminal is assumed to use the same amount of energy as the export terminal. Electricity consumption is set to 0.00085 MJ_{ele}/MJ_{LNG} for operation of the import terminal [6]. In this model, electricity is supplied by Singapore's electricity mix, resulting in a primary auxiliary energy demand of 0.002 MJ_{aux}/MJ_{out} and GHG emissions of 0.12 gCO_2eq/MJ_{out}. It is assumed that 0.0025 MJ_{main}/MJ_{out} of the natural gas evaporates and is flared during terminal operations (adding 0.14 gCO_2eq/MJ_{out}). In order to cover the broad range of values in the literature [6,8,18,41], evaporation losses are set to almost zero (0.000065 MJ_{main}/MJ_{out}) in the **min** scenario and 0.01 MJ_{main}/MJ_{out} in the **max** scenario.

LNG distribution. Different distribution methods are possible. Ship-to-ship (STS) is the most promising solution for LNG bunkering, with advantages including large bunker volumes and high flexibility. During unloading of cargo at terminals, bunker ships can deliver the volume demanded to cargo ships. [49] A model similar to that of conventional fuel distribution is chosen. It is further assumed that fuel barges are loaded directly at the LNG import terminal. Electricity demand for pumps is already included in the electricity demand of the terminal. In the LNG process chain, distribution covers fuel transport from the terminal to the customer. The lower density of LNG compared to conventional fuels is taken into account by adjusting the fuel consumption of the LNG bunker barge. LNG distribution results in energy consumption of 1.001 MJ_{main}/MJ_{out} and GHG emissions of 0.04 gCO_2eq/MJ_{out}.

2.4.3 Biofuels

A description of input data for the biofuel pathways in Table 2 is given in this Chapter. A more detailed assessment of process data, sources, and applied assumptions for the pathways is given in Annex C.3 in the Supplementary Materials of this article.

Cultivation of oil palms. The biofuels discussed here are based on palm oil because of the high potential for such sourcing in the surrounding regions [50] and high oil yields per area [51]. Palm oil is extracted from fresh fruit bunches (FFBs) of oil palms harvested on plantations. GHG emissions caused by land use change (LUC) are not taken into account here, although the effects of LUC are discussed in Chapter 3.3. Energy demand and resulting emissions are caused by use of fertilisers, diesel for machinery, and direct emissions from plantation use. Based on the palm cultivation process and transport to the oil mill, the total auxiliary energy demand for the cultivation process is 0.090 MJ_{aux}/MJ_{out} (0.070 MJ_{aux}/MJ_{out} to 0.110 MJ_{aux}/MJ_{out}) and GHG emissions are 10.40 gCO_2eq/MJ_{out} (5.40 gCO_2eq/MJ_{out} to 15.40 gCO_2eq/MJ_{out}). These broad ranges were chosen with regard to the big differences in the investigated literature [6,16,52–54].

Extraction of CPO. Production of crude palm oil from FFBs involves several stages. In the first stage, FFB oil fruit is separated from bunches. The fruit is treated and empty fruit bunches (EFBs) are sorted out. Pressing is applied to obtain oil from the fruit. In the post- processing stage, water and solids are removed from the oil. Many co-products are produced during oil extraction that can be processed to improve the efficiency of the process. Based on literature values, assumptions are made to allow modelling of crude palm oil production [6,52–55]. In a simple model, we assume that the oil yield comprises crude palm oil and crude palm kernel oil output. Combustion of the fibres and hulls of the FFBs produces heat and is used for electricity production; however, we do not take surplus heat or electricity produced from fibres and hulls into account. EFBs are used to substitute part of the fertiliser demand at cultivation and generate a small amount of energy and carbon credits. Electricity generation and methane capture of palm oil mill effluent (POME), which is only applied in the **min** scenario, leads to energy and carbon credits. The overall process parameters are 2.000 MJ_{main}/MJ_{out} (1.818 MJ_{main}/MJ_{out} to 2.381 MJ_{main}/MJ_{out}) for production plus −0.005 MJ_{aux}/MJ_{out} (−0.068 MJ_{aux}/MJ_{out} to −0.005 MJ_{aux}/MJ_{out}) from credits and a GHG emissions factor of 24.95 gCO_2eq/MJ_{out} (−6.76 gCO_2eq/MJ_{out} to 24.95 gCO_2eq/MJ_{out}).

Transport of CPO to SG. Transport includes transport from the oil mill to the local port, storage, sea transport to Singapore, and storage in Singapore. The overall energy consumption for CPO transport from South East Asia to Singapore is 0.013 MJ_{aux}/MJ_{out}, and the resulting GHG emissions are 0.91 gCO_2eq/MJ_{out}.

Production of HRJ/HRD. In the pathways investigated, hydrogenated renewable jet fuel (HRJ) and hydrogenated renewable diesel (HRD) are produced for use in ships and aircraft. The hydrogenation process was selected because of its superior fuel qualities compared to other processes and the existing refinery capacity in Singapore [56]. Different studies have investigated the production of HRJ and HRD, and yields of hydrotreated fuel as well as the ratio of the main input CPO and hydrogen vary by process and scenario. Energy use and emissions depend on the amount of hydrogen required, which in turn depends on selected process type and technologies [6,21,57]. We assume a fixed share of 1.000 MJ_{main}/MJ_{out} and varying auxiliary energy demand of 0.120 MJ_{aux}/MJ_{out} (0.100 MJ_{aux}/MJ_{out} to 0.140 MJ_{aux}/MJ_{out}). Emissions are set to 8.00 gCO_2eq/MJ_{out} (5.00 gCO_2eq/MJ_{out} to 10.00 gCO_2eq/MJ_{out}).

Distribution. For the processes of distribution of HRJ and HRD, a model similar to that of conventional fuel distribution is selected. The overall energy consumption for HRJ distribution is 0.004 MJ_{aux}/MJ_{out} and GHG emissions are 0.22 gCO_2eq/MJ_{out}. The resulting energy consumption for HRD distribution is 0.003 MJ_{aux}/MJ_{out} and GHG emissions are 0.17 gCO_2eq/MJ_{out}.

2.4.4 Liquid Hydrogen

A description of input data for the liquid hydrogen pathway in Table 2 is given in this Chapter. A more detailed assessment of process data, sources, and applied assumptions for the pathway is given in Annex C.4 in the Supplementary Materials of this article.

Multiple pathways are possible for supplying Singapore with liquid hydrogen for bunkering purposes. The selected pathway here represents a zero emission pathway in which hydrogen is generated in the Middle East with renewable energy and imported to Singapore. Unlike Singapore, the Middle East offers perfect conditions for excess energy production: relatively low population densities, large desert area, and high renewable energy potential. Although liquid hydrogen (LH_2) transport is not yet utilised there, compared to gaseous pipeline transport or high voltage direct current (HVDC) transport of electricity, this mode combines the advantages of less grid-bound infrastructure and requires no large scale liquefaction facilities in Singapore [58].

Electricity generation. The WTT approach does not take energy demand or emissions for manufacturing, installation, and disposal into account. Therefore, auxiliary energy use and GHG emissions are set to zero. The main energy input is solar irradiation. A value of E_{main} for transformation of primary energy from renewable energy sources to secondary energy of 1.000 MJ_{main}/MJ_{out} is chosen.

Hydrogen electrolysis. Electrolysis of water is a process in which electricity is used to split water into hydrogen and oxygen. High pressure alkaline and polymer electrolyte membrane (PEM) electrolysis of water are the most promising technologies for hydrogen production from renewable energy sources. PEM electrolysis has the advantage of higher efficiencies in partial load, but it is not yet available on a very large scale. Systems with several hundreds of megawatts are under development and will be available in the near future [59]. As the efficiencies for both electrolysis technologies are similar [60], no further distinction is made between these types. In accordance with literature sources, a broad range of energy consumption for large scale electrolysis of 1.260 MJ_{main}/MJ_{out} to 1.640 MJ_{main}/MJ_{out} is assumed [6,16,58,60–64]. The average energy demand is set to 1.500 MJ_{main}/MJ_{out}. Electrolysis of water does not cause any direct GHG emissions, and the energy required to extract water from sea water is negligible compared to the electricity demand of electrolysis.

Hydrogen liquefaction. To transform hydrogen from a gaseous to a liquid state, it must be cooled down to a temperature of 20 K. To avoid losses of liquid hydrogen caused by energy generated when spin isomers of hydrogen change from the ortho- to the para-form, ortho-to-para conversion must be performed. A detailed description of different liquefaction processes was developed by Amos. [65] In this paper, we assume an electricity demand for liquefaction of 0.280 MJ_{ele}/MJ_{out} in a range from 0.210–0.300 MJ_{ele}/MJ_{out}. Literature values show an even broader range with more extreme values [6,16,61–63,66–68].

Hydrogen ocean transport. Transport of hydrogen by ocean tankers includes three process stages: loading at the export terminal, ocean transport, and unloading at the import terminal in Singapore. Although, there are no LH_2 ocean carriers in operation today, extensive research has been performed on the subject [63,68,69]. LH_2 transport has also been investigated in recent publications and projects [70,71]. Using these sources, a simple model for hydrogen carriers is developed based on boil-off losses, transport distance, and ship speed. In addition, different terminal losses are assumed for transfer of LH_2. The resulting energy demand for ocean transport including energy consumption of import and export terminals ranges from 1.049 MJ_{main}/MJ_{out} to 1.100 MJ_{main}/MJ_{out} with an average of 1.085 MJ_{main}/MJ_{out}.

