Technische Universität München
Lehrstuhl für Erneuerbare und Nachhaltige Energiesysteme

The impact of a sustainable energy supply on global hub cities — a discussion based on the example of Singapore

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Vollständiger Abdruck der von der Fakultät für Elektrotechnik und Informationstechnik der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation.

Vorsitzender: Univ.-Prof. Dr.-Ing. Ulf Schlichtmann

Prüfer der Dissertation:

1. Univ.-Prof. Dr. rer. nat. Thomas Hamacher
2. Univ.-Prof. Dr. rer. pol. Andreas Pyka

Die Dissertation wurde am 24.03.2016 bei der Technischen Universität München eingereicht und durch die Fakultät für Elektrotechnik und Informationstechnik am 21.11.2016 angenommen.

Abstract

The objective of the thesis is to investigate the impact of sustainable energy supply on global hub cities. Hub cities have emerged because of economic benefits. They structure international networks as central nodes by specialising on production, trade, distribution of particular products and services, and the creation of knowledge. Emergence of hub cities has been caused by economic and technological progress inherently supplied by fossil energy carriers. Environmental concerns, import dependencies, technological progress, and unpredictability of costs for fossil energy carriers accelerate the transformation of energy use and supply towards sustainable energy systems. The resulting changes with regard to sources, technology, locations, distribution systems, and costs will affect the future role of hub cities.

An analysis of energy systems of current hub cities shows that fuel supply for international transport is a major challenge on the path towards sustainable energy supply. Based on the example of Singapore, a detailed analysis is conducted to study its energy system, possible sustainable transport fuels, and resulting opportunities and challenges. As shown in this thesis resource potentials of alternative transport fuels are limited. Liquefied natural gas is identified as the only short- to mid-term alternative to conventional fuels. While a fully indigenous energy supply is highly unlikely, alternative energy carriers offer the possibility to decrease the city's dependency on oil and oil products and diversify its energy mix. Expected synergies of alternative with conventional energy carriers outweigh possible disadvantages related to Singapore as an energy hub. Its potential to transform its petroleum into a multi-energy hub is highlighted. Potential domestic reduction of Singapore's greenhouse gas emissions is limited on a local scale. However, interferences with international bunker markets offer the possibility to affect and reduce greenhouse gas emissions of international transport significantly.

The transferability to other hub cities and induced trends towards regionalisation are discussed. It is concluded that sustainable energy supply questions the structure of today's world economy and strengthens forces towards regionalisation. Hub cities will continue their dominance if their economic benefit, caused by specialisation, is higher than the additional costs caused by sustainable supply of these.

Kurzfassung

Ziel der Arbeit ist die Einflüsse nachhaltiger Energieversorgung auf globale Hub Cities zu untersuchen. Diese entstehen aufgrund wirtschaftlicher Vorteile und strukturieren als zentrale Knoten globale Netzwerke indem sie sich auf Produktion, Handel, Verteilung von bestimmten Waren und Dienstleistungen und auf die Generierung von Wissen spezialisieren. Die Entstehung von Hub Cities wird durch ökonomischen und technischen Fortschritt bedingt und durch die Versorgung mit fossilen Energieträgern ermöglicht. Umweltbedenken, Importabhängigkeit, technischer Fortschritt und die hohe Preissensitivität dieser Brennstoffe beschleunigen die Transformation von Energieverbrauch und -versorgung hin zu nachhaltigen Energiesystemen. Die sich daraus ergebenden Veränderungen bezüglich Energiequellen, Technologien, Örtlichkeiten, Verteilungssystemen und Kosten werden die künftige Rolle von Hub Cities beeinflussen. Eine Analyse gegenwärtiger Energiesysteme von Hub Cities zeigt, dass die Treibstoffversorgung des internationalen Personen- und Gütertransports eine besondere Herausforderung auf dem Weg hin zu einer nachhaltigen Energieversorgung darstellt. Anhand des Beispiels des Stadtstaates Singapur wird eine detaillierte Analyse des Energiesystems, möglicher alternativer Kraftstoffe für das internationale Transportwesen und sich daraus ergebender Chancen und Herausforderungen für die Stadt durchgeführt. Es wird gezeigt, dass die Verfügbarkeit alternativer Kraftstoffe begrenzt ist. Einzig Flüssigerdgas wird als kurz- bis mittelfristige Alternative zu konventionellen Kraftstoffen identifiziert. Während eine vollständige Eigenversorgung mit Energie höchst unwahrscheinlich ist, können alternative Kraftstoffe dazu beitragen die Abhängigkeit Singapurs von Rohöl und Ölprodukten zu reduzieren und den Importmix zu diversifizieren. Erwartete Synergien zwischen alternativen und konventionellen Energieträgern überwiegen mögliche Nachteile im Hinblick auf Singapur als zentraler Knoten für Energieverteilung. Während die nationalen Einsparpotentiale von Treibhausgasemissionen in Singapur begrenzt sind, eröffnet der hohe Marktanteil an der Betankung von Schiffen und Flugzeugen die Möglichkeit diese Emissionen auf globaler Ebene stark zu reduzieren. Die Übertragbarkeit der Ergebnisse auf andere Hub Cities und mögliche Regionalisierungstendenzen werden diskutiert. Zusammenfassend lässt sich feststellen, dass eine nachhaltige Energieversorgung die bestehenden Strukturen des Weltwirtschaftssystems in Frage stellt und eine Regionalisierung begünstigt. Solange jedoch die wirtschaftlichen Vorteile von Hub Cities größer sind als die, durch eine nachhaltige Energieversorgung bedingten, zusätzlichen Kosten werden diese Städte weiterhin das Weltwirtschaftssystem dominieren.

Acknowledgements

This thesis had been written during my work as a research associate at the Institute for Energy Economy and Application Technology, TUM CREATE, and at the Chair of Renewable and Sustainable Energy Systems.

First, I would like to thank Prof. Thomas Hamacher for his guidance and great support. Our close collaboration and frequent discussions allowed me to do my research in a perfect working environment. My sincere thanks go to Prof. Andreas Pyka for reviewing the thesis and drawing my attention to further interesting aspects and publications in the field of economic geography. I am also grateful to Prof. Ulf Schlichtmann for kindly agreeing to chair the exam.

During my time at the Institute for Energy Economy and Application Technology, TUM CREATE, and at the Chair of Renewable and Sustainable Energy Systems, I had the opportunity to work in excellent teams with great colleagues. Thank you for your support, sharing your ideas, and friendship. Further, I want to thank my students for their interest and dedication to our research.

Special thanks go to my family for their continuous support, considerate advice, and patience.

Munich, December 2016
Karl Schönsteiner

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1 Introduction

1.1 Motivation

Since the industrial revolution, our world economic system has been fuelled by the exploitation of fossil energy carriers. In this period, major trends have had a lasting effect on development. Global population has been rising from less than 1 billion to 7.3 billion people (UN 1999; UN 2015a). Relative growth of urban population has been even stronger (UN 2015b). Innovations, advancements in technology, and cheap availability of energy have led to a globalised world economic system (Krugman et al. 2012; WTO 2013b).

As a consequence, the present structures of settlements and economic activity have emerged. A couple of especially powerful cities organise flows of goods, people, knowledge, and supply global markets with specialised services. These agglomerations are characterised by a high dependence on energy imports and fossil energy.

However, social, and environmental challenges force sustainable developments. A sustainable energy supply, based on renewable energy carriers, is often seen as an essential part of sustainability. In contrast to high local energy demand created by centralised structures, renewable energies are often characterised by limited local availability (Smil 2015b). Therefore, sustainable energy supply will act as a possible centrifugal force that might question the economic advantage of large cities and current organisation of networks.

Created by forces of globalisation and trade, Singapore is a perfect example to investigate the effects of a sustainable energy supply on hub cities. Singapore contains one of the world’s largest ports and is the most important port for marine fuel supply of international transport (World Shipping Council 2014; Singapore DOS 2015). Its international airport is one of the world’s leading airport hubs (CAG 2015). With several large refineries, the city-state is a leading exporting refinery centre and its highly specialised petrochemical and electronics industry contribute significantly to its manufacturing output (Singapore EDB 2015a; Singapore MTI 2014). Furthermore, Singapore is a leading financial and wealth management centre (Z/Yen Group 2014). Owing to its unique position in the middle of Southeast Asia, between China and India, Singapore is part of one of the world’s fastest developing regions.

1.2 Thesis conception and contributions

Objective, findings, and applied methods. Objective of the thesis is to investigate the impact of a sustainable energy supply on global hub cities. On the example of Singapore, a detailed analysis is performed to study its energy system, possible sustainable transport fuels, and emerging opportunities and challenges. Transferability to other hub cities and induced trends towards regionalisation are discussed.

The three main findings from this thesis are:

- Detailed analysis shows that gains of economic efficiency of hub cities come at the costs of increased local energy demand.
- Singapore would be severely affected by a sustainable energy supply, but is in a promising position to influence and adapt to future developments.
- Sustainable energy supply of hub cities will impact their existing business models, alter their economic advantages, and has the potential to restructure global networks towards regionalisation.

Methodologies applied to answer the research questions are:

- Literature review to identify forces that shape the formation of hub cities and affect future developments (Chapter 2).
- Data collection and analysis to study existing energy systems, impacts of new technologies, and emerging trends (Chapters 3, 4).
- Well-to-tank analysis to calculate robust indicators for energy efficiency, specific emissions, and costs of established and alternative transport fuels. (Chapter 5).

Structure and contributions. The structure of the thesis is described by assigning its contributions to the particular Chapters in which these are derived:

In Chapter 2, the emergence of hub cities and their importance for the world economic system is explained. Sustainable energy supply is identified as a possible game changer that questions the economic benefit of hub cities.

Chapter 3 conducts a detailed analysis of energy consumption and impacts of specialisation effects on hub cities in general and on Singapore in particular. It is concluded that hub cities are highly dependent on fossil energy carriers and energy imports. Especially, fuels for international marine and aviation transports cause huge local energy demands.

Chapter 4 opposes future trends in and forecasts of transport demand to possible technological improvements of transport technologies. It is summarised that energy demand in Singapore is expected to increase in the future.

Specific factors for energy demand, emissions, and costs of conventional and alternative transport fuels in Singapore are derived based on a well-to-tank (WTT) analysis. A detailed description of the underlying methodology and the results is given in Chapter 5.

Chapter 6 uses the investigations performed in the previous chapters to identify opportunities and challenges for Singapore arising from the interplay of globalisation and sustainable developments. An outlook on applicability and transferability on results to other hub cities concludes that Singapore is an extreme example for a hub city, but energy demand caused by specialisations challenges hub cities in general. It is further highlighted that more research is required to oppose benefits of hub cities to increasing challenges caused by a sustainable energy supply in order to assess its impact on networks in general.

1.3 Related work

In the following, related literature used to collect data and answer research questions is summarised according to its purpose. Chapter 1.3 gives only a very brief summary of applied literature sources in each Chapter. More detailed insights, specific applications, and derived results are presented in the respective Chapters.

Chapter 2 introduces economic and geographic theories and describes current structures of the world economy and future challenges. Based on publications of P. Krugman basic fundamentals how trade does emerge from the diversity of countries and economies of scale are presented (Krugman et al. 2012). By citing further publications of P. Krugman, M. Fujita, and H. Konishi it is explained how cities evolve using neo classical theories (Fujita et al. 1999; Krugman 1999; Fujita & Mori 1996; Konishi 2000). The evolutionary economic geography and the institutional economic geography represent additional approaches to explain the growth of cities and deliver extended findings of neo classical theories (Boschma & Frenken 2006; O'Neill 2002; Boschma & Martin 2010). A selection of basic economic and geographical theories is presented, which offer important insights into the development of cities: the Von Thünen model, Christaller's theory of central places, the base-multiplier analysis, the market potential analysis, Perroux's growth pole theory, and a comparison of Marshall and Jacob externalities (Fujita et al. 1999; Kaplan et al. 2009; Hospers 2004; Van Der Panne 2004). Characteristics of transport and networks and the formation of hubs are explained with regard to related literature (Krugman 1999; Rodrigue et al. 2013; WTO 2013b; O'Kelly 1998; Neal 2014; Fujita et al. 1999; UNCTAD 2015; Barabási & Bonabeau 2003). These descriptions are used to support the definition of hub cities given in this thesis.

Past and present developments in world trade are summarised based on publications of the WTO, P. Krugman, and R. Walter (WTO 2013a; WTO 2014; Krugman et al. 2012; Walter 2006). The increasing importance of cities is demonstrated with reference to urbanisation data of the United Nations and results of investigations done by B. Mohanty, R. Florida et al., and X. Q. Zhang (UN 2015b; Mohanty 2012; Florida et al. 2009; Zhang 2011). Examples for present world cities are given investigating rankings that are measuring the importance of cities (Friedmann 1986; GaWC 2014; MMF 2013; Citi 2013; PWC 2014; A.T. Kearney 2015).

While the WTO identifies shaping aspects of future trade in its World Trade Report 2013 (WTO 2013b), the special role of energy in the economy is investigated in this thesis. Typical facets of energy systems are discussed and linked to related literature (Smil 2015b). B. Mohanty's terminus 'Petropolis' is used to characterise current structures (Mohanty 2012). Sustainable developments are identified as future trends. The interpretation of sustainability is explained and further extended (UN 1987; Drexhage & Murphy 2010; Pufe 2014). Sustainability of trade is further investigated and includes findings of the WTO (WTO 2011; UNCTAD 2015; Mohanty 2012). Implementation of a sustainable energy supply is identified as a key measurement to force and support sustainable developments.

Chapter 3 discusses the effects of specialisation on limited regional space in general and investigates the energy system of Singapore in particular. Motivated by research about economic output and energy consumption (Stern 2010; Smil 2010), developments are investigated on global and local scale. Data are derived from V. Smil and discussed in the context of other data sources for global energy consumption (Smil 2010; Newell & Qian 2015). Based on indicators, which link GDP, energy use, land area, and population, the spatial energy consumption related to GDP is analysed for different countries (Schönsteiner & Hamacher 2014).

Current status of Singapore's economy and economic specialisations are described summarising various literature and statistical data about the country itself, the port, the airport, and other economic characteristics (Singapore DOS 2015; UNCTAD 2015; Singapore EDB 2015a; CAG 2015; Z/Yen Group 2014; Ng 2012; Platts 2014; Singapore MTI 2014). Singapore's rise to a global hub is analysed on basis of historic data, political guidelines, and industry specific reports (Singapore NLB 2015; Commonwealth Secretariat 2014; Singapore EDB 2015b; Singapore MTI 2015; Ng 2012; PSA International Pte Ltd 2015; Singapore EMA 2014; Neste Oil 2014; Long & Tan 2010; Singapore EDB 2015a). The framework for future developments of Singapore's economic system is discussed by addressing climate policies, population growth, infrastructure, and economic developments (Singapore NCCS 2012; Singapore 2015; Singapore MND 2013; Singapore MPA 2013; Singapore MT 2013; Nkomo 2013; CAG 2015; Platts 2014).

Singapore's energy system is analysed on a broad basis of literature sources. These are compared and assessed to derive a better picture of Singapore's energy flows and GHG emissions. Besides statistical data published by national authorities, also data from international organisations and private companies are compared and an energy balance is developed (Singapore EMA 2015; IEA 2015a; U.S. EIA 2016; Singapore MEWR 2014; IE Singapore 2015; Singapore MPA 2014). In addition, the results of publications dealing with a developed energy model for Singapore are summarised (Wagner et al. 2012; Wagner et al. 2014). Greenhouse gas emissions are discussed on basis of national and international statistical data (Singapore 2015; Singapore NEA 2014; IEA 2015a; U.S. EIA 2016; BP plc 2015b).

Chapter 4 gives an outlook for future trends in international transport and analyses current technology and technological potential of transport technologies. Current situation and future trends of marine transport are summarised based on reports published by the International Maritime Organization (IMO), the United Nations, and Lloyd's Register (IMO 2014; UNCTAD 2014; Fang et al. 2013; LR 2014a). Future growth in transport capacity is opposed to environmental goals and efficiency improvements, which are implemented by the IMO (IMO 2011; U.S. EPA 2010; U.S. EPA 2011; IMO 2015b; Mohn 2014; LR 2014b; MPEC n.d.; IMO 2015a).

The historic development, current status, and future efficiency potentials of marine transport technology are summarised from various technical reports and publications (U.S. EPA 2008; Vergara et al. 2012; ABS 2013; DNV GL n.d.; DNV GL 2014; Brennecke 1981; Kemp 2000; Röder 2008; Kamei 2013). The impact of economies of scale and slow steaming on fuel efficiency is discussed (Rodrigue 2015; Diekmann & Rosenthal 2013; ABS 2013). Characteristics of different marine fuels, the associated drive trains, technologies, advantages, and disadvantages are derived from various literature sources and assessed to investigate the technological potentials (McGill et al. 2013; Singapore MPA 2015; U.S. EPA 2008; MAN Diesel & Turbo 2015; Hansen et al. 2014; Brynolf 2014; Kolwzan et al. 2012; Vergara et al. 2012; Opdal & Hojem 2007;

Burel et al. 2013; DNV Germany 2011; Abe 1998; Verhelst 2014; Szwaja & Grab-Rogalinski 2009; Vogler & Sattler 2016; Luckose et al. 2009).

Current status and past developments of aviation transport are identified on basis of industry reports and data (IATA 2015a; Leahy 2015; ATAG 2015; IATA 2013). Further, forecasts for the future development of the aviation industry and air transport demand are summarised (Leahy 2015; Boeing 2015; Mensen 2013). These are opposed to environmental goals of the international community and the aviation industry (ICAO 2013; ATAG 2012; ATAG 2013; ICAO 2011; IATA 2015a; ATAG 2010; IATA 2014; ICAO 2012).

Historic developments of aviation technology are explained on basis of publications by K. Engmann, H. Mensen, and ATAG (Engmann 2013; Mensen 2013; ATAG 2010). In its roadmap, IATA predicts future technological improvements in aviation (IATA 2013; IATA & GIT ASDL 2009). Single measures are studied in detail based on a broad literature review (TUHH - IFS n.d.; Engmann 2013; IATA & GIT ASDL 2009; ICAO 2013; Airbus et al. 2014; Balageas 2006; Khan et al. 2014; ATAG 2010; Mensen 2013). Further improvements in energy efficiency of air transport can be achieved by operational and infrastructure measures (ATAG 2010; ICAO 2013; Lufthansa Group 2015; Mensen 2013; IATA 2013). A detailed introduction about alternative aviation fuels, their development, characteristics, and sustainability is presented (ICAO 2013; IATA 2014; Sims et al. 2008; ATAG 2011; IATA & GIT ASDL 2009; Godula-Jopek & Westenberger 2016; Airbus 2003).

Chapter 5 covers parts of an article published by K. Schönsteiner et al. that presents a methodology to derive performance indicators about energy efficiency, GHG emissions, and costs of energy carriers. This methodology is applied to derive specific values for marine and aviation bunker fuels in Singapore.(Schönsteiner et al. 2016)

Before the LCA assessment is conducted, related literature is identified (Edwards et al. 2014; JEC n.d.; Argonne 2015; IINAS 2015; UBA 2016; ecoinvent n.d.; Bengtsson et al. 2012; Bengtsson et al. 2011; Verbeek et al. 2011; Chryssakis 2013; Brynolf 2014; Elgowainy et al. 2012; Stratton et al. 2010; Saynor et al. 2003; Pereira et al. 2014; Verein Deutscher Ingenieure (VDI) 2012; Dreier 2000). In order to derive Singapore specific process parameters an extensive collection of input data was performed:

- *Conventional fuels* (OGP 2014; OGP 2013; IE Singapore 2015; Smith et al. 2013; ENI spa 2013; ENI spa 2014; Cai et al. 2013)

- *Natural gas* (Turner & Barker 2013; Edwards et al. 2014; ARB California & US EPA 2009; OGP 2014; IEA ETSAP 2010; Skone 2012; Lowell et al. 2013; Verbeek et al. 2011; Shell 2010; BG Group plc 2015; Kannan et al. 2005; Qatargas n.d.; Attah & Bucknall 2013; Wang et al. 2014; Aldous & Smith 2012; Chryssakis 2013; GL 2013)
- *Biofuels* (U.S. DA 2015b; Kurki et al. n.d.; Choo et al. 2011; Argonne 2015; Edwards et al. 2014; Uusitalo et al. 2014; Schmidt 2007; Lee & Ofori-Boateng 2013; Stratton et al. 2010; ifeu 2006)
- *Hydrogen* (Hamacher 2014; Fred Farchmin 2014; Felgenhauer & Hamacher 2015; Edwards et al. 2014; Simbeck & Chang 2002; Ruth et al. 2009; Ball & Wietschel 2009; Acar & Dincer 2014; Argonne 2015; Amos 1999; Ohlig & Decker 2014; Stolzenburg & Mubbala 2013; Barckholtz et al. 2013; Abe 1998; Oyama et al. 2012; Mortimer et al. 2013)
- *Economic data* (Ship & Bunker 2015; Theo 2015; IATA 2015b; Walker 2015; IEA ETSAP 2013; Timera Energy 2015; Timera Energy 2013)

Chapter 6. In order to assess availability of alternative energy carriers, a variety of literature is used (Wagner et al. 2014; Stich & Massier 2015; IEA 2014a; IGU 2015; BP plc 2015a; Exxon Mobil 2015; BGR 2014; U.S. DA 2015a; U.S. DA 2015b; Schönsteiner et al. 2016; IEA PVPS 2015).

Opportunities and challenges for Singapore and transferability of results to other hub cities are discussed with regard to literature sources analysed in the previous Chapters. These were extended by several specialised studies and articles in order to cover regional specialities and trends (IEA 2015b; Turner & Barker 2013; SLNG 2015; IEA 2013; Rogers & Stern 2014; DE-CIX Management GmbH 2015; Trauthig 2014; Herzog & Poguntke 2013).

Chapter 7. Finally, the results of the thesis are summarised with regard to findings derived in the previous Chapters.

1.4 Publications

The analysis of Singapore's energy system is related to some prior works. Some contributions in Chapter 3 are partly published in:

- Schönsteiner, K. & Hamacher, T., 2014. *Effects of Sustainable Energy Supply on Global Transportation Hubs*, Munich. Available at: https://mediatum.ub.tum.de/node?id=1229066.
- Wagner, M., Schönsteiner, K. & Hamacher, T., 2012. Impacts of photovoltaics and electromobility on the Singaporean energy sector. In *Energy Procedia*. Elsevier BV, pp.126–134.
- Wagner, M., Schönsteiner, K. & Hamacher, T., 2014. Model-Based Analysis of Singapore's Energy System. In I. Dincer, A. Midilli, & H. Kucuk, eds. *Progress in Sustainable Energy Technologies: Generating Renewable Energy*. Springer International Publishing. Available at: http://link.springer.com/10.1007/978-3-319-07896-0.

The methodology and results of the conducted pathway analysis of transport fuels in Singapore presented in Chapter 5 is published in:

- Schönsteiner, K., Massier, T. & Hamacher, T., 2016. Sustainable transport by use of alternative marine and aviation fuels—A well-to-tank analysis to assess interactions with Singapore's energy system. Renewable and Sustainable Energy Reviews, 65, pp.853–871. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032116303550.

The final discussion of effects of sustainable energy supply on hub cities, presented in Chapter 6, includes contributions which are partly published in:

- Schönsteiner, K., Massier, T. & Hamacher, T., 2016. Sustainable transport by use of alternative marine and aviation fuels—A well-to-tank analysis to assess interactions with Singapore's energy system. Renewable and Sustainable Energy Reviews, 65, pp.853–871. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032116303550.
- Wagner, M., Schönsteiner, K. & Hamacher, T., 2014. Model-Based Analysis of Singapore's Energy System. In I. Dincer, A. Midilli, & H. Kucuk, eds. *Progress in Sustainable Energy Technologies: Generating Renewable Energy*. Springer International Publishing. Available at: http://link.springer.com/10.1007/978-3-319-07896-0.

Finally, a selection of publications is given. Elements were created in parallel with the research for this topic, but are not a part of the thesis. Nevertheless, they give additional insights about sustainable energy solutions that will affect the established systems:

- Reuter, B. et al., 2013. Life Cycle Greenhouse Gas Analysis for Automotive Applications – A Case Study for Taxis in Singapore. *International Journal of Smart Grid and Clean Energy*, 3(2), pp.127–134.
- Schönsteiner, K. et al., 2014. Veränderte Anforderungen an städtische Energieinfrastrukturen durch die Energiewende. *Energiewirtschaftliche Tagesfragen*, 10, pp.75–78.
- Wagner, M. et al., 2014. *Energienutzungsplan für die Stadt Ingolstadt*, München. Available at: http://www2.ingolstadt.de/media/custom/465_9988_1.PDF?1409130575.