Hydrogen distribution. Energy distribution of LH_2 in Singapore involves distinct demand for storage, truck/vessel transport, and evaporation losses at loading/unloading operations. The overall distribution process for liquid hydrogen to ships or aircraft is heavily dependent on evaporation losses during loading and unloading. Energy demand for transport is nearly negligible, as transport distances are very small. Based on unrecoverable boil-off losses of 0.02 MJ/MJ_{out} at truck/barge loading and unloading, overall energy consumption of the distribution process is 1.046 MJ_{main}/MJ_{out}. It is assumed that part of the boil-off losses in different process stages could be recovered to produce the electricity required for terminal operations and re-liquefaction of hydrogen. As it is assumed that transport trucks and barges are powered by hydrogen, no GHG emissions are caused in the process of hydrogen distribution. The best case scenario assumes that BOG losses can be reduced to 0.01 MJ/MJ_{out}. This results in 1.026 MJ_{main}/MJ_{out} for marine and aviation distribution. However, an increase in evaporation losses to 0.03 MJ/MJ_{out} would lead to a total energy demand of 1.067 MJ_{main}/MJ_{out}. The differences between aviation distribution and marine fuel distribution are very low and the high uncertainties for fuel distribution are assumed to be equal. As a representative for aviation distribution, values for marine fuel distribution are used in the combined pathway. This reduces the number of overall pathways and enables a more compact discussion without affecting the results.

2.4.5 Economic Data

Prices for different fuels are assessed based on market prices and historical developments. While this procedure is applicable for MFO, MGO, Jet fuel, and LNG, costs for biofuels and hydrogen are more difficult to determine. Table 3 gives an overview of the selected price range of conventional fuels and biofuels as well as costs for single hydrogen processes. Based on these, future LH_2 generation costs are calculated. Fuel prices are highly dependent on the evolution of the oil price, which dropped significantly in 2014/2015. MFO prices changed from over 600 USD/t in August 2014 to 270 USD/t in January 2015, while MGO prices dropped from 900 to 480 USD/t in the same period [72]. To cover these developments, a price range from 270 to 700 USD/t (7–17 USD/GJ) is selected for MFO and 500 to 1,100 USD/t (12–

26 USD/GJ) for MGO. Jet fuel prices show a very similar development path to MGO prices [73,74], and the same price range is set for MGO. LNG prices in Asia dropped from a high of nearly 20 USD/mmBtu in 2014 to 7 USD/mmBtu in mid-2015 [75], and an LNG range of 7–19 USD/GJ is selected for this investigation. Suitable prices of hydrogenated vegetable fuels were not available. IEA estimates that feedstock costs are 35–40% of advanced biofuel costs [76]. Based on a 40% feedstock cost and the cost evolution of palm oil in recent years, ranges of 23 USD/GJ (400 USD/t palm oil) to 57 USD/GJ (1000 USD/t palm oil) are set for HRD and HRJ, respectively.

Table 3: Input data used to assess economic impact of substitutions

Input data fuel prices and processes LH_2				
		USD/GJ_{out}		
		min	*ave*	*max*
Fuel prices	MFO distributed	7.0	10.0	17.0
	MGO/Jet distributed	12.0	17.0	26.0
	LNG distributed	7.0	10.0	19.0
	HRJ/HRD distributed	23.0	35.0	57.0
LH_2 processes	Electricity generation	8.5	15.6	41.5
	Hydrogen electrolysis	4.9	17.0	35.6
	Hydrogen liquefaction	2.1	4.2	6.2
	Hydrogen ocean transport	1.0	2.0	3.0
	Hydrogen distribution	1.0	2.0	3.0

As no data are available for large scale hydrogen costs, a rough estimation of hydrogen costs is done to forecast a range of future fuel costs for liquid hydrogen. All calculations assume an interest rate of 6% and 20-year depreciation, resulting in an annuity factor of 0.087. PV costs in the Middle East are set to 8.5 USD/GJ (**min**), 15.6 USD/GJ (**ave**), and 41.5 USD/GJ (**max**) based on data from WEIO 2014 for the Middle East [77] but assume lower capital costs for PV in the **ave** (900 USD/kW) and **min** scenario (400 USD/kW).

Generated power has to be directly used in electrolysis to produce hydrogen. Costs for electrolysis excluding the electricity price are 35.6 USD/GJ today and are assumed in the **max** scenario (assuming investment costs of 2000 USD/kW_{H2}, 2.5% annual O&M costs on the basis of investment costs, and full load hours identical to those of electricity production). In the **ave** scenario, these costs will decline to 17.0 USD/GJ, assuming lower investment costs of 1000 USD/kW_{H2}. 4.9 USD/GJ could be achieved in the **min** scenario by reducing investment costs to 300 USD/kW_{H2}.

For the liquefaction plant, higher full-load hours of 7,500 h are assumed to reduce the installed capacity. Storage costs and efficiencies are included in the liquefaction plant data. In the **max** scenario, investment costs are set to 1,500 USD/kW_{LH2} and annual O&M costs are 2.5% of total investment costs. Costs for liquefaction excluding electricity cost are 6.2 USD/GJ. These costs are reduced with declining investment costs: 1,000 USD/kW LH_2 (**ave)** and 500 USD/kW LH_2 **(min**) to 4.2 USD/GJ (**ave**) and 2.1 USD/GJ (**min**).

Costs for ocean transport are estimated on the basis of LNG transport costs. In the present model, fuel requirements are supplied by BOG, the costs of which are already taken into account by upstream pathways and losses within the transport process. No additional fuel costs have to be considered. Additional costs include chartering fees, port costs, canal costs, costs for insurance, and general overhead and trade costs [78]. As with LNG shipping, costs would be highly dependent on fluctuating charter rates and distance travelled [78,79]. Typical non-fuel costs for LNG shipping excluding fuel cost and boil-off are estimated to range from 0.3 to 1.2 USD/GJ_{LNG}, as stated in the literature [79]. Lower temperatures, more advanced technology, and reduced energy density than LNG suggest higher costs for LH_2 carriers. Non-fuel costs for LH_2 carriers are set to 1.0 USD/GJ in the **min**, 2.0 USD/GJ in the **ave**, and 3.0 USD/GJ in the **max** scenarios.

Costs of LH_2 distribution as bunker supply in port are currently not available and hard to estimate as relevant technologies, such as barges and infrastructure, do not exist. As with LH_2 ocean carriers, energy costs are defined by process efficiency and related upstream costs. Additional non-energy costs of fuel distribution are assumed to be similar to the non-energy costs of LH_2 ocean transport. Smaller carrier, storage, and transported volume scales would imply higher specific non-fuel costs, but significantly reduced transport distances lead to a reduction in costs. Costs are estimated to 1.0 USD/GJ in the **min**, 2.0 USD/GJ in the **ave**, and 3.0 USD/GJ in the **max** scenarios.

3 Results

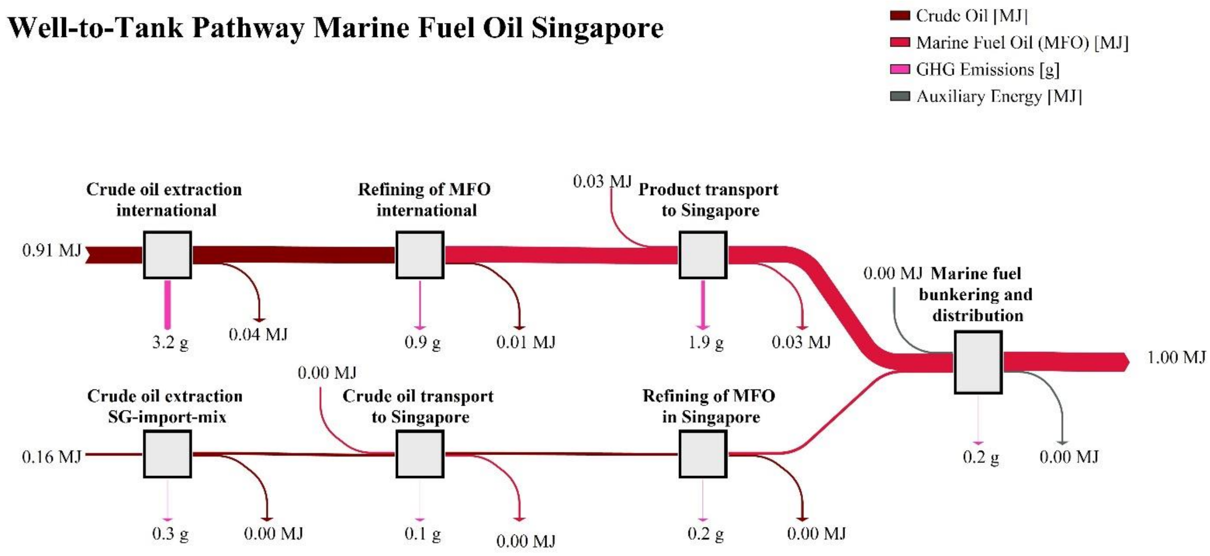
For each process chain, the resulting cumulative energy demand CED and GHG emissions were assessed. The impacts of technical developments are discussed on the basis of the reported parameters, with single process parameters altered to their best and worst case values to show the impact of single developments on the total process chain in terms of energy use and GHG emissions. Pathways for fuel production were compared by reporting parameters. Generalisations of the results derived in our study were discussed on the basis of a comparison with the related literature.

3.1 Assessment of Individual Pathways

By applying the methodology described above to the process parameters, process chains for conventional fuels, LNG, biofuels, and hydrogen were generated. Energy flow and emissions for each process chain were analysed and visualised using Sankey diagrams.

3.1.1 Conventional Fuels

Figure 4 shows the results for the conventional fuel pathways. As only a small share of bunker fuels is produced in Singapore and most are imported, production of MFO consists of two main paths. Different colours are used to denote the respective energy carriers within the process chain.



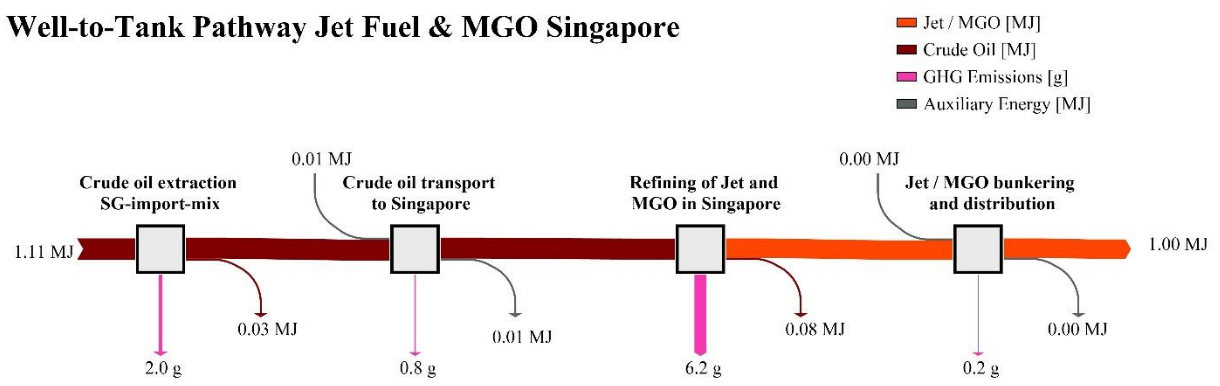


Figure 4: Energy flow and GHG emissions for MFO, MGO and Jet fuels in Singapore

Most energy is lost in the Crude Oil Extraction International process (0.04 MJ/MJ_{MFO}). Product Transport to Singapore is a major consumer of energy (0.03 MJ/MJ_{MFO}) within the process chain. Owing to the high refinery efficiency for heavy products, contributions of refineries to energy consumption and emissions are low. Losses and GHG emissions for fuel distribution are nearly negligible owing to very small transport distances within Singapore. The overall energy consumption to supply 1 MJ_{MFO} fuel in Singapore is 1.09 MJ/MJ_{MFO}. Upstream GHG emissions add up to 6.7 gCO_2eq/MJ_{MFO}.

The process chain to supply MGO or Jet fuel in Singapore is very similar. A difference between the pathways arises from differences between fuel distribution from the refinery to the port in the MGO process chain and fuel distribution from the refinery to the airport in the Jet fuel process chain. The highest impact on energy consumption and emissions in Singapore comes from refining crude oil to middle distillates, with 0.08 $MJ/MJ_{final\ fuel}$ of energy lost and 6.2 $gCO_2eq/MJ_{final\ fuel}$ emitted in this process step. By contrast, crude oil production and transport are highly efficient owing to extraction in the Middle East and comparably short transport distances. The impact of fuel distribution on energy requirements and GHG emissions of process chains is quite limited in both pathways. The overall CED is 1.12 $MJ/MJ_{final\ fuel}$ for both pathways, while GHG emissions of the MGO and Jet fuel pathways total 9.1 gCO_2eq/MJ_{MGO} and 9.2 gCO_2eq/MJ_{Jet}, respectively.

3.1.2 Liquefied Natural Gas

The energy flow and upstream GHG emissions of LNG as a bunker fuel for ships in Singapore is visualised in Figure 5. Natural gas, LNG, and auxiliary energy are distinguished by different colours.

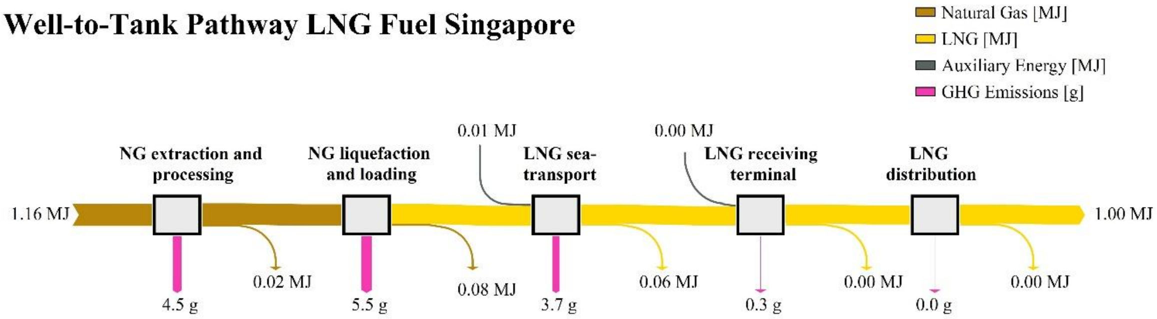


Figure 5: Energy flow and GHG emissions for LNG as a bunker fuel for ships in Singapore

It is seen that most energy (0.08 MJ/MJ_{LNG}) is expended in the liquefaction process. LNG transport (0.06 MJ/MJ_{LNG}) and natural gas extraction and processing (0.02 MJ/MJ_{LNG}) increase the CED. The impact of the LNG receiving terminal and distribution to ships on the 1.17 MJ/MJ_{LNG} CED is comparably low. Allocation of GHG emissions is similarly distributed. Natural gas liquefaction and loading (5.5 gCO_2eq/MJ_{LNG}) has the highest GHG emissions within the process chain, followed by natural gas extraction and processing (4.5 gCO_2eq/MJ_{LNG}) and LNG sea transport (3.7 gCO_2eq/MJ_{LNG}). The LNG receiving terminal (0.3 gCO_2/MJ_{LNG}) and the LNG distribution process have only minor impacts on the overall upstream emissions of 14.1 gCO_2eq/MJ_{LNG}.

3.1.3 Biofuels

Figure 6 visualises energy flow and GHG emissions for HRJ and HRD in Singapore. Different colours are used to distinguish between intermediate products, auxiliary energy, and energy source. The HRJ and HRD process chains differ in the fuel distribution process only.

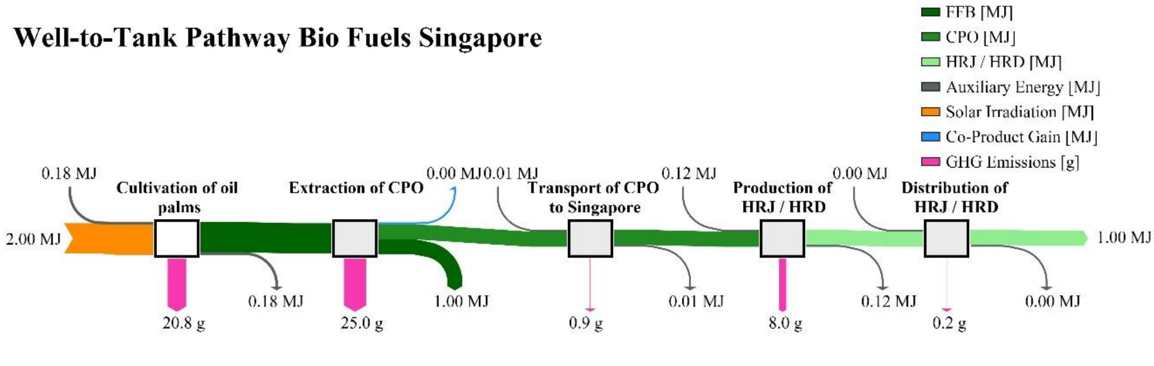


Figure 6: Energy flow and GHG emissions for hydrogenated renewable jet fuel and diesel in Singapore

The overall CED is particularly affected by the extraction of crude palm oil (CPO) (1.00 MJ/$MJ_{final\ fuel}$). Cultivation of oil palms (0.18 MJ/$MJ_{final\ fuel}$) and production of hydrogenated fuel (0.12 MJ/$MJ_{final\ fuel}$) cause significant energy losses. Transport of CPO (0.01 MJ/$MJ_{final\ fuel}$) and fuel distribution contribute only marginally to the overall CED (2.31 MJ/$MJ_{final\ fuel}$). GHG emissions are highest for extraction of CPO (25.0 $gCO_2eq/MJ_{final\ fuel}$), cultivation of oil palms (20.8 $gCO_2eq/MJ_{final\ fuel}$), and production of fuels (8.0 $gCO_2eq/MJ_{final\ fuel}$). Transport of CPO (0.9 $gCO_2eq/MJ_{final\ fuel}$) and distribution of fuels (0.2 $gCO_2eq/MJ_{final\ fuel}$) have little impact on pathway emissions. The overall upstream emissions in the hydrogenated diesel and jet fuel pathways add up to 54.8 gCO_2eq/MJ_{HRD} and 54.9 gCO_2eq/MJ_{HRJ}, respectively. Technological improvements and handling of co-products can have a high influence on CED and GHG emissions. Impacts are further discussed in Chapter 3.2.

3.1.4 Liquid Hydrogen

Energy flow for liquid hydrogen as a zero emission fuel in Singapore is visualised in Figure 7.