2 World trade and urban structures

Chapter 2 introduces theories to explain the interrelations between globalisation, world trade, and urbanisation. Today's structure of the world's economic system and the formation of hub cities are analysed. A sustainable energy supply is identified as a possible game-changer that could dampen further economic growth or even reduce the importance of hub cities.

In Chapter 2, the emergence of present structures of cities and trade is explained. Based on economic and geographic theories, principles behind trade and formation of cities are discussed in Chapter 2.1. Trade generates economic welfare for all countries. Economies of scale offer economic advantages and determine our current organisation of trade and the world economy, which is based on specialised, interconnected hubs or hub cities. Chapter 2.2 presents the past development and composition of trade, analyses the importance of cities, and discusses their role in the world economy. In the last century globalisation, technology, and resource availability resulted in a rapid growth in world trade and international relationships. World trade led to a highly interconnected system of international supply chains. Some cities are of special importance for this system and essential to organise world trade. Chapter 2.3 identifies possible game changers that could lead to a change of current structures. Energy and its role in sustainable development are identified as possible challenges for our current economic system organised by hub cities.

2.1 Economic and geographic theories

The present distributions of wealth and population and thereby urban and rural structures were highly influenced by historic economic development. World trade and international division of labour are basic components of our world's economic system. Within this Chapter, origins of trade and the resulting structures are explained.

2.1.1 Trade and specialisation

Trade, the process of buying, selling, or exchange of goods and services, is caused by welfare gains of trade partners. Economic theory distinguishes two fundamental characteristics that generate these additional benefits: the diversity of countries and advantages arising from economies of scale. (Krugman et al. 2012)

The diversity of countries is determined by specific circumstances: different climate conditions are suitable for certain kinds of vegetation and agricultural use; access to raw materials and commodities facilitates production of specific products; and countries differ in productivity and technology. Level of education, specific abilities, labour costs, and personal ambition of workers vary in each country. Availability of capital and present status of economic development are further characteristics. Trade between different countries always increases the economic benefit for both countries. As described within the Ricardo model, even countries that are less competitive in all production factors than other countries profit from international trade. While highly efficient countries are able to specialise on certain product groups to maximise their utility, missing products are imported from less efficient countries. All trade partners benefit from comparative advantages. By substituting domestic goods by imports, short-term damage to single individuals is possible, which is caused by the characteristic that immobile factors (e.g. machinery or real investment), in contrast to mobile factors (e.g. capital), are not able to be transformed immediately and free of costs from one sector into another. Considering the overall economic utility, it makes good economic sense to support negatively influenced sectors on a national level instead of avoiding external trade. (Krugman et al. 2012)

First developed by E. Heckscher and B. Ohlin, the factor proportions theory implies that external trade is caused by unequally distributed abundant factor endowments in different countries. Trade of goods substitutes missing or scarce production factors in countries, while goods that utilise the abundant production factors are exported. This theory is not able to simulate real interactions as factor prices are not fully balanced. A strong discrepancy of resources, trade barriers, and differences in technology are some of the possible reasons for this behaviour. The compensation of missing production factors by trade is one important driver for world trade but is not sufficient to explain its structure. (Krugman et al. 2012)

While the diversity of countries only explains the motivation of different countries to trade goods, advantages arising from mass production explain trade between countries with similar resources and technologies. One positive effect of mass production is economies of scale, meaning that unit costs are declining with increasing production quantity. While internal economies of scale describe internal effects of mass production within one company, external economies of scale describe positive effects caused by other companies of the same sector in the spatial surroundings. Economies of scale force countries to focus on a few products for export while missing products are imported from other specialised countries. Consequently, economies of scale increase competitiveness beyond comparative advantages and facilitate international division of labour and trade. The outcomes are international markets and a greater variety of products at lower costs in each country, along with worldwide efficiency gains and increasing welfare. (Krugman et al. 2012)

2.1.2 Agglomerations and cities

External economies of scale are limited to local surroundings and result in the formation of clusters of similar economic activity. First, A. Marshall defined three factors, which were extended by succeeding economists, causing these agglomerations: the ability to employ specialised suppliers, labour market pooling, and spread of knowledge and information (knowledge externalities). Accordingly, formation of local clusters is favoured that supports growth of cities resulting from required labour and supporting services. P. Krugman and others describe these concentrating factors as centripetal forces and oppose centrifugal forces that limit the growth of cities. Examples for limiting factors are: availability of land and resources, increasing land rents caused by limited supply, and other diseconomies of scale such as congestion, air pollution, and crime. In theory, there is an optimal size of cities caused by interactions of centrifugal and centripetal forces. (Fujita et al. 1999; Krugman et al. 2012; Fujita & Thisse 2013; Krugman 1999)

Initial formation of clusters at selected locations is often determined by coincidences or marginal advantages. For instance, the construction of the Erie Canal made New York City the most important port at the East Coast and initiated the rise of NYC to one of the most important centres of economic activity, political power, and cultural influence. Many big cities profit from natural advantages such as ports and access to water ways (Fujita & Mori 1996). The disappearance of initial advantages does not necessarily result in declining importance or population of cities, as self-enforcing effects lead to further growth. For example, the Erie Canal is hardly used for trade today, but New York remained one of the world’s most powerful cities. Thus, political decisions and structural measures can initialise certain developments and can have long lasting effects. H. Konishi strengthens that the basis for the formation of a city is set by the initial locational advantage, while its present structure is determined by economies of scale and other factors. (Krugman 1999; Konishi 2000)

It is important to mention, that there is no generally accepted and proven theory how cities evolve. Beside the presented theories of P. Krugman’s ’new economic geography’ and related fields, often summarised as ‘neoclassical theory’, there are more theories about regional economics and planning. According to R. Boschma and K. Frenken, two other theories describe the formation of cities (Boschma & Frenken 2006): the ‘institutional economic geography’ and the ‘evolutionary economic geography’.

The institutional economic geography investigates the influence of institutions on spatial economic development. Institutions comprise of social routines, rules, and regulations that shape and support economic activity but also organisational forms such as firms, markets, or labour unions. Institutions are assumed to be the determining factor for economic development. Utility maximisation, the basic element of neoclassical models, is critically assessed, as institutions are presumed to be more important in order to explain the behaviour of individuals. Market forces are not denied, but a focus is set on the explanation of institutional effects that shape these forces. Methodologies in the institutional approach are less model based than in the new economic geography and real places instead of neutral theoretical space are discussed. The institutional economic geography can be best described as a *“collection of ideas and approaches that share common concepts and interests in explaining particular phenomena”*. (O’Neill 2002; Boschma & Frenken 2006)

According to R. Boschma and R. Martin, the basic concern of the evolutionary economic geography is with *“the processes by which the economic landscape – the spatial organisation of economic production, circulation, exchange, distribution and consumption - is transformed from within over time”* (Boschma & Martin 2010). The evolutionary approach on economic geography demonstrates *“how geography matters in determining the nature and trajectory of evolution of the economic system”* (Boschma & Martin 2010). In contrast to the other approaches, historical development influences the current state of economic distribution. (Boschma & Frenken 2006). Central driver of economic development and the main focus of the analysis is the behaviour of heterogeneous firms in a competing environment. Behaviour and success of firms are dependent on routines, e.g. processes, patterns, and practices, which were developed and selected in the past. Therefore, the evolutionary approach is path dependent (Boschma & Frenken 2006). Not only costs, as discussed in neoclassical models, but especially knowledge and innovation intensify competition. Agglomerations are explained by the observation that successful firms grow faster and create more knowledge spill-overs and spin-offs, which are mainly situated in close geographical proximity. Other advantages, which favour regional proximity of economic activity, are firm diversification, mobility of labour, social networking, and other effects of agglomeration economies (Boschma & Martin 2010). A theoretical modelling approach starting on neutral space, similar to the neoclassical approach, is set as a starting point in evolutionary economic geography. In the next steps, the neutral space is transformed by the evolutionary approach into a real space (Boschma & Frenken 2006). One central finding of evolutionary economics, which is helpful to discuss the central research question of the thesis and is further discussed in Chapter

6.2.3, is that *“long-term development of regions depends on their ability to develop new sectors or new market niches that have their roots in the current regional knowledge base. It means that regional economies should branch into new directions rather than start from scratch when they diversify* (Boschma & Martin 2010)*.”*

In economic geography, R. Boschma and R. Martin distinguish three approaches for the emergence of agglomerations (Boschma & Martin 2010): the evolutionary approach and its *“historically grown spatial concentration of knowledge residing in organizational routines”*; the neoclassical approach and its *“rational location decisions”*; the institutional theory and the *“set-up of specific local institutions”* as main driver for agglomerations. A comprehensive discussion of commonalities and differences between the three approaches towards economic geography is done by (Boschma & Frenken 2006; Boschma & Martin 2010). All theories offer valuable insights about the formation of cities that are essential to investigate impacts of a sustainable energy supply on global hub cities.

A selection of other theories, which influenced above presented theories and further increase the understanding of spatial or sectoral economic development, are summarised in the following:

- Von Thünen developed a model that explained the structure of the surroundings of a city by setting transport costs and land use for production of different crops into relation in order to develop a rent gradient. (Fujita et al. 1999)
- Christaller founded the theory of central places to describe the distribution of market towns and administrative cities within a region by including the interactions of economies of scale and transport costs into his theory. (Fujita et al. 1999; Kaplan et al. 2009)
- The base-multiplier analysis distinguishes between exports and local demand. While exports are the base of economic activity, supporting services for the city’s population and local industry are developing in a certain relation with the base activity. The analysis shows that interactions of economies of scale and local demand have a self-reinforcing effect. (Fujita et al. 1999; Kaplan et al. 2009)
- Market potential analysis showed that agglomerations of production have also a high market potential and are therefore self-reinforcing. (Fujita et al. 1999)
- In 1955, F. Perroux developed the growth pole theory to explain processes of economic growth over time. In contrary to equilibrium growth models, economic growth is based on dynamic units such as individuals, firms, industries, or nations and their uneven innovation potentials. The associated unbalanced growth results

in structural change, linkage effects, and polarisation. (Hospers 2004; Kaplan et al. 2009)

- There are different types of agglomeration externalities. The presented Marshall externalities in the beginning of this Chapter discuss industry specific knowledge spill-overs within one industry or between similar industries for the investigated area. These intra-industry spill-overs lead to specialisation and are also referred to as localisation externalities. In contrast, Jacobs investigates spill-overs between different complementary industries. For instance, innovations or technologies developed in one industry help to improve processes or products in a complementary industry. Jacobs argues that these ‘diversification externalities’ accelerate innovation and increase competitiveness of multiple industries. There is an ongoing discussion about what type of externalities are more conductive for innovation and regional developments. (Van Der Panne 2004)

2.1.3 Transport costs and hubs

International trade is heavily dependent on distance and economic power of countries to each other. Gravity models of trade describe trade activity between two countries based on economic power (GDP) and distance. P. Krugman analyses that typical studies assume that an increase in distance by 1% leads to a decline in trade by 0.7%. This is caused partly by higher transport costs of goods and services and partly by weaker relations between inhabitants of both countries. (Krugman et al. 2012)

‘The Review of Maritime Transport 2015’ analyses costs of marine transport and identifies determinants of trade costs (UNCTAD 2015): besides absolute distance, also the position within transport networks is of great importance for transport costs; factors such as traded products, volume, frequency, port infrastructure, trade and transport facilitation, competition on transport routes, trade flows and imbalances, trade tariffs, and regulations influence costs of transport.

Beside agglomerations of economic activity, external economies of scale affect transport of goods and passengers. Transport costs decline with increasing quantity of traded products, commodities, and passengers. This behaviour forces the formation of transport hubs (Krugman 1999). J. P. Rodrigue analyses the advantages of transport hubs. While ‘economies of scale on connections’ allow more frequent services, ‘economies of scale on the transport hub’ offer a more efficient distribution system as a bigger quantity of one good is processed. ‘Economies of scope in the use of shared transhipment facilities’ lead to lower unit costs for each transported good and a higher quality of the infrastructure (Rodrigue et al. 2013). By this, hubs make trade of goods economical that would otherwise not be traded internationally (WTO 2013b). According to UNCTAD, trade is the *“backbone”* of globalisation and an enabling factor for marine related products and services (UNCTAD 2015).