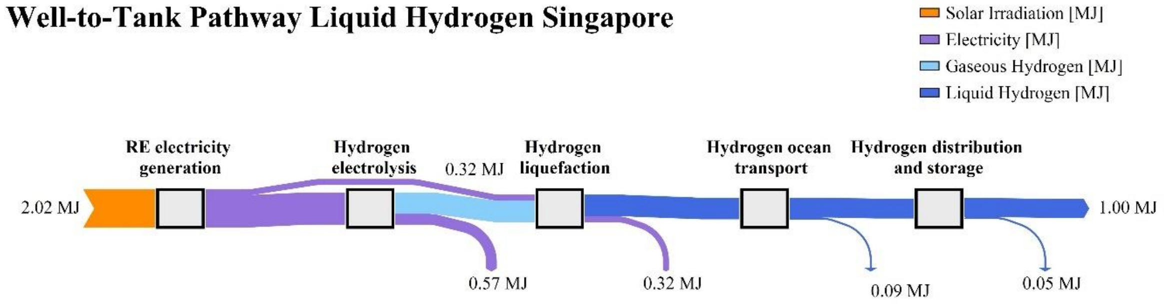


Figure 7: Energy flow and GHG emissions for liquid hydrogen as zero emission fuel in Singapore

Different colours are used to distinguish among the different intermediate products and the energy source. No emissions occur in this process chain, as required auxiliary energy is produced within the hydrogen pathway. For electricity generation from renewable energy sources, a conversion efficiency of 100 % is assumed in line with the above defined methodology. Most energy is lost in the hydrogen production process (0.57 MJ/MJ_{LH2}), followed by hydrogen liquefaction (0.32 MJ/MJ_{LH2}) and ocean transport (0.09 MJ/MJ_{LH2}). Owing to leakage, energy losses in LH_2 distribution (0.05 MJ/MJ_{LH2}) are significant. The overall CED of the process chain is 2.02 MJ/MJ_{LH2}. Technological improvements and future capacity to handle hydrogen leakage losses will have a big impact on overall energy efficiency of this pathway.

3.2 Sensitivity Analysis

The above results for the CED and the GHG emissions of various pathways depend heavily on input data. **Min** and **max** values are chosen with regard to uncertainties in technological processes and possible future developments. Their impacts on well-to-tank (WTT) energy demand and GHG emissions for the whole process chain are shown in Table 4. Sensitivities of process chains are investigated by substituting **ave** parameters with **min** and **max** values according to Table 2.

Table 4: Impact of process parameters on WTT energy use and WTT GHG emissions

	Input data processes	WTT energy use		WTT GHG emissions	
		impact process chain		*impact process chain*	
		min	*max*	*min*	*max*
MFO	Crude oil extraction (SG mix)	-1%	+9%	-1%	+9%
	Crude oil extraction (Int.)	-3%	+28%	-3%	+29%
	Crude oil transport	-0%	+2%	-0%	+2%
	Product transport to SG	-19%	+15%	-20%	+15%
	Refining of MFO	-5%	+41%	-5%	+41%
	Marine fuel distribution	=	=	=	=
MGO	Crude oil extraction (SG mix)	-6%	+49%	-3%	+50%
	Crude oil transport	-1%	+11%	-1%	+12%
	Refining of MGO	-29%	+30%	-29%	+29%
	Marine fuel distribution	=	=	=	=
LNG	NG extraction and processing	-7%	+20%	-16%	+24%
	NG liquefaction and loading	-9%	+22%	-9%	+16%
	LNG sea-transport	-26%	+4%	-20%	+3%
	LNG receiving terminal	-2%	+5%	-1%	+4%
	LNG distribution	=	=	=	=
HRD	Cultivation of oil palms	-3%	+3%	-18%	+18%
	Extraction of CPO	-20%	+32%	-61%	+7%
	Transport of CPO to SG	=	=	=	=
	Production of HRD	-2%	+2%	-5%	+4%
	Distribution of HRD	=	=	=	=
LH_2	Electricity generation	=	=	=	=
	Hydrogen electrolysis	-27%	+16%	=	=
	Hydrogen liquefaction	-8%	+2%	=	=
	Hydrogen ocean transport	-7%	+3%	=	=
	Hydrogen distribution	-4%	+4%	=	=
Jet	Crude oil extraction (SG mix)	-6%	+49%	-3%	+50%
	Crude oil transport	-1%	+11%	-1%	+12%
	Refining of Jet	-29%	+29%	-29%	+29%
	Jet fuel distribution	=	=	=	=
HRJ	Cultivation of oil palms	-3%	+3%	-18%	+18%
	Extraction of CPO	-20%	+32%	-61%	+7%
	Transport of CPO to SG	=	=	=	=
	Production of HRJ	-2%	+2%	-5%	+4%
	Distribution of HRJ	=	=	=	=

3.2.1 Conventional Fuels

Marine fuel oil (MFO) has a very efficient upstream pathway (WTT energy use 0.09 MJ/MJ_{MFO}, WTT GHG emissions 6.7 g/MJ_{MFO}). As fuel oil imports dominate bunker fuel sales in Singapore, the impacts of processes that concentrate on MFO production in Singapore are limited. Refining efficiency in the average scenario is set relatively high and implies a high straight-run share of fuel oil. Higher complexities of refinery processes or the implementation of regulations could lead to significantly higher WTT energy demand and emissions. An increase of refinery losses from 1.014 to 1.05 MJ/MJ_{out} would result in 41% higher pathway losses and GHG emissions. Energy losses of fuel oil transport are hard to predict. The higher efficiency described in Table 2, which arises from lower transport distances, would lead to reductions in energy demand (19%) and GHG emissions (20%). An even higher increase of transport distance to 10,000 nm, as described in Table 2, results in 15% higher energy use and GHG emissions over the process chain. More energy intensive global oil extraction would lead to 28% higher energy demand and 29% higher GHG emissions. Other changes in process parameters have less impact on the MFO process chain.

Process chains for Marine gas oil (MGO) and Jet fuel show a very similar behaviour (the respective WTT energy uses are 0.12 $MJ/MJ_{final\ fuel}$ and WTT GHG emissions are 9.1 gCO_2eq/MJ_{MGO}, 9.2 gCO_2eq/MJ_{Jet}). The **ave** scenario assumes crude oil extraction from the Middle East, which is highly efficient. A change of crude oil sources or higher share of unconventional oil would result in more energy intensive extraction. An increase from 1.024 to 1.08 MJ_{main}/MJ_{out} would result in 49% higher energy demand and 50% higher GHG emissions. The impact of crude oil transport is rather limited, as its efficiency is already quite high. A higher average transport distance as indicated in Table 2 leads to 11% higher energy use and 12% higher GHG emissions. Refinery efficiency for middle distillates is assumed to be lower than that of heavy products. A higher straight-run share of products would result in less energy demand and lower emissions. A decrease of energy demand of refining would result in 29% reductions in process chain energy demand and GHG emissions. An increase could lead to 29% higher WTT energy demand and upstream GHG emissions (with MGO experiencing a 30% higher energy demand).

3.2.2 Liquefied Natural Gas

The LNG pathway shows high energy efficiency and low GHG emissions (WTT energy use 0.17 MJ/MJ_{LNG}, WTT GHG emissions 14.1 gCO_2eq/MJ_{LNG}). In three of the processes of the LNG process chain, the impacts of **min** and **max** values are significant. A broad range of literature values is reported for energy demand and emissions of natural gas extraction and processing. The stated **min** value would reduce total energy demand by 7% and GHG emissions by 16%. The **max** value would increase process chain energy demand by 20% and GHG emissions by 24%. Higher liquefaction efficiencies could reduce overall energy use and GHG emissions by 9% while lower efficiencies and higher leakage would increase energy demand by 22% and emissions by 16%. Transport distance could have a high impact on the overall pathway: a reduced transport distance would lead to a reduction of energy (26%) and GHG emissions (20%); an increase would raise process chain energy use by 4% and GHG emissions by 3%. The impact of different vaporisation rates at the import terminal could reduce (energy losses 2%, GHG emissions 1%) or increase (energy losses 5%, GHG emissions 4%) the overall contribution to upstream energy demand and GHG emissions.

3.2.3 Biofuels

The process chains for HRJ and HRD are highly correlated, with only fuel distribution showing slight differences (with WTT energy use of 1.31 $MJ/MJ_{final\ fuel}$ and WTT GHG emissions of 54.8 gCO_2eq/MJ_{HRD}, 54.9 gCO_2eq/MJ_{HRJ}, respectively). While the impact of the **min** and **max** values of cultivation of oil palms have only limited effects on process chains in terms of energy (±3%), GHG emissions could vary by ±18% owing to high uncertainties concerning fertilisers and N_2O field emissions. Extraction of CPO from FFBs has the highest impact on process chain energy demand and GHG emissions. Aside from process efficiencies, these values are highly influenced by co-products and handling of palm oil mill effluent (POME). While the **min** values would reduce the energy demand by 20% and GHG emissions by 61%, the **max** values would increase energy demand by 32% and emissions by 7%. The best- and worst-cases for production of HRJ or HRD from CPO have only limited impacts: ±2% on WTT energy consumption and -5% or +4% on GHG emissions.

3.2.4 Liquid Hydrogen

The efficiency of the liquid hydrogen pathway could be further increased or decreased based on different **min** and **max** values in terms of energy, although there is no difference in terms of GHG emissions (in the **ave** scenario, WTT energy use is 1.02 MJ/MJ_{LH2} and WTT GHG emissions are 0.0 gCO_2eq/MJ_{LH2}). Higher efficiencies of electrolysis would decrease energy demand by 27%, and lower efficiencies would lead to an increase in energy consumption of 16%. The impact of liquefaction is -8% (**min**) or +2% (**max**). Based on alterations in BOG, the energy demand of ocean transport could influence process chain energy consumption by -7 % (**min**) or +3 % (**max**). Varying leakage loss, which dominates distribution loss, has an impact on pathway energy loss of ±4 %.

3.3 Comparison of Pathways

3.3.1 Cumulative Energy Demand

Figure 8 compares the CED of the investigated pathways by allocating the energy losses occurring in single processes to the four main groups described in Chapter 2.2.

The summation of energy losses in all groups and the energy content of the final fuel is equal to the CED in the **ave** scenario. To show the impact of possible developments and uncertainties, the total CEDs of all process chains with **min** (-) and **max** values (+) selected for every process are displayed. The final fuel energy content is 1 MJ in all process chains.

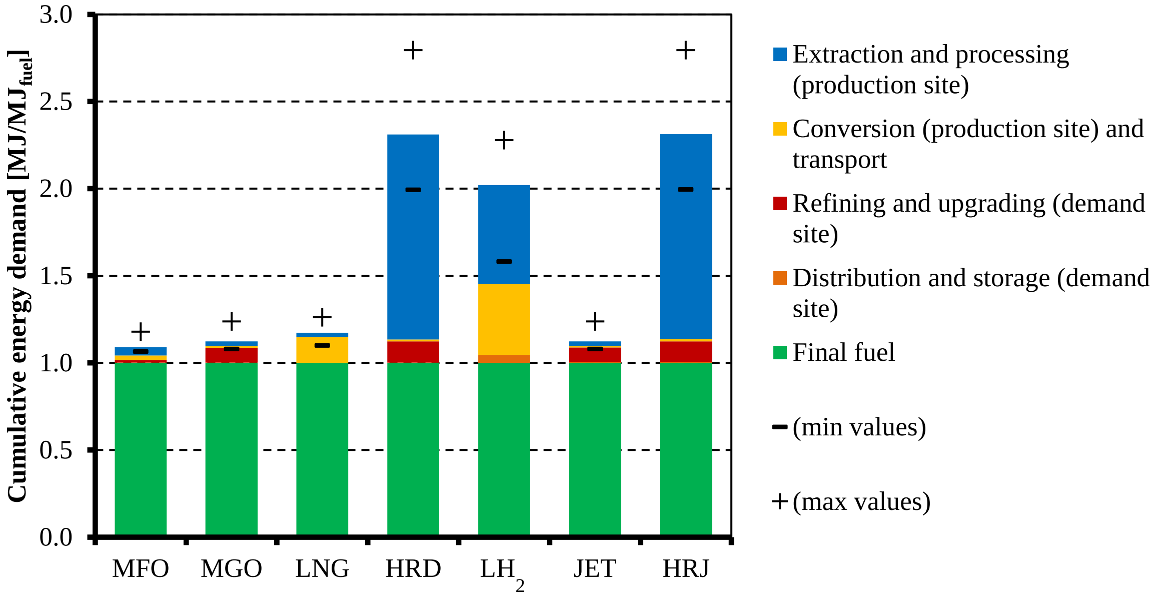


Figure 8: Cumulative energy demand of fuel process chains by process stage

The MFO pathway shows the highest energy efficiency. Extraction and processing (0.05 MJ/MJ_{MFO}) and transport (0.03 MJ/MJ_{MFO}) contribute most to upstream energy demand. The CED could be further reduced from 1.09 MJ/MJ_{MFO} to 1.07 MJ/MJ_{MFO} by applying **min** values in all processes. Calculation with **max** values leads to an energy demand of 1.18 MJ/MJ_{MFO}. $(EROI_{min} = 15,\ EROI_{ave} = 11,\ EROI_{max} = 6)$

Jet and MGO reach a CED of 1.12 $MJ/MJ_{final\ fuel}$ with average values. While **min** values would reduce the CED to 1.08 $MJ/MJ_{final\ fuel}$, **max** values would lead to an increase to 1.24 $MJ/MJ_{final\ fuel}$. Compared to the MFO scenario, there are lower energy losses in the extraction and processing and the transport processes but significantly higher losses in the refining and updating processes. $(EROI_{min} = 13,\ EROI_{ave} = 8,\ EROI_{max} = 4)$

The CED in the LNG process chain is higher than that of conventional fuels. In the **ave** scenario the CED is 1.17 MJ/MJ_{LNG}. **Min** values could reduce the CED to 1.10 MJ/MJ_{LNG}, while **max** values would increase it to 1.26 MJ/MJ_{LNG}. Transport, which includes losses during liquefaction, ocean transport, and at the receiving terminal, dominates the WTT energy consumption.

As no further refining or upgrading is required at the demand site, there is no contribution to the CED. ($EROI_{min} = 10,\ EROI_{ave} = 6,\ EROI_{max} = 4$)

The upstream energy demand of HRJ and HRD is dominated by the extraction and processing phase, which includes cultivation of oil palms, transport to oil mills, and production of crude palm oil (CPO) from fresh fruit bunches (FFB). In the **ave** scenario, this phase contributes 1.18 $MJ/MJ_{final\ fuel}$ to the CED of 2.31 $MJ/MJ_{final\ fuel}$. The second highest fraction of upstream energy is used by the hydrogenation process in the refining and upgrading phase. By applying **min** values, the CED could be further reduced to 1.99 $MJ/MJ_{final\ fuel}$. **Max** values result in CEDs of 2.79 MJ/MJ_{HRD} and 2.80 MJ/MJ_{HRJ}. ($EROI_{min} = 1,\ EROI_{ave} = 0.8,\ EROI_{max} = 0.6$)

The underlying process chain for LH_2 as a bunker fuel in Singapore results in a CED of 2.02 MJ/MJ_{LH2} in the **ave** scenario. 0.57 MJ/MJ_{LH2} are consumed in the extraction and processing phase in which hydrogen is generated by electrolysis. Hydrogen liquefaction and ocean transport are allocated to the transport phase, which requires an additional 0.41 MJ/MJ_{LH2}. Further refining and upgrading is not applied in Singapore. Distribution of LH_2 is more energy intensive (0.05 MJ/MJ_{LH2}) than for other fuels owing to assumed leakage losses. For the **min** scenario, a CED of 1.58 MJ/MJ_{LH2} is calculated. Applying **max** values in every process results in a CED of 2.28 MJ/MJ_{LH2}. ($EROI_{min} = 1.7,\ EROI_{ave} = 1.0,\ EROI_{max} = 0.8$)

3.3.2 GHG Emissions

In Figure 9, the GHG emissions of the investigated fuel process chains are allocated to process stages. Fossil GHG emissions of final fuels are included in this comparison. The underlying process chain of LH_2 leads to no direct or upstream GHG emissions.

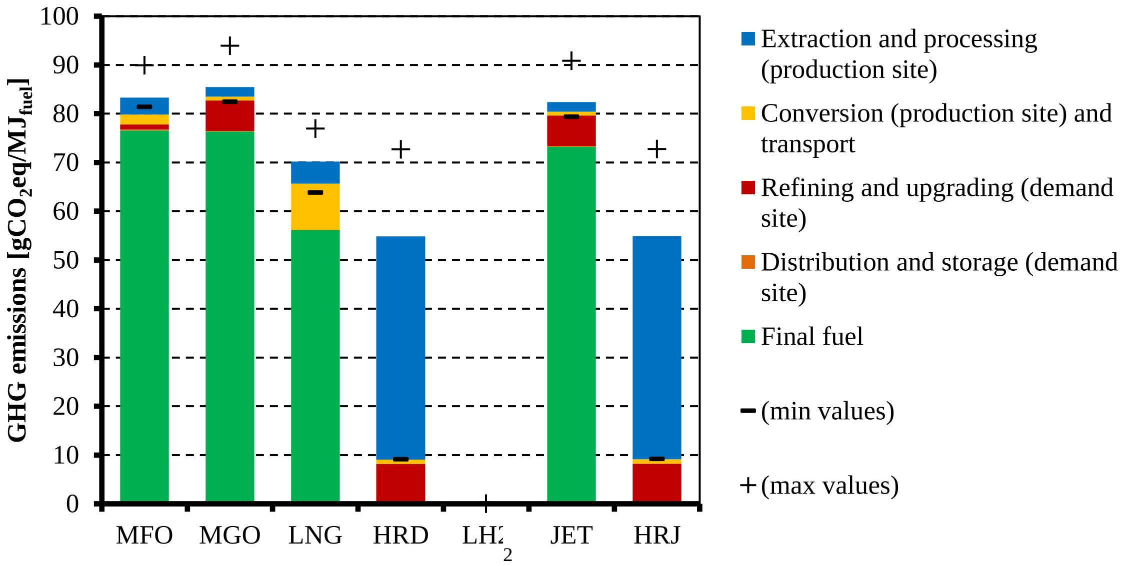


Figure 9: GHG emissions of fuel process chains by process stage

GHG emissions of fossil fuels are dominated by direct emissions. Distribution to sectors is very similar to distribution of primary energy consumption. The upstream emissions of MFO are 6.7 gCO_2eq/MJ_{MFO}. Assuming direct emissions of 76.5 gCO_2eq/MJ_{MFO}, these add up to 83.3 gCO_2eq/MJ_{MFO}. In the **min** scenario, emissions could be reduced to 81.4 gCO_2eq/MJ_{MFO}; in the **max** scenario, it increased to 89.9 gCO_2eq/MJ_{MFO}. Upstream GHG emissions for MGO and Jet fuel are 9.1 gCO_2eq/MJ_{MGO} and 9.2 gCO_2eq/MJ_{Jet}, respectively. As direct emissions of MGO (76.3 gCO_2eq/MJ_{MGO}) are higher than direct emissions of jet fuel (73.2 gCO_2eq/MJ_{Jet} [21]), their resulting overall emissions are higher and increase to 85.5 gCO_2eq/MJ_{MGO} in the **ave** scenario. Applying **min** and **max** values leads to emissions of 82.5 gCO_2eq/MJ_{MGO} and 93.9 gCO_2eq/MJ_{MGO}, respectively. Total emissions for jet fuel are 82.4 gCO_2eq/MJ_{Jet} (**min**: 79.4 gCO_2eq/MJ_{Jet}, **max**: 90.9 gCO_2eq/MJ_{Jet})