A hub is by definition the centre of a wheel or a centre of activity. As one outcome of his research about scale-free networks, A. L. Barabási showed that many different complex systems, such as power grids, transport networks, or the internet, are based on networks with several especially popular nodes – also described as hubs (Barabási & Bonabeau 2003). This term is very common in the field of transport in which it describes the centre of a typical hub and spoke network. Hub networks offer the advantage of a more efficient transport network as the number of connections is reduced compared to a point-to-point network (Rodrigue et al. 2013). M. O’Kelley defines hubs as *“special nodes that are part of a network, located in such a way as to facilitate connectivity between interaction places”* (O’Kelly 1998). Typically, air transport and container transport are often organised in hub networks. According to Z. P. Neal, city planners often try to generate hubs in order to make their city a ”hub of activity” to become a focal point in urban networks (Neal 2014). A city that serves as a hub has an economic advantage over other locations (Fujita et al. 1999).

In the context of this thesis hub cities are defined as cities that structure international networks as central nodes by specialising on production, trade, and distribution of selected products or services and the creation of particular knowledge.

2.2 Present economic structure and world cities

After the theoretical discussion of trade and the formation of cities, historic developments, the current status of trade, and its composition are analysed. The importance of cities for the world economy is highlighted and insights about the best integrated cities into the world economy are given.

2.2.1 Past development and composition of trade

The existence of a world system or a world economic system traces back to ancient history. Findings from the Western Asian and Egyptian area witness early international trade relationships. Walter shows on basis of selected case studies the historic development of the world economic system. (Walter 2006)

In the last centuries, new technologies in transport, information, and communication have been leading to lower transport costs and stronger international trade relations. Yet, wars, economic depressions, and protectionism have been slowing international cooperation and hindering globalisation. The World Trade Organisation (WTO) distinguishes between three phases of globalisation. A first globalisation from 1800 to 1914 was followed by a de-globalisation from 1914 to 1945 caused by wars and economic recessions, and a re-globalisation since 1945. Since 1980, world trade has been characterised by a strong growth. World trade of goods has been growing by 7% p.a. and international services by 8% annually. (WTO 2013b)

Figure 2-1 visualises the development of worldwide exports in comparison to economic and demographic developments since 1970. Exports and GDP are reported in constant prices.

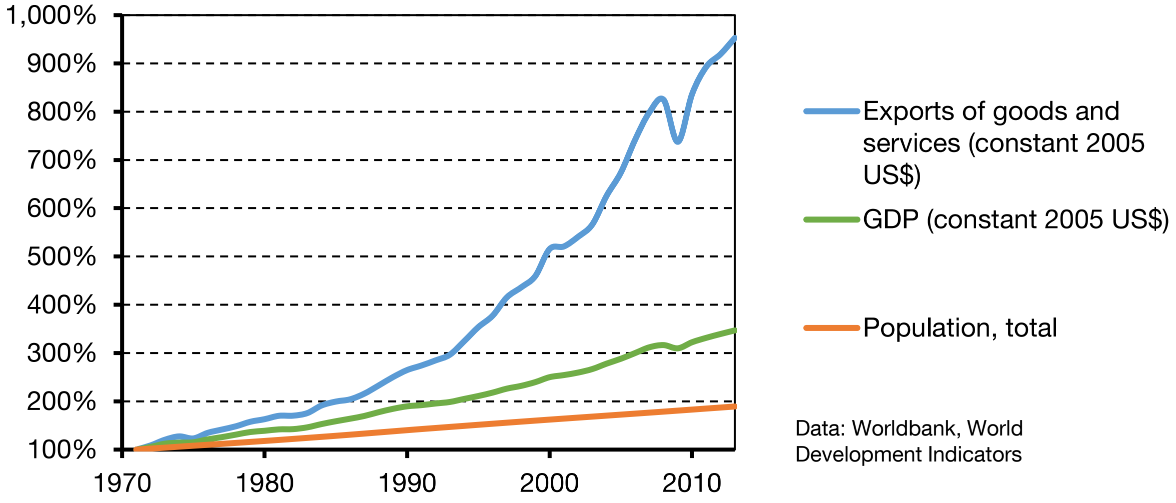
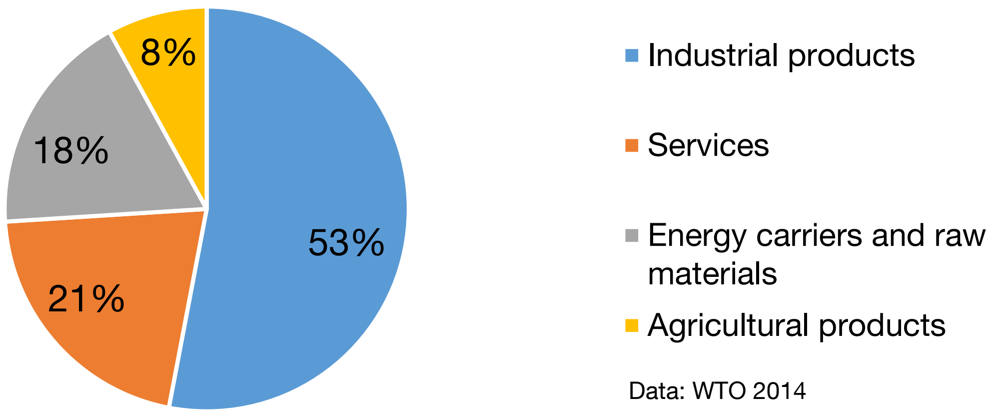


Figure 2-1: Growth of exports compared to GDP growth and population growth since 1970

Development of world population shows a relatively steady growth. GDP growth and especially exports of goods and services are characterised by much stronger fluctuations in the examined period. While world GDP declined 2% during the financial crisis in 2009, value of world exports decreased by more than 10%. It is important to emphasise that energy and commodity prices have a big impact on this value. Figure 2-1 points out that external trade has been growing significantly faster than GDP. This was not only caused by additional exports, but especially by international division of labour. Products and their components are no longer manufactured within the borders of one country. Instead, different stages of production are spread over several countries. As a consequence, a product can cause trade flows worth a multiple of its price. (Krugman et al. 2012)

Till 1970, agricultural products had been representing the biggest share of external trade. As visualised in Figure 2-2, the share of industrial products on world external trade in 2013 was 53%, followed by services (21%), energy carriers and raw materials (18%), and agricultural products (8%) in 2013 (WTO 2014).



Data: WTO 2014

Figure 2-2: Structure of world trade

In the case that 'total value added' instead of 'total export value' is summarised for every country, the share of services doubles while the share of industrial products declines significantly (WTO 2013b). The importance of services in external trade has been increasing in the last years. Besides the classic services transport and tourism, share of other services, such as communication, finance, construction services, licences, and computer and information services, has been increasing even stronger. A current trend is the offshoring of services. Instead of supplying services locally, services are delivered from abroad in equal quality (e.g. IT support). (Krugman et al. 2012)

2.2.2 Importance of cities

As shown in Chapter 2.1, cities offer self-reinforcing economic advantages leading to growth in activity and size. Within the last 65 years there has been a strong growth in world population. This development has been accompanied by a strong urbanisation. Urban population has been growing at a faster rate than rural population. In 1950, 70% of world population was rural. In 2014, 54% of world population was urban. It is expected that urbanisation and growth of population will continue over the next decades. (UN 2015b)

Related literature shows that urbanisation and economic growth are closely connected in the economic development of countries. Less urbanised areas, such as Asia and Africa, will see a strong urbanisation accompanied with GDP growth (Mohanty

2012). R. Florida et al. investigate the share of economic activity generated by metropolitan regions. Metropolitan areas with more than one million people generate 52% of world economic output, while domiciling only 20% of world population. Metropolitan share of economic activity is lower in Europe (41%) and BRIC countries (33%) and higher in North America (54%) and Emerging Economies (61%). These figures emphasise that cities are more efficient in generating economic output than rural areas. (Florida et al. 2009)

The United Nations Human Settlement Programme stresses the close relation of globalisation and global cities. It defines globalisation as *"… the development of stronger links between countries and the breaking down of existing barriers as a result of technological communications and international regulations and re-regulations".* Global cities, which are often characterised by excellent transport infrastructure, act as hubs to link hinterland connections of goods, people and information to the global economy. (Zhang 2011)

2.2.3 Ranking cities

Different rankings investigate which cities are most important and offer the best opportunities by a variety of criteria such as economic strength, research and innovation, human capital, finance, accessibility, liability, governance, and other topics (Friedmann 1986; MMF 2013; GaWC 2014; Citi 2013; A.T. Kearney 2015; PWC 2014). Different methodologies are applied. Table 2-1 summarises a selection of rankings.

Table 2-1: Rankings of world cities

Study		**Friedman**	**GaWC**		**MMF**		**Citigroup**		**A.T. Kearney**		**PWC**	
Year		1986	2012		2013		2025		2015		2014	
Results	Primary	London	Alpha ++	London	1st	London	1st	New York	1st	New York	1st	London
		Paris		New York	2nd	New York	2nd	London	2nd	London	2nd	New York
		Rotterdam	Alpha+	Hong Kong	3rd	Paris	3rd	Singapore	3rd	Paris	3rd	Singapore
		Frankfurt		Paris	4th	Tokyo	4th	Hong Kong	4th	Tokyo	4th	Toronto
		Zurich		Singapore	5th	Singapore	5th	Tokyo	5th	Hong Kong	5th	San Francisco
		New York		Shanghai	6th	Seoul	6th	Sydney	6th	Los Angeles	6th	Paris
		Chicago		Tokyo	7th	Amsterdam	7th	Paris	7th	Chicago	7th	Stockholm
		Los Angeles		Beijing	8th	Berlin	8th	Stockholm	8th	Singapore	8th	Hong Kong
		Tokyo		Sydney	9th	Vienna	9th	Chicago	9th	Beijing	9th	Sydney
		Sao Paulo		Dubai	10th	Frankfurt	10th	Toronto	10th	Washington, D.C.	10th	Chicago
		Singapore				…		…		…		…
Source		(Friedman 1986)	(GaWC 2014)		(MMF 2013)		(Citi 2013)		(A.T. Kearney 2015)		(PWC 2014)	

Friedman identifies powerful cities in his 'World City Hypothesis' as world cities and categorises eleven primary cities in developed and emerging countries (Friedmann 1986). The 'Globalization and World City (GaWC) Network' analyses the offices of 175 international service companies and classifies cities in different categories, with Alpha++ and Alpha+ being the most important (GaWC 2014). The 'Global Power City

Index 2013' ranks cities by power including multiple criteria (MMF 2013). The study 'Hot spots 2025' commissioned by the Citigroup benchmarks future competitiveness of cities for 2025 (Citi 2013). The 'Global Cities Index' shows the current performance of cities (A.T. Kearney 2015). PricewaterhouseCoopers ranks cities in its 'Cities of Opportunities' report to identify best cities for business opportunities (PWC 2014). Selected studies are not comprehensive, as there are more rankings by different institutions for past and future years. However, this collection represents studies of different timeframes, criteria, and institutions.

Besides the fact that applied methodologies are different, results are very similar. This is remarkable, as studies cover a timeframe of nearly 40 years. The theory of self-reinforcing effects of agglomerations, discussed in Chapter 2.1 and stressing that it is easier for established nodes of activity to obtain leadership, is supported by these rankings. It is common consensus that London and New York are the most important and influential cities. Paris and Singapore are listed in every ranking and seen as very influential. Only in the Cities of Opportunities report, Tokyo is not ranked as one of the ten best cities (PWC 2014). Its working age population, risk of natural disasters and costs are seen especially critical. Hong Kong achieves a top ranking in four studies. A better placing in the Global Power City Index is prohibited by deficits in cultural interaction, liability and environment (MMF 2013). According to Friedman's World City Hypothesis, Hong Kong is only a secondary world city (Friedmann 1986). However, it has to be highlighted that his investigation was published in 1986 and does not reflect the subsequent rise of emerging economies. All these cities are international hub cities, often in multiple aspects in terms of finance, trade, aviation, administration, education and industrial clusters. In three studies, Sydney is seen as one of the most important cities. It is the largest city in Australia and its centre for multinational companies and banks. According to PWC Sydney offers excellent quality of living, sustainability, health and security (PWC 2014).