GHG emissions from using natural gas are lower owing to its reduced carbon content. Upstream emissions are slightly higher compared to conventional fuels. Our calculation produces emissions of 70.2 gCO_2eq/MJ_{LNG} in the **ave** scenario, while GHG emissions are 63.8 gCO_2eq/MJ_{LNG} and 77.0 gCO_2eq/MJ_{LNG} in the **min** and **max** scenarios, respectively. In the combustion of HRD and HRJ, no fossil GHG emissions occur as carbon is captured during the cultivation of plants. Upstream emissions are dominated by emissions from the extraction and processing phase (cultivation and oil production), which contributes 45.7 $gCO_2eq/MJ_{final\ fuel}$ to the total emissions of 54.8 gCO_2eq/MJ_{HRD} and 54.9 gCO_2eq/MJ_{HRJ}. Input data and handling of co-products has an especially high influence on these process chains. **Min** scenarios lead to GHG emissions of 9.1 gCO_2eq/MJ_{HRD} and 9.2 gCO_2eq/MJ_{Jet} and **max** scenarios lead to 72.7 gCO_2eq/MJ_{HRD} and 72.7 gCO_2eq/MJ_{HRJ}.

One major impact factor in assessing biofuels is land use change (LUC). The effects of LUC can be significant but are not taken into account in this investigation. Emissions from land use change can have a large impact on overall emissions depending on original land use and the type of biomass feedstock used. Edwards [6] pointed out that palm oil can increase emissions significantly when rain forests are converted to plantations (175.4 gCO_2eq/MJ allocated LUC emissions). Peat land conversion increases emissions to 680 gCO_2eq/MJ based on a 4 t/ha oil yield. By contrast, emissions can decrease when grassland is converted (−72.8 gCO_2eq/MJ).

3.3.3 Costs

The costs of final fuels resulting from our modelled process chain of hydrogen and taken from market data are displayed in Figure 10. Prices for fuels are determined by markets; as there is no market for hydrogen, its costs are assessed based on the underlying process chain. Allocating costs to process stages, extraction and processing add 50.8 USD/GJ_{LH2} and conversion and transport (including liquefaction and ocean transport) add 6.8 USD/GJ_{LH2}. Distribution costs account for 2 USD/GJ_{LH2}. Total costs of hydrogen in the **ave** scenario are 59.6 USD/GJ_{LH2}. Based on the chosen methodology, losses in subsequent processes increase costs allocated to upstream processes. For instance, when energy is lost in transport owing to leakage, more hydrogen has to be produced at the production site and increases costs at this stage accordingly. Electricity generation costs are a major determinant of hydrogen costs. Applying **min** values 22.9 USD/GJ_{LH2} could be achieved. In the **max** scenario, costs are 149.8 USD/GJ_{LH2} and significantly higher compared to the other scenarios. Costs for hydrogen are higher than costs of conventional fuels over the last years. However, in the **min** scenario, similar costs as for biofuels could be reached. It should be noted that hydrogen propulsion systems might attain higher efficiencies than conventional fuels. Further research has to be done to determine future price levels of conventional and alternative fuels in Singapore.

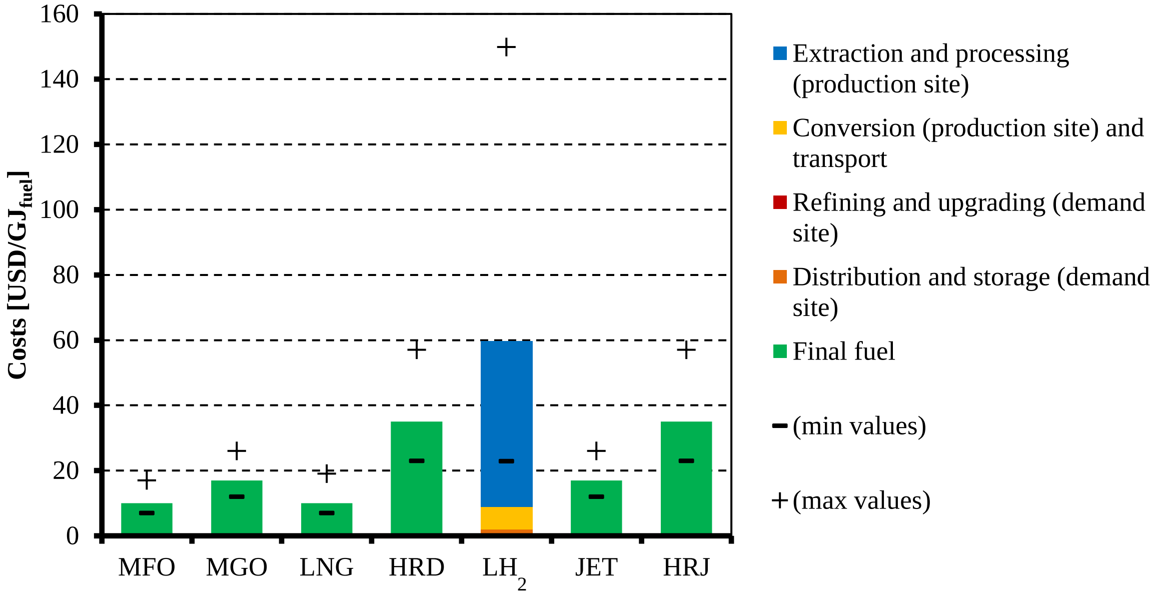


Figure 10: Costs of fuel process chains by process stage

3.4 Comparison of Pathways with Related Literature

Results of the WTT analysis of Singapore's pathways were compared to the outcomes of the other studies discussed in Chapter 2.1. It should be emphasised that, in addition to methodologies and input data, the investigated regions and fuels differed. However, as a means of generalising the results and identifying possible unexpected deviations from values derived from related literature, this comparison is reasonable.

Parameters for WTT energy use and WTT GHG emissions from selected similar pathways from the literature are compared to the WTT indicators derived in this study. WTT indicators are selected in order to avoid differences caused by varying fuel properties in the studies in question and therefore do not include energy content or the GHG emissions of fuel combustion. Although most studies summarise GHG emissions on a WTT basis, WTT energy use is reported in few studies. There are only very limited data available on WTT fuel costs in the literature, making a comparison of cost indicators infeasible. Selected scenarios from literature sources were associated with the derived pathways for Singapore and presented in Table 5

Table 5: Scenarios from selected literature sources associated to the derived pathways for Singapore

Related Literature	MFO	MGO	LNG	HRD	LH_2	JET	HRJ
JRC [6]	HFO	COD1	GRLG1	POHY1a	WDEL1/LH1		
Bengtsson [7]	HFO	MGO	LNG	BTL			
Verbeek [18]	HFO	MGO	LNG Qatar				
Chryssakis [8]	HFO	MGO	LNG Qatar	Biodiesel	H2 RE		
Brynolf [19]	HFO	MGO	LNG	BTL_W			
Stratton [21]						Crude to conv. jet fuel	Palm oils to HRJ (LUC-P0)
Saynor [22]					H_2 OSW		Biodiesel

Figure 11 presents a visualisation of the results of this comparison. Indicators calculated in this paper are presented by range (grey columns representing the extreme values in the **min** and **max** scenarios) and **ave** value for each pathway. The results of similar pathways found in related literature, if available and applicable, are represented by coloured markers.

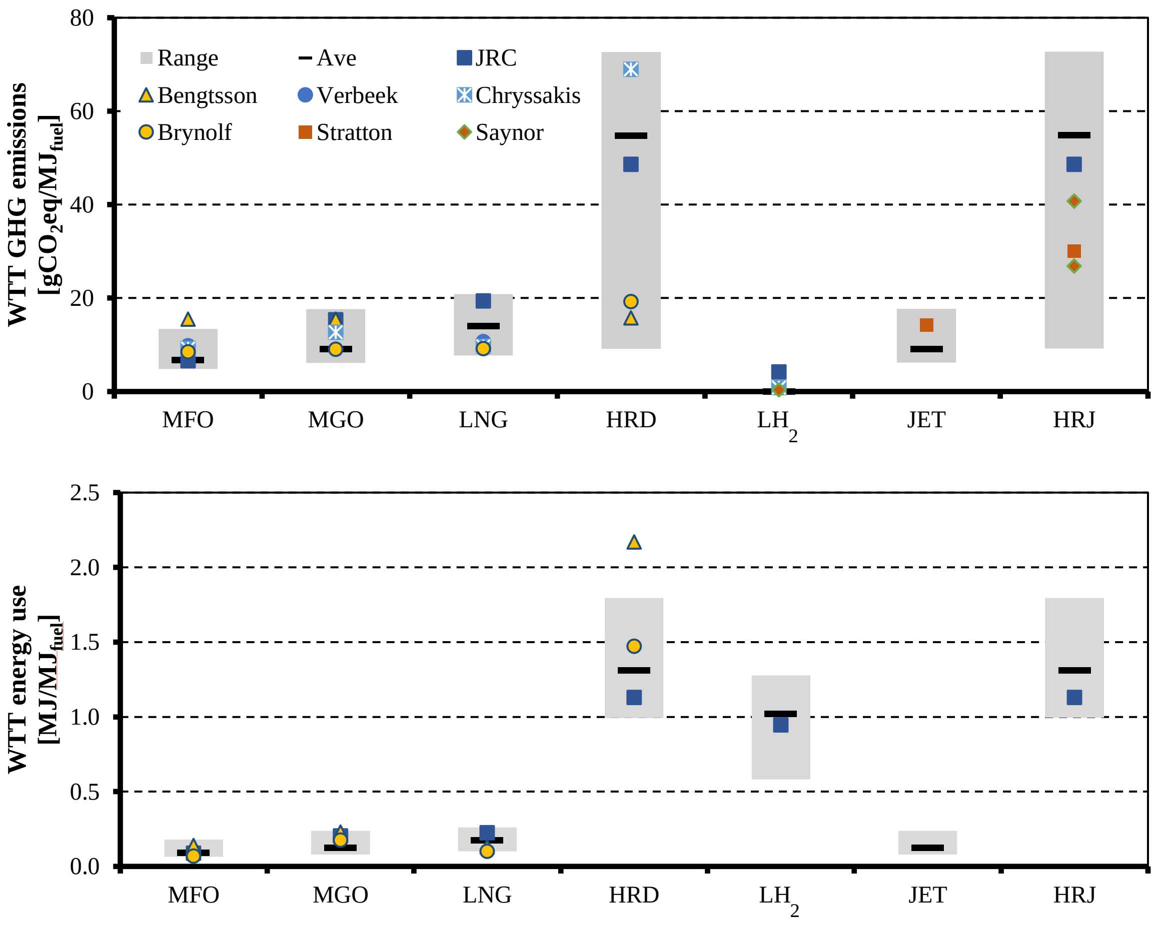


Figure 11: Comparison of Well-to-Tank GHG emissions and WTT energy use with other studies

The overall fit of results derived from Singapore to indicators derived from related literature is within expectations. The conventional fuels MFO, MGO, and JET are within a very narrow range. Owing to the assumed high efficiencies of oil refining in Singapore, the **ave** values are on the lower range compared to the corresponding literature values. WTT indicators for LNG are of the same order of magnitude. Natural gas extraction sites, liquefaction efficiency, transport technologies, and distances differ from corresponding values in the investigated literature, and our adaption to suitable values for Singapore explains the differences (compare Chapter 2.4). Values for the investigated biofuels HRD and HRJ and the related literature values show the biggest differences. This behaviour is expected, as not only transport distances differ, but different kinds of biofuel feedstock and conversion technologies are investigated. WTT indicators of liquid hydrogen are quite similar as well. As the pathways in the literature also use electricity from renewable energy sources for hydrogen production and liquefaction, GHG emissions are nearly zero. The overall calculated WTT energy efficiency of hydrogen production in this study is similar to that in the JRC WTT study.

Summing up, the indicators calculated for Singapore based on the presented methodology are in good agreement with values from the related literature. In general, conventional fuels and LNG are characterised by low WTT energy use and GHG emissions. WTT indicators for biofuels are significantly higher and especially dependent on feedstock production and conversion technologies, but the absence of fossil GHG emissions upon fuel combustion results in overall GHG savings. Liquid hydrogen from renewable energy sources shows low specific emissions and high WTT conversion losses caused mainly by hydrogen production and liquefaction.

A more detailed comparison between these results and the findings of the existing literature, including differences in single processes and detailed review of methodology, was not conducted.

4 Discussion

4.1 Energy Use in Singapore

As a country scarce in terms of fossil energy carriers, Singapore is heavily dependent on energy imports. Its energy supply is dominated by oil trading. Singapore Energy Statistics recorded 162 Mtoe (6.8 EJ) of energy imports and 86 Mtoe (3.6 EJ) of energy exports for 2014 [80]. Thus, 76 Mtoe (3.2 EJ) of energy are used in Singapore for different purposes. BP also reports a value of 76 Mtoe (3.2 EJ) [81]. Based on the newest available data from the IEA, total primary energy consumption is 73 Mtoe (3.1 EJ), while the current EIA estimate is 78 Mtoe (3.3 EJ) [15,82]. All of these values include local energy consumption and international bunker fuels for ships and aviation. International marine bunker sales were 42 million tonnes in 2014. This amount has remained constant since bunker sales peaked at 43 million tonnes in 2011 [10]. Official values for aviation bunker sales are not available. The IEA records values of 7 Mtoe (0.3 EJ) for international aviation bunkers and 41 Mtoe (1.7 EJ) for international marine bunkers in 2012. Thus, the total primary energy supply of Singapore is 25 Mtoe (1.0 EJ). [15] Changes in bunker fuel supply will therefore have a greater impact on sustainable developments on a global scale than sustainability measures taken within Singapore. However, the fuel supply is highly interrelated to the refining and economic activity in Singapore. In the following paragraphs, future challenges and opportunities are discussed.

4.2 Availability of Alternative Bunker Fuels and Import Dependency

For total substitution of Singapore's bunker fuels, huge quantities of alternative energy carriers would be required. In 2013, 237 million tonnes of LNG (11.6 EJ) were traded [83]. A complete substitution of Singapore's marine bunker fuels would translate into 35 million tonnes of LNG (1.7 EJ). Especially in the Asia-Pacific region, a forecasted tripling of demand by 2035 will result in strong market growth [84]. As future availability of natural gas resources is assumed to be higher than remaining potential of oil resources [85], even a complete substitution of conventional bunker fuels seems possible. The potentials of other substitutes are significantly smaller. Global palm oil production increased from 53 million tonnes per year in the period 2011/2012 to 61 million tonnes per year in the period 2014/2015. Currently, 33 million tonnes are produced in Indonesia, 19.8 million tonnes in Malaysia, and 8.7 million tonnes in other countries. [86] Total substitution of Singapore's bunker fuels by HRD and HRJ would result in 54 million tonnes of additional palm oil demand, which would require a huge increase in palm oil production and would nearly double today's cultivation area of FFBs. In light of environmental concerns, it is quite doubtful that this solution is sustainable. Hydrogen production today is mainly based on fossil energy carriers [58]. In this study, hydrogen supply assumed production from renewable energy sources, and it was assumed that energy efficiencies can be increased by 15% when hydrogen is used. This would reduce the amount of final energy required to 1.7 EJ for marine and aviation bunkers. Required electricity demand based on the above assessed **ave** pathways (2.02 MJ_{ele}/MJ_{out}) is 3.5 EJ. Assuming a land use factor of 31 MW/km^2 for solar PV [87] and a capacity factor for the Middle East of 22% [77], the resulting area required for production of marine and aviation fuels is roughly 16,000 km^2 (PV capacity 508 GW). There may be further reduction potentials in the required land area and generating capacity owing to higher efficiencies in the upstream pathway (**min**, 1.58 MJ_{ele}/MJ_{out}) or higher land use efficiencies of PV technologies. Worldwide installed PV capacity in 2014 was only 177 GW [88]; however, rapid growth of global capacity, possible technological improvements, and the ability to use deserted lands for power production offer a more sustainable outlook than biofuels. Other technologies such as wind or concentrated solar power plants are possible options for providing the required power generation capacity that are not discussed in this study.

By looking at these figures, it is quite obvious that Singapore's dependency on energy imports will still continue when alternative bunker fuels are supplied instead of conventional bunker fuels. Owing to Singapore's limited land area, it is impossible to decouple it from international energy markets. Imports of alternative fuels might lead to more diversification of Singapore's energy sources and therefore result in less dependency on single countries or regions.

4.3 Interactions of Alternative Bunker Supply with the National Economy

In the past, Singapore's economic growth was closely linked to the oil trade and oil refining. In his book, "Singapore, the Energy Economy", Ng states [89]:

"Singapore might not have survived the 1960s and prospered thereafter had it not built its economy on the foundations of oil refining and trading, and support for oil and gas exploration and production."

Alternative bunker fuels might challenge existing structures in Singapore. Singapore's sophisticated refineries, which produce large shares of higher value products, are more robust to changes in bunker fuel supply, as their core businesses are less affected by alternative bunker fuels. In light of the large amounts of energy required to substitute bunker fuels, a quick change is rather unlikely–especially toward biofuels or hydrogen. With its LNG terminals and a major biofuel refinery, Singapore is very well-positioned for possible future trade of alternative energy carriers. Energy trading experience and a strong financial background will help Singapore transform its oil-focussed trading hub into a multi-energy trading hub. This development could even strengthen Singapore's position as a central energy trading hub by reducing its import dependencies and broaden its product range.

Singapore is a trading hub for oil products owing to its unique geographical position, excellent infrastructure, transparent market, and refining and bunkering businesses. Aside from trading, there is also a high local demand for oil products owing to the presence of refineries and bunkering, which supports the position of Singapore as an oil trading hub. However, there is no significant local demand for alternative fuels. Although, natural gas consumption in Singapore in 2012 was 9 Mtoe (0.4 EJ) [80], this is a very small amount compared to refinery inputs of 57 Mtoe (2.4 EJ) [80] and 48 Mtoe (2.0 EJ) of international bunker fuels supplied [15]. LNG trade in Asia is dominated by Japan, South Korea, and China, which supply large domestic markets [90,91]. Introducing LNG as a bunker fuel in Singapore will increase local demand and strengthen Singapore's claim to becoming a price setting trading hub for LNG. Owing to its small local demand, bunker sales offer a great opportunity for Singapore to increase its importance in future energy markets and guarantee a larger domestic gas market with more participants and cargo handling.