A few smaller cities with high sustainability and quality of living possess economic specialisations, mainly in the financial sector, and offer good prospects for sustainable development. Examples are: Toronto, Stockholm, Frankfurt, Zurich and San Francisco.

Summing up, population, size, resources, or economic power are not decisive if a city is influential or not. However, the top ranked cities have in common that they keep an excellent integration into world economy and aggregate flows of goods, capital, information and people. Although emerging economies have showed faster growth in economic power than developed countries this did not lead to a shift of power between cities yet. Instead of a dominance of megacities with more than 15 million in population, current studies suggest that especially smaller cities that offer innovative power, good access to capital, and economic specialisations will become more important in the future owing to their ability to offer a good quality of living and sustainability (PWC 2014; A.T. Kearney 2015).

2.3 Sustainability of future trade

This thesis focuses on the influence of a sustainable energy supply on hub cities and shows the prospects of future developments. In a first step, shaping factors of future trade are summarised. The role of energy in the economy is discussed and characteristics of sustainable developments are introduced. In this chapter, energy supply is identified as a major hurdle for hub cities to achieve sustainable development.

2.3.1 Shaping aspects of future trade

Chapters 2.1 and 2.2 explain how current trade structures, which are organised by cities and hubs, have emerged. A couple of new trends will influence future trade structures, cities, and global networks. The Wold Trade Organization (WTO) identifies six fundamental economic factors that will shape future development of world trade by influencing comparative advantages and economies of scale (WTO 2013b):

- *Demography*: Population growth, urbanisation and growing middle class will increase demand of international transport, lead to new focus points of consumption, and alter comparative advantages by affecting efficiencies.
- *Investment*: Investments lead to more participants in world trade. Foreign investments create capital, knowledge, and technologies. Changes in comparative advantages are a result.
- *Technology*: Current structure of world trade was enabled by technology and decreasing transport costs enabling a better communication and shaping comparative advantages. Further developments will influence future trade structures.
- *Energy and natural resources*: Different aspects, such as availability, environment, production costs, and technological progress, affect comparative advantages and costs of energy and natural resources. Rising demand and increasing costs are expected in the long term, which will shape future structures of trade.
- *Transport costs*: Volume, direction, and composition of international trade is influenced by transport costs. Technologies, competition, policies, taxes, and energy costs affect future costs of transport. Economies of scope in transport hubs reduce transport costs and make trade of products more attractive.

- *Institutions*: This term summarises norms, laws, politics, regulations, and treaties. Institutions can improve efficiency and increase economic activity by enabling a better integration of national economies into global value chains.

2.3.2 The role of energy in economy

As the WTO points out above, different aspects of energy affect international trade by shaping comparative advantages and influencing economies of scale (WTO 2013b). In the following, these aspects are further classified into five dimensions (Figure 2-3), extended, and discussed:

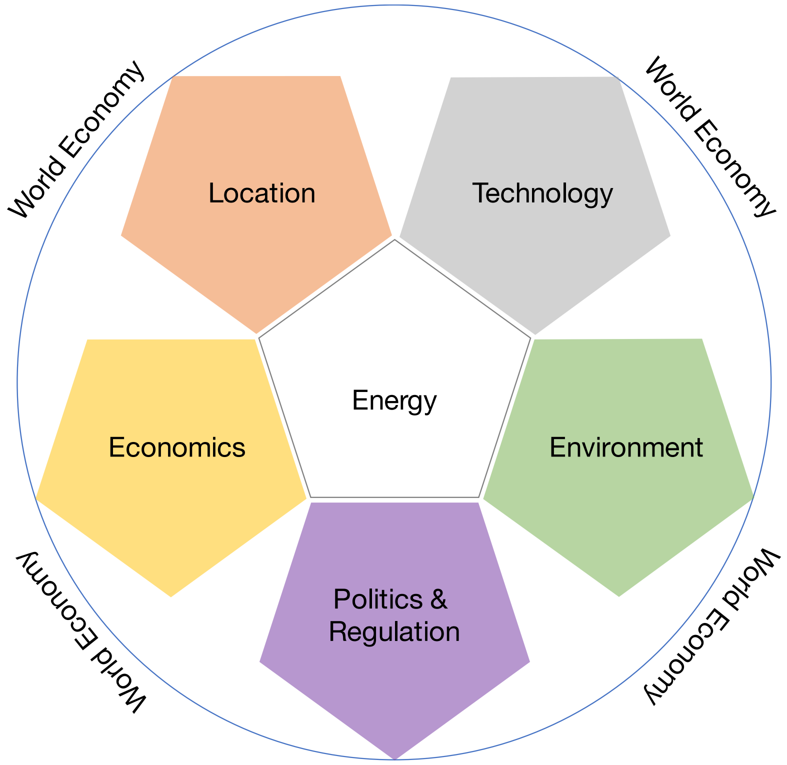


Figure 2-3: Five dimensions of energy influencing world economy

Location. Resource potentials and current production of energy based on fossil and renewable sources are unevenly distributed globally and limited locally.

Fossil energy carriers, such as oil, coal, and gas, are allocated according to their geological deposits. Different types of deposits and locations require different types of technologies and logistics to extract their energy. As a consequence, costs are specific to locations. Production of fossil energy carriers offers an extremely high availability of energy locally caused by high energy densities. Deposits are depleting when energy is extracted. The extracted energy has to be converted and transported before it can be used for its final purpose.

Availability of renewable energy carriers, such as solar, wind, hydro and biomass, is dependent on inexhaustible renewable energy potentials. Potentials are unevenly distributed globally, often temporary, and locally limited by production technology, land requirements, and economics. Different locations have different costs of renewable production. Often locations of production and demand are distant and force transport of energy.

Fossil energy carriers benefit from scale economies in production, transport and consumption and are transported over large distances. In contrast, renewable energy carriers are characterised by diseconomies of scale in production. As the most economic renewable potentials are used first, the production of additional renewable energy requires utilisation of less favoured production sites. Conflicts between land use of energy production and food production are critical. Compared to fossil energy carriers the transport distances of energy derived from renewable energy sources are lower.

Energy demand is agglomerated at cities while less demand occurs in rural areas. There are strong variations depending on climate conditions, economic power, sector of industry, welfare, population, and population density.

The dependencies between economic activity and energy demand are further investigated in Chapter 3. More information about power densities of conventional energy carriers, renewable energy carriers, and energy consumers can be derived from the book ‘Power Density’ by V. Smil (Smil 2015b).

Technology. While the existing technologies are improved and enable better economic efficiencies for production, transport, conversion, and end-use of energy, new alternative technologies allow to extract unused resource potentials at competitive costs, e.g.: technologies to harvest renewable energies from wind and solar are changing current structures of electricity supply in many markets; electric vehicles and unconventional drive trains start to substitute conventional gasoline or diesel vehicles. However, new technologies do not necessarily mean renewable or more environmental friendly technologies, e.g.: discovery and extraction of unconventional oil and gas resources in the US had significant impact on US energy imports, global oil trade, and energy prices; larger container ships make transport of goods more fuel efficient and therefore cheaper.

Environment. Energy production, supply, and consumption impact the environment and therefore reduce the attractiveness of certain energy carriers at different degrees.

Mitigation of climate change and the avoidance of pollution are important aspects in our society today. Especially fossil energy carriers have big environmental impacts at their extraction, processing, and consumption, e.g. unconventional oil recovery from oil sands is seen as a major polluter, refining of gasoline produces emissions and toxic by-products, and conventional cars produce air emissions that affect air quality in densely populated urban areas. However, the production of renewable energy has implications on the environment as well, e.g. nearby settlements, wind power plants, or transmission lines, which link places of supply and demand, are often a matter of public rejection. Frequently, environmental issues lead to policy actions and stricter regulations.

Economics. The costs of energy extraction, processing, transport, and distribution vary by location, type of energy carrier, technology, and financial, political, and regulatory frameworks. A pure economic optimisation results in minimal energy costs and in a maximum of economic activity. In order to achieve this, trade and transport of energy is necessary. However, environmental issues can affect long term costs of energy, e.g. health impact of coal firing may outweigh economic benefits. Therefore, minimum costs of energy do not necessarily result in a long term maximum of economic activity. Further, the economics highly interact with the locations of supply and demand, boundary conditions, and technologies.

Policy and regulation. Policies and regulations affect the availability of energy by economic conditions. In order to achieve certain political goals, such as reduction of import dependency, trade sanctions, or environmental specifications, it might be necessary to set incentives for market participants or regulate energy markets. This results in a deviation of a pure economic optimum and higher energy costs at least in the short term. Instead of the most economical energy carriers less economical energy sources or technologies might be chosen. Examples are the priority of renewable energy in the German power system, biofuel shares in fuels for passenger cars, or double-hulled instead of single-hulled oil tankers.

Historic development. Caused by an absence of economic transport systems in the past, cities had to supply their demand by their local hinterland. A city of this type is called ‘Agropolis’. During the 20th century information and technology lead to declining transport costs and resulted in the emergence of cities that have been dependent on fossil fuels to supply their multiple demands over long distances and are consequently called ‘Petropoleis’ (Singular Petropolis) (Mohanty 2012). Current structures of mega cities and hub cities would not be possible without international transport based mainly on petroleum fuels.

2.3.3 Sustainable development

Climate change, resource depletion, urbanisation, and unequal distribution of welfare challenge existing structures of the world economy and raise the question what role the existing Petropoleis will play in the future. Sustainable development is seen as an essential part in future economic development in order to solve aforementioned challenges. The concept of sustainable development was fundamentally shaped by the World Commission on Environment and Development in 1987:

“Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs.“ (UN 1987)

There are different approaches how sustainability or sustainable development can be achieved. A very popular concept is the concept of the ’three pillars of sustainability‘. A development is characterised as sustainable, if the three pillars economic development, social equity, and environmental protection converge equally (Drexhage & Murphy 2010). The model can be applied to different entities – on global scale, to countries, or to companies. There is no common procedure to measure or assess sustainability on basis of the three pillars. Figure 2-4 visualises the three pillars of sustainability as overlapping circles. The interactions between the three dimensions are represented by intersections. Other and more specified illustrations of the ‘three pillars of sustainability’ are presented and discussed by I. Pufe (Pufe 2014).

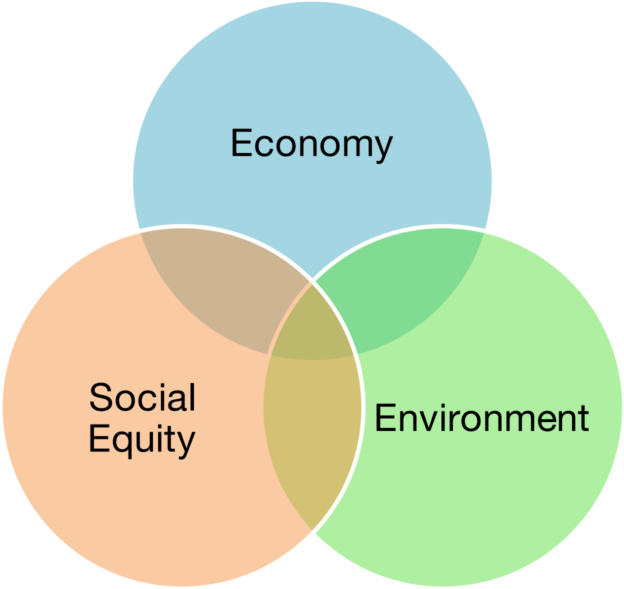


Figure 2-4: Three pillars of sustainability

As shown in Chapter 2.1, world trade offers advantages for economic development: economic efficiency and social development are increased by stimulating economic growth attached with increasing welfare and alleviation of poverty in developing countries. The WTO emphasises that trade helps increasing the efficiency of scarce resources allocation and favours the distribution of environmental products, technologies, and services to all countries (WTO 2011). Hub cities improve the process of globalisation by agglomerating flows of people, goods, and knowledge. By this, higher economic efficiencies of global value chains are possible and international distribution of labour is more economical. Summing up, world trade and formation of hub cities generate economic advantages and favour social equity. Environmental technologies profit from scale effects, market access, and knowledge transfer. Trade may affect the environment positively by increasing higher income levels that may lead to additional demand of environmentally friendly technologies (WTO 2011).