According to Ng [89], Singapore's economic model is dependent on cheap energy. This statement is true–not only with respect to costs of energy for Singapore, but especially for costs of international transport. Singapore is highly dependent on trade between countries and a global division of labour. Indisputably, the port is one major column of Singapore's economic system. Most containers (85 %) are transhipped [92] and its bunker fuel supply makes Singapore the world's most important bunkering port. Unlike most other countries, Singapore does not have a large local market. Alternative energy carriers may not only affect costs of energy supply but also costs of transport. As shown in Chapter 3.3, costs of alternative fuels are higher than costs of conventional fuels. When transport costs increase, local production of goods becomes more attractive. This might reduce the average transport distances and the quantities of long distance trade. This possible trend to localism in trade and energy is the biggest threat to Singapore's economic system. Therefore, cheap energy and affordable transport is of key interest to Singapore in order to obtain its central position in a global economy.

4.4 Effects on GHG Emissions of International Transport

Absolute reductions of carbon emissions in Singapore are difficult to achieve. Based on a national energy model of Singapore published by Wagner at al. [93], only integration of nuclear power into the electricity mix would enable a reduction of absolute carbon emissions prior to 2050. Large-scale integration of PV into the Singapore power grid will not be sufficient to realise GHG emissions reductions. Another option to mitigate GHG emissions is to import electricity from neighbouring countries. The effects of trans-border electricity trade in enhancing the integration of renewables in the ASEAN countries were analysed by Stich and Massier [94]. According to Singapore's Intended Nationally Determined Contributions (INDC) to reducing greenhouse gas emissions [95], the government intends to reduce emission intensity by 36 % in 2030 compared to 2005 levels. Furthermore, total GHG emissions are aimed to peak at 65 million tonnes in 2030. These figures do not include bunker fuels. Supplying alternative bunker fuels to marine and aviation industry could however have a positive impact on overall CO_2

emissions. On the basis of the pathways developed in this study and IEA data for energy consumption, the overall GHG emissions of bunker fuels are calculated to be 140–155 million tonnes for international marine bunkers (assuming MFO) and 23–26 million tonnes for international aviation bunkers. As shown in Chapter 3.3, alternative fuels could reduce these emissions significantly. A complete substitution of conventional marine bunker sales using LNG could reduce total GHG emissions by 22–30 million tonnes. Biofuels could reduce GHG emissions of marine and aviation bunker fuels by 35–144 million tonnes. LH_2 use could even result in a complete elimination of GHG emissions. These figures show that Singapore's potential to reduce CO_2 emissions is limited on a local scale, but the potential impacts of bunker fuel supply change could lead to much higher emission savings than local measurements indicate. By implementing strategies to reduce emissions from international bunker fuels, Singapore could significantly contribute to the mitigation of climate change, an additional motivation for Singapore to pursue a leading role in the transformation of sustainable transport technologies.

5 Conclusion

Any sustainable energy system in Singapore must take the bunker fuel supply into account, not only because of the large share of international bunker fuels in Singapore's energy balance, but especially because of its interactions with Singapore's economic system.

Analysis of well-to-tank energy demand shows that LNG has a similar cumulative energy demand as that of conventional bunker fuels, while biofuels extracted from palm oil and liquid hydrogen from renewable energy sources have much higher primary energy demand and losses during fuel production. The total GHG emissions of bunker fuels could be slightly reduced by using LNG; the reduction potential of biofuels is higher. Assuming best practice scenarios, significant reductions of GHG emissions are possible. Complete avoidance of GHG emissions is possible when bunkers are substituted with liquid hydrogen from renewable energy sources. Fuel costs of alternative fuels are similar in the case of LNG and significantly higher for biofuels and hydrogen, whose costs are highly influenced by future technological development.

The resource potential of alternative fuels might limit the availability of alternative fuels as bunker fuels in Singapore. While LNG is available in sufficient quantities, huge land use requirements for palm oil cultivation make complete substitution of bunker sales with biofuels highly unlikely. A combined scenario in which marine bunker fuels are substituted by LNG and aviation bunkers are substituted by biofuels seems more realistic. A zero-emission liquid hydrogen supply would require long distance imports from regions rich in renewable energy potential. In the future, Singapore will depend on energy imports to supply its energy demand. Alternative bunker fuels could contribute to diversifying energy carriers and decreasing dependence on crude oil and petroleum products. As Singapore's refineries produce high value products, the effect of alternative bunker fuels on local refineries should be limited. Furthermore, alternative bunker fuels could contribute to the transformation of Singapore's oil focussed trading hub into a multi-energy trading hub. The high local energy demand caused by bunker sales would support this transformation by decreasing dependency on customers in other countries. Fighting climate change is a major concern in Singapore. Policies show that its potential to reduce GHG emissions from local consumption are limited owing to its lack of renewable energy sources. However, its leading role in the international bunker business offers Singapore the unique possibility to influence the overall GHG emissions of international transport. In this report, we have shown that substitution of conventional bunker fuels offers a large potential for reducing GHG emissions.

The biggest threat to Singapore's economic system is an increase in fuel and transport costs, which could lead to more localism and a reduction of trade and transport volumes. Therefore, cheap energy is vital for Singapore's economy. Higher transport costs are not necessarily caused by alternative transport fuels, since the volatile costs of conventional bunker fuels and dependency on a single energy source can lead to cost increases as well. In order to develop an economic model that is ready for the coming decades, it is of key interest to Singapore to enable affordable and sustainable transport. The city-state will be unable to implement radical changes in the global energy and transport system on its own; instead, a high flexibility is required to adapt to international developments in energy trading and sustainable development. The use of alternative bunker fuels in addition to conventional fuels offers the possibility for diversifying Singapore's oil portfolio and transforming Singapore into a multi-energy trading hub without endangering Singapore's current position as a leading port and oil trading hub.

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Nomenclature

ASEAN	Association of Southeast Asian Nations
ave	Scenario based on average values or the average value of a process parameter
BP	BP plc
BOG	Boil-off gas
$c_{GHG,i}$	Specific GHG emissions per unit of energy output of process i
$c_{Costs,i}$	Specific costs per unit of energy output of process i
C_i	Costs of process i
C_{PATH}	Overall costs of the WTT pathway
CED	Cumulative energy demand
CPO	Crude palm oil
$E_{Aux,i}$	Part of $E_{Uti,i}$ which is additionally required for process i and not a part of $E_{Main,i}$
$E_{Disp,i}$	Energy demand for disposal of process i
$E_{In,i}$	Energy inputs in process i
$E_{L,i}$	Energy loses of process i
$E_{Main,i}$	Part of $E_{Uti,i}$ which is transformed into the target product of process i
$E_{Out,i}$	Energy outputs of process i
$E_{Prod,i}$	Energy demand for construction or production of process i
$E_{Uti,i}$	Energy demand for utilisation of process i
EFBs	Empty fruit bunches
EJ	Exa joule (Unit)
EROI	Energy Returned on Energy Invested
$EROI_x$	EROI of the scenario x (x = min, ave, max)
FE	Final Energy
FFBs	Fresh fruit bunches

FT	Fisher-Tropsch
g_{Path}	Overall efficiency of supply
gCO_2eq	Gram of carbon dioxide equivalent (Unit)
GEMIS	Global Emission Model for integrated Systems
GHG	Greenhouse gas
GHG_i	GHG emissions of process i
GHG_{PATH}	Upstream GHG emissions or WTT GHG emissions of total pathway
GJ_x	Giga joule of commodity x (Unit)
GTL	Gas-to-Liquid
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GW	Giga watt (Unit)
H_2	Hydrogen
HRD	Hydrogenated renewable diesel fuel
HRJ	Hydrogenated renewable jet fuel
IEA	International Energy Agency
IE Singapore	International Enterprise Singapore
INDC	Intended Nationally Determined Contributions
IOGP	The International Association of Oil & Gas Producers
Jet	Jet fuel
JEC	Collaboration of JRC, EUCAR and CONCAWE
JRC	Joint Research Centre of the European Commission
kW	Kilo watt (Unit)
LCA	Life Cycle Assessments
LNG	Liquefied Natural Gas
LH_2	Liquid Hydrogen
LUC	Land use change

max	Scenario based on maximum values or maximum value of a process parameter
mmBtu	Million British Thermal Units
min	Scenario based on minimum values or minimum value of a process parameter
MFO	Marine Fuel Oil
MGO	Marine Gas Oil
Mtoe	Million tonnes of oil equivalent (Unit)
MJ_{aux}	Mega joule of auxiliary energy input (Unit)
MJ_{main}	Mega joule of main energy input (Unit)
MJ_{out}	Mega joule of energy output (Unit)
MJ_x	Mega joule of commodity x (Unit)
PE	Primary Energy
PEM	Polymer Electrolyte Membrane
POME	Palm oil mill effluent
PRESAV	Potential for Renewable Energy Sources in Aviation
PV	Photovoltaics
STS	Ship-to-ship
t	Tonne (unit)
TTW	Tank-to-Wheel
UK	United Kingdom
US	United States
USD	United States Dollar (Unit)
WTP	Well-to-Propeller
WTT	Well-to-Tank
WTW	Well-to-Wheels (road transport) or Well-to-Wake (aviation)

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