However, trade has some indirect negative effects on sustainable development. First, a faster economic growth leads to a larger economy with higher levels of output. It is likely that economic efficiency in some areas will not grow with the same speed as economic output. Therefore, more input resources are required. This increases pressure on the environment and harvesting of resources. Favoured by trade, structures of specialisations and agglomerations have some negative impacts on sustainability. As mentioned in Chapter 2.1, agglomerations are accompanied by centrifugal forces that limit growth. Congestion, pollution, land rents, air quality, crime, and other disadvantages of agglomerations affect especially social equity and environment.

Policies and regulation are needed to enforce sustainable development and balance all three pillars of sustainability: economy, social equity and environment.

The United Nations Conference on Trade and Development (UNCTAD) identifies how sustainable developments in transport could be achieved. The suggestions highly affect structures of current transport networks (UNCTAD 2015): a shift of modal split towards more sustainable solutions (e.g. ship transport instead of truck or train transport), reshaping of supply chain design (e.g. locating places of production nearer to places of consumption), and use of more energy efficient transport technologies (e.g. larger ships) and networks will challenge existing structures. Infrastructure improvements and extension might lead to new comparative advantages (e.g. extension of canals or ports). Sustainability of transport could be increased by new technologies such as low carbon fuels, more use of information and communication, and intelligent transport systems. Organisational measures like trade facilitation (e.g. decrease delays at borders) and improved cooperation and stakeholder networking, could further improve the sustainability of transport. Additional measures to improve sustainability are described for ports. UNCTAD summarises that regulation and a rising demand of industry for sustainable transport are the main drivers of sustainable developments in transport (UNCTAD 2015).

B. Mohanty sees cities as focus points for sustainable developments because of their big share on the global economy and their potential to catalyse further sustainable developments in other regions (Mohanty 2012).

2.3.4 Energy as a key to sustainable development

Many problems related to environmental aspects including pollution and air emissions are caused by fossil energy carriers. Typical examples are air pollution, pollution of soil and water, and carbon emissions. Policies supporting sustainable development are often focussing on increasing energy efficiency and substituting fossil energy carriers by renewable energies or switching to lower carbon energy carriers. A more environmental friendly energy supply is a key measure to balance the three pillars of sustainability.

The effects of sustainable developments on current trade structures and hub cities are not clear yet. Regarding rising energy prices, caused by peak oil, Rodrigue pointed out:

„While globalization was favoured by cheap and efficient transport systems, the new relationships between transport and energy are likely to restructure the global network of production and distribution towards regionalization“(Rodrigue et al. 2013).

Since then, with the discovery and extraction of unconventional oil resources and resulting shifts in global energy distribution, changes in energy trade, increased competition, exploding oil production, and comparably low oil prices, the costs of energy for transport use have declined. However, policies could force sustainable developments that might increase transport costs significantly and revive trends towards regionalisation.

It is a fact that high local energy demand of cities, which is caused by specialisation and high population density, leads to dependencies on fossil energy carriers, energy imports, and energy prices. On the contrary, sustainable energy systems are determined by low specific energy requirements, diseconomies of scale of energy generation, and regionalism. These contrary characteristics will challenge hub cities in the future and are discussed in more detail in the next Chapters.

3 Energy demand and economic activity

Chapter 3 discusses the effects of specialisation on limited regional space in general and on the example of Singapore in detail. As shown in this Chapter, economic activity in hub cities leads to high specific energy consumption. Especially fuels for international transport lead to very high local energy demands. This causes dependencies on energy imports and fossil energy carriers.

In Chapter 3.1 a short description about recent developments in the world's energy demand is given. Based on energy intensity, typical hub structures are compared to more decentralised structures. While a decoupling of energy demand and economic output is achieved in larger countries, a strong coupling is continuing in hub structures. Singapore is a perfect example for a hub city. In Chapter 3.2 Singapore's rise from a small village at the Singapore River to a global metropolis is shown. Policies and forecasts oppose Singapore's aims to limit total GHG emissions by increasing carbon efficiency to strong growth of its population, economic power, and specialisations in the transport sector. The energy flows and the energy use within the city are reconstructed on basis of different energy statistics in Chapter 3.3. The energy consumption is further split up into specific sectors. Fuels for international transport are identified as a significant share of Singapore's energy use, which results in high GHG emissions globally. A sustainable energy supply needs therefore to take energy demand caused by international transport into account.

3.1 Global and regional developments

3.1.1 Global developments

Global economic growth in the last centuries has been accompanied by additional consumption of energy. There are a couple of different institutions that publish data about world energy production and consumption. Besides others, famous examples are the International Energy Agency (IEA) as an organisation of the OECD, the Energy Information Authority (EIA) as a part of the US department of energy, the United Nations Statistics Division, and energy major BP. Studies about primary energy consumption focus mainly on the last decades and results differ by publisher. Reasons for these differences are different data sources and applied methodology. For instance, BP and EIA only include traded energy in their statistics and neglect use of non-traded traditional biomass. Furthermore, R. Newell and Y. Qian investigate that efficiency factors of non-combustible fuels, energy contents of different energy carriers, and definitions of energy carriers, regions, and historical data differ. (Newell & Qian 2015)

Detailed statistics of world energy consumption since 1800 by fuel source is published by V. Smil and visualised in Figure 3-1 (Smil 2010). In the second half of Figure 3-1, the shares of the different energy sources on world primary energy consumption and their developments are visualised for the same period.

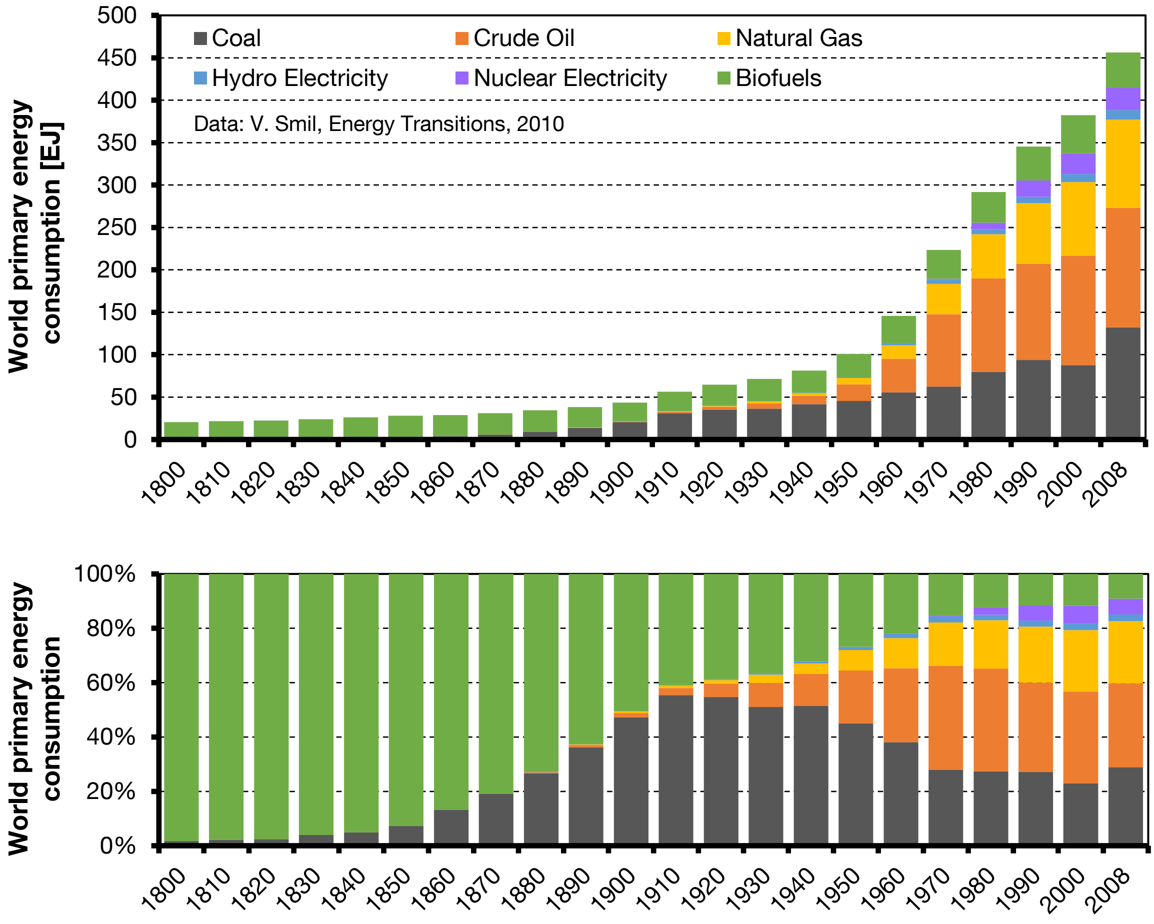


Figure 3-1: World primary energy consumption by source

In 1800, just in the middle of the industrial revolution, the mix of energy carriers consisted mainly of traditional biomass, particularly fuelwood. At this time coal started to substitute biomass and contributed to energy supply as an additional source of energy. It became the most important energy source at the beginning of the 20th century. Energy demand has been rising steadily till 1912 and the preludes to the World War I. With rising demand of oil and also of natural gas the energy mix started to transform. Especially oil demand has been growing in the next decades. Globalisation and economic growth boosted global demand of energy. Oil became the world's most important energy carrier between 1960 and 1970 by surpassing coal. The first and the second oil crisis in 1973 and in 1979/1980 led to a temporary decline of primary energy. These events resulted in a stronger increase of gas as a primary energy carrier and forced the development of nuclear power plants and renewable energy carriers. The nuclear accidents in Chernobyl (1986) and Fukushima (2011) slowed nuclear growth; especially in some industrialised countries such as Germany or Switzerland. Since 2000 coal has been the fastest growing source of energy owing to high energy demand forced by fast economic growth in emerging economies (World Economic Forum & IHS CERA 2013). Latest figures of V. Smil indicate, that oil (30%) and coal (28%) have the largest share on primary energy demand followed by gas (22%). Nuclear energy contributes with 4% to global primary energy supply. Share of renewable energy sources is comparably low. Traditional Biomass (7%), hydro (6%), and other renewables (2%), such as wind, solar, and geothermal energy, total to 15% of the global primary energy supply (Smil 2015a). Current developments of the energy mix are driven by the discovery and the exploration of unconventional sources for gas and oil, which have been becoming economically viable with high energy prices before the world financial crisis in 2007. As demonstrated in the figure above, current energy consumption is more dependent on coal, oil, gas, and nuclear as ever before. Effects of the currently low energy prices on the future mix of world energy sources are still uncertain and will depend on further development of energy prices, technologies, and policies.

Research has shown that there is a strong correlation between energy use and economic output. D. Stern investigated the role of energy in economic growth and came to the conclusion that *“energy use and output are tightly coupled”* (Stern 2010). V. Smil noticed that growth of commercial energy consumption was similar to GDP during the 20th century (Smil 2010). These global observations are assessed further on a regional level.

3.1.2 Regional developments

The above discussed mechanisms of world trade led to the emergence of hub cities and the formation of agglomerations with especially high economic activity. Therefore, energy consumption is not equally distributed, but concentrated on multiple places that are linked to and dependent on places of energy production, refining, and transport from remote areas. As shown in Chapter 2 economic developments lead to the emergence of hub cities. It is emphasised that energy might become a limiting factor in future economic activity.

Energy demand in spatial resolution is often quite different to global energy demand as local availability of energy resources is determining energy supply. Figure 3-2 visualises the development of primary energy consumption from 1990 to 2011 in selected countries depending on GDP, area, and population. The selected methodology is similar to results published prior by K. Schönsteiner and T. Hamacher (Schönsteiner & Hamacher 2014). The underlying data are derived from IEA statistics and data about land area of countries (IEA 2014b).

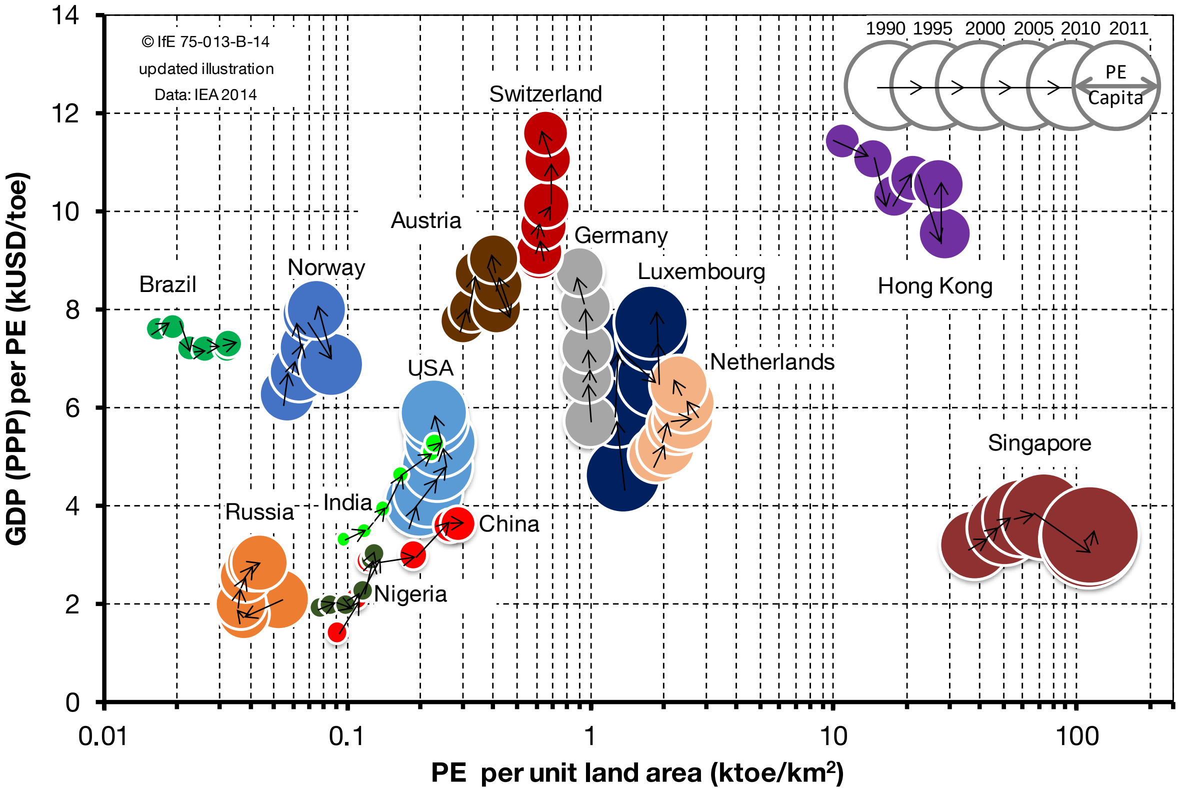


Figure 3-2: Development of energy and economic indicators for selected countries

Primary energy (PE) supply is based on the primary energy consumption of the country and the fuel demand for international marine bunkers and aviation bunkers. Primary energy supply per unit of land area is expressed in ktoe/km². Land area of Singapore changes slightly over the time period owing to landfill operations (Singapore DOS 2015). For other countries, land area is set constant over the examined time period. Therefore, changes in primary energy consumption in each country are indirectly taken into account on the horizontal axis. As expected, large and densely populated countries reach lower specific values of PE per unit of land area than city states such as Singapore or Hong Kong. While developed countries such as Germany, the USA, or the Netherlands reduced their primary energy demand in the last decade marginally, developing countries such as Brazil, China, and Russia and hub cities such as

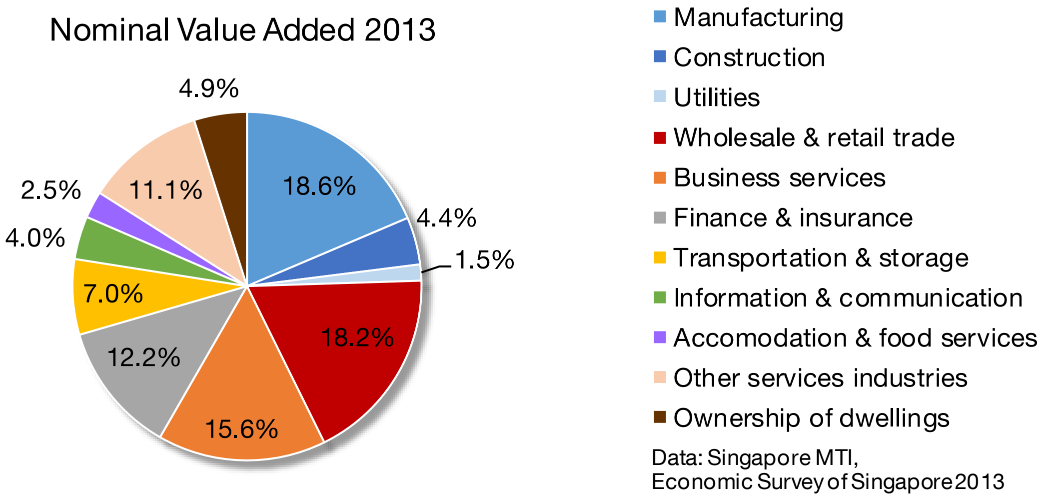
Hong Kong and Singapore have had a significant growth in primary energy consumption. Singapore's energy consumption in 2011 reached 114 ktoe/km^2, which is in the same order of magnitude as its annual solar radiation. GDP is measured in Power Purchasing Parities (PPP) USD 2005 and set in relation to primary energy. This ratio indicates the efficiency of the economy. Nearly all countries have reached higher efficiencies in the last decades. However, improvements in the hub cities Singapore and Hong Kong were limited or even negative. The indicator PE/Capita remained around the same level in OECD countries but increased in developing countries and the investigated hub cities Singapore and Hong Kong. While energy demand in developing countries has been increasing with economic growth, energy demand in hub cities has been rising especially strong owing to the growing world economy and higher transport demand. Summing up, in OECD countries there is a decoupling of GDP growth and growth in energy use. In contrast, developing countries show a stronger correlation of these values. In the very high income countries Hong Kong and Singapore the economic performance and the energy use are still tightly coupled. Therefore, hub cities face much stronger challenges in transforming their fossil fuel based energy systems into sustainable energy systems. Reasons for the above described behaviour are investigated in detail on the example of Singapore in the following Chapters.

3.2 Singapore – a typical hub city

3.2.1 Economic activity

Singapore is a city state in Southeast Asia. In 2014, its population reached 5.5 million and its land area was 718.3 km^2 (Singapore DOS 2015). This makes Singapore to one of the world's most densely populated countries. Singapore is a hub city for various different economic activities. According to UNCTAD, Singapore is the second largest container port, which is only surpassed by the port of Shanghai (UNCTAD 2015). Singapore's port is the most important supplier of bunker fuels with 42 million tonnes of bunker sales in 2014 (Singapore DOS 2015). Its Changi airport, which handled 54 million passengers, 1.8 million tonnes of airfreight, and 347 thousand aircraft movements in 2013/2014 (CAG 2015)), and its regional leadership in aerospace maintenance, repair and overhaul, manufacturing and further aviation services make Singapore to a major aerospace hub (Singapore EDB 2015a). Z/Yen Group ranked Singapore in the Top 4 of the Global Financial Centres Index and as Southeast Asia's most important financial centre (Z/Yen Group 2014). A sound financial background has been supporting Singapore's growth by financing trade, transport, and major investments (Ng 2012). Refining and oil trade has been a major column for Singapore's economic growth. Singapore is one of the largest exporting refinery centres. Over 800 oil traders (Singapore EDB 2015a) and more than 20 million cubic meters of oil storage capacity (Platts 2014) witness Singapore's position as Asia's most important oil trading hub. Rig building, marine engineering, and offshore support services emphasise Singapore's importance in the oil industry (Singapore EDB 2015a).

Figure 3-3 visualises Singapore's nominal value added by sector in 2013. This gives a first impression about its economy and its business model.



Data: Singapore MTI,
Economic Survey of Singapore 2013

Figure 3-3: Structure of Singapore's economy by Nominal Value Added in 2013

Besides petroleum products (46 billion SGD), electronic (90 billion SGD) and chemical products (54 billion SGD) contributed most to Singapore's manufacturing output (290 SGD). Singapore is a high developed service economy. While goods producing industries (manufacturing (18.6%), construction (4.4%) and utilities (1.5%)) accounted for 24.5% of the nominal value added, services producing industries added 70.6%. These included the wholesale and retail trade (18.2%), business services (15.6%), finance and insurance (12.2%), transportation and storage (7.0%), information and communication (4.0%), accommodation and food services (2.5%), and other services industries (11.1%). Ownership of dwellings added 4.9% nominal value. (Singapore MTI 2014)

As shown above, Singapore is a hub for several industries and services. In order to further investigate the economic characteristic, energy consumption, and sustainability of Singapore, past economic developments are shown and an outlook of future developments and policy targets is given in the following paragraphs.

3.2.2 Rise to a global hub city

Singapore's economic wealth and prosperity today had been shaped by its historic development. The time from 1299 to 1599 is known as the classical emporium. Owing to its unique geographical position between the Indian Ocean and the South Chinese Sea, which is part of the Pacific Ocean, Singapore became an important regional port in the late 13th century. Conflicts resulted in the destruction of Singapore's port and settlements by the Portuguese in 1587. The period from 1600 to 1818 has been characterised by maritime rivalries. These were caused by European powers that wanted to strengthen the position of their colonies. Other ports were founded in the region. The arrival of the British initialised Singapore's rise as a colonial port city from 1819 to 1945. Singapore was re-established as an important trading port. This period had been shaped by excessive economic and population growth. The British supremacy was interrupted from 1942 to 1945 when the Japanese occupied Singapore. With the end of World War II, Singapore was given back to the British. Rising disbelief in the ability of the British Empire to protect Singapore forced the movements towards an independent state. Singapore became fully internal self-governed in 1959. In 1963, it merged with Malaya owing to assumed benefits for the economy and long term political stability. This alliance had lasted only for a short period caused by several political, social, and ethnic tensions. Singapore demerged with Malaysia in mutual agreement and became the Republic of Singapore in 1965. Since then, economic development was determined by high governmental interventions and setting up a business-friendly environment to attract external trade and investments. By ensuring that Singapore emerged as a multi-hub in the transport, manufacturing, and services sector, policies strongly supported Singapore's development to a global hub city. (Singapore NLB 2015; Commonwealth Secretariat 2014)

Recent developments of Singapore's society and economy are visualised in Figure 3-4 and explained in detail in the following paragraphs.

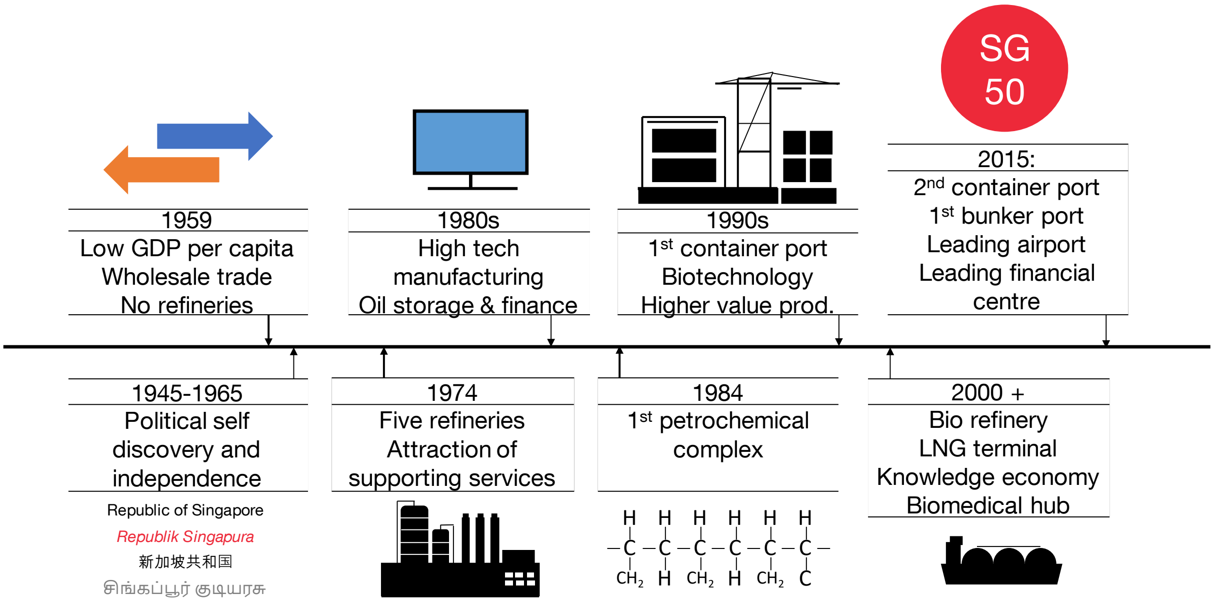


Figure 3-4: Overview of Singapore's recent developments

In the first two decades, economic development was based on oil refining and on manufacturing of electronic products (Singapore EDB 2015b; Commonwealth Secretariat 2014). In 1959, when Singapore became a self-ruled country, there were no refineries in Singapore. Commerce contributed most to Singapore's GDP of 320 USD/capita (Singapore EDB 2015b). Singapore was highly dependent on wholesale trade, while the manufacturing sector contributed only by 11% to Singapore's GDP (Singapore MTI 2015). In the next two decades, the economy was transformed from import substitution to export oriented (Singapore MTI 2015). Attracting major oil refineries affected also maritime trade. In 1972, 80% of cargos handled were petroleum related goods. Consequently, also supporting services, such as trading, shipping, engineering services, fuel storage and distribution, and finance and banking, were attracted (Ng 2012). In 1974, there were five refineries in Singapore with an output of one million barrel per day. In parallel with the refining business, Singapore developed a marine and offshore support centre. In 1974, Singapore became world leader in building jack-up rigs for the extraction of oil and gas. (Ng 2012)

In the 1980's, the economy had been further diversified by switching to production of high-tech products such as integrated circuits, computer parts, and disc drives (Singapore EDB 2015b). Singapore started to establish a 'Total Business Centre' and attracted service institutions and companies from finance, insurances, medicine, education, lifestyle, software, and IT (Singapore EDB 2015b). In 1984, the Southeast Asia's first petrochemical complex opened after 14 years of planning and development (Ng 2012). Singapore's port became the world's busiest port by shipping tonnage in 1982 and with more than 5 million TEUs the world's busiest container port in 1990 (PSA International Pte Ltd 2015). Port and airport have not only shaped the growth towards a leading transport hub, but also attracted companies from the marine and aviation sector. Shipyard operations, vessel design and engineering, and marine equipment and services have been performed in Singapore (Singapore EDB 2015a). Owing to the oil crises in the 1970's, oil storage, oil trade, and trade finance showed rapid growth in the following decades. Prior oil storage was mainly used for transhipment as part of the distribution system. The first independent oil terminal was built in 1983 and set the starting point for another prospering business in Singapore. Besides transhipment and bulk breaking operations, fuel blending became an important part of storage operations and boosted trade with petroleum products. In addition to transhipment trade, arbitrage trade became interesting. Growth in oil finance took account of the changes in global oil supply, as the seven oil majors were losing their dominance towards a larger number of independent market participants. Importance of the established structured financing had been declining while demand transactional financing had been growing. These developments strengthened Singapore's financial sector. (Ng 2012)

In the 1990's, the industry was transforming in order to produce higher value products (Singapore EDB 2015b). Jurong Island was created to host an integrated oil – petrochemical – chemical hub and increase efficiency of these industries (Ng 2012). A second petrochemical complex was built and more foreign investment was attracted in the petrochemical sector (Ng 2012). Biotechnology sciences were supported to diversify products and increase business opportunities. (Singapore EDB 2015b)

The petrochemical sector was further developed by opening two petrochemical complexes in the 2000's (Ng 2012). In the second half of the decade new policies were brought into place to increase R&D spending significantly from 2.25% to 3% (Singapore EDB 2015b). Additional efforts are taken to transform Singapore into a knowledge based economy. Further milestones were achieved in the 2010's with the opening of Jurong Aromatics Corp (JAC), further investments in Jurong Island, and the petrochemical sector (Ng 2012). Singapore's first LNG Terminal opened in 2013. A second LNG Terminal is planned at the east side of Singapore to supply gas consumers and increase energy security (Singapore EMA 2014). One of the largest renewable fuel production plants opened in 2010 (Ng 2012). An increase in production capacity is planned for 2015 (Neste Oil 2014). Starting with trade finance in its early years, government lead incentives, tax rates, and economic development in the Asian region established Singapore as the leading financial and wealth management centre in Southeast Asia today (Long & Tan 2010).

To prepare for future developments Singapore has been attracting companies in relatively new fields of economic activity such as biomedical manufacturing and services, clean energy technologies, and environment expertise. Extensive R&D programs support these developments. (Singapore EDB 2015a; Singapore EDB 2015b; Singapore MTI 2015)

3.2.3 Political objectives and future developments

Singapore introduced several measures to speed up sustainable developments. In 2010, the National Climate Change Secretariat (NCCS) was founded to coordinate international climate change developments and national actions and commitments (Singapore NCCS 2012). Four major fields of action are identified (Singapore NCCS 2012): reduction of carbon emissions in all sectors, adaption to climate change effects, support climate friendly technologies and solutions, and participation in international partnerships as well as increasing awareness of own population. In 2015, Singapore published in its intended nationally determined contribution (INDC) that it aims to increase energy efficiency by 36% compared to 2005 levels and let carbon emissions peak at around 65 Mt till 2030 (Singapore 2015).

However, there are future developments that will shape future economic activity and energy demand.

Ministry of National Development expects a population growth till 2030 in a range from 6.5 to 6.9 million people. The island size is forecasted to grow to 766 km^2. Land area for ports and airports is forecasted to double compared to 2010. Accordingly, size of household, retail, office area, and other buildings will increase. Within the extension of public transport, rail networks will be doubled. The importance of the high-end manufacturing, financial and business hub is emphasised in order to establish good jobs. New urban centres are developed to decentralise Singapore's Central Business District (CBD) focused structure and enable shorter commute distances for workers. (Singapore MND 2013)

In order to prepare for a future increase of world trade, Singapore extends its port. In 2014, 34 million TEU were handled (Singapore DOS 2015). The completion of Pasir Padang Terminal will increase Singapore's container capacity to 50 million TEU/a. A long term plan is to consolidate all container operations at new terminals in Tuas with a capacity of 65 million TEU/a. (Singapore MPA 2013)

In order to shape Singapore's future as an aviation hub and secure its leading position in Southeast Asia, the inter-agency Changi 2036 Steering Committee was established in 2012 consisting of eight government agencies and Changi Airport Group (CAG) (Singapore MT 2013). The panel expects annual growth rate of passenger traffic by 5% until the end of 2020 and 4% between 2020 and 2030 (Nkomo 2013). An extension of Changi Airport's handling capacity to 135 million passengers per annum till mid-2020 is planned. This corresponds with a doubling of today's capacity. Central parts of these developments are a new Terminal (T5) with a handling capacity of more than 50 million passengers p.a. and an extension of the two into a three runway system (Singapore MT 2013). In order to attract passengers to use Changi airport as their preferred transit hub, special emphasis is set on lifestyle projects, shopping experience and convenient procedures. (CAG 2015)

Owing to limited land area future potential of additional bunker storage in Singapore is very limited. There are many oil storage projects in the immediate surroundings of Singapore (Platts 2014).

3.3 Energy and emissions in Singapore

3.3.1 Energy flows

Before energy consumption in Singapore can be analysed, data about energy flows have to be collected from different energy statistics and other publications.

The economic activity in Singapore causes high energy demand per capita and unit of land area. This demand is met by energy supply. Indigenous production and energy imports can be distinguished at the supply side.

Owing to its small land area, high population density, and scarcity of energy resources, Singapore's indigenous energy production is very low. So is its renewable energy potential. In 2014, 25 MW_{ac} of solar PV were installed in Singapore (Singapore EMA 2015). The Ministry of Environment and Water Resources (MEWR) publishes a value of 1.3 MWh (4.5 PJ) electricity generated from waste incineration in 2013 (Singapore MEWR 2014). Most indigenous energy is produced of waste.

Singapore Energy Statistics 2015 reports a value of 621.2 ktoe (26 PJ) for energy production in 2012 from other sources than petroleum products, natural gas, and coal. This value includes electricity production from solar, municipal waste, and biomass (Singapore EMA 2015). According to data of IEA for 2012 indigenous energy production was 603 ktoe (25 PJ) (IEA 2015a). US EIA sets this value to 0.006 PBtu (6 PJ) for total primary energy production (U.S. EIA 2016). Differences in statistics may occur owing to different methodologies. Causes are highlighted in Chapter 3.1 and are discussed in more detail by R. Newell and Y. Qian (Newell & Qian 2015).

In order to supply its energy demand Singapore is dependent on energy imports. Energy flows in and out of Singapore are assessed on basis of data from IE Singapore for 2014 (IE Singapore 2015). Flows are categorised with regards to ‘Singapore Energy Statistics 2015’, which will later be used as basis for own calculations of energy flows.

In 2014, 39 million tonnes of crude oil imports arrived predominantly from the Middle East (over 80%). More specific data are visualised in Figure 3-5. 5 million tonnes of condensates of crude petroleum oils were imported in relatively equal shares mainly from Australia (48%) and Qatar (46%). Together with natural gas liquids, refinery feedstocks, additives, and other hydrocarbons these amounts are accounted to crude in Singapore Energy Statistics 2015. (IE Singapore 2015; Singapore EMA 2015)

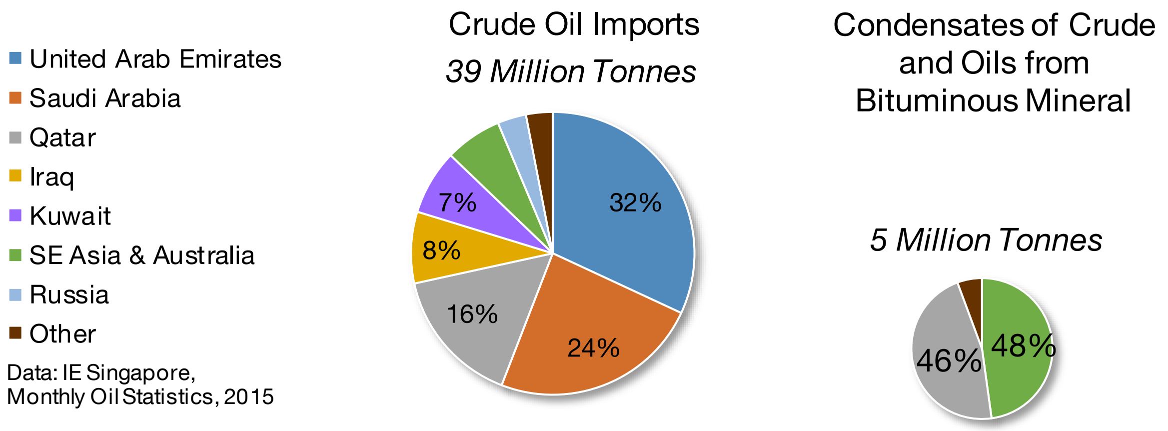
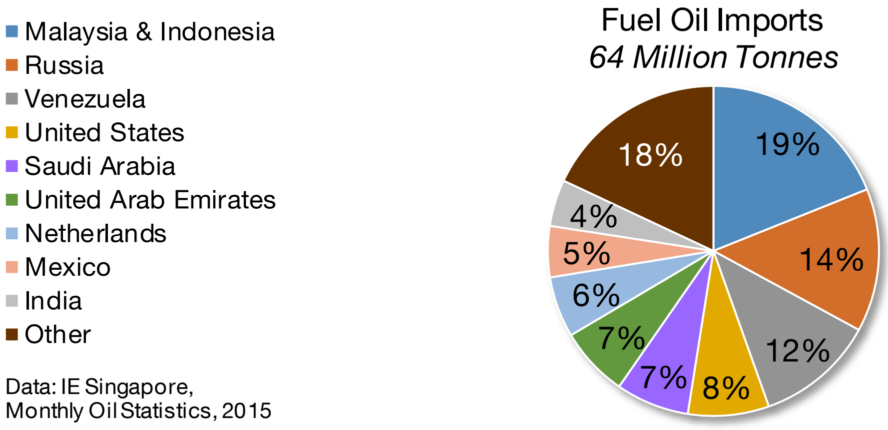


Figure 3-5: Crude oil imports to Singapore by country of origin in 2014

Imports of petroleum products were much more diversified. As visualised in Figure 3-6, 64 million tonnes of fuel oil were imported from Malaysia and Indonesia (19%), Russia (14%), Venezuela (12%), USA (8%), Saudi Arabia (7%), UAE (7%), Netherlands (6%), Mexico (5%), India (4%), and others countries (18%). (IE Singapore 2015)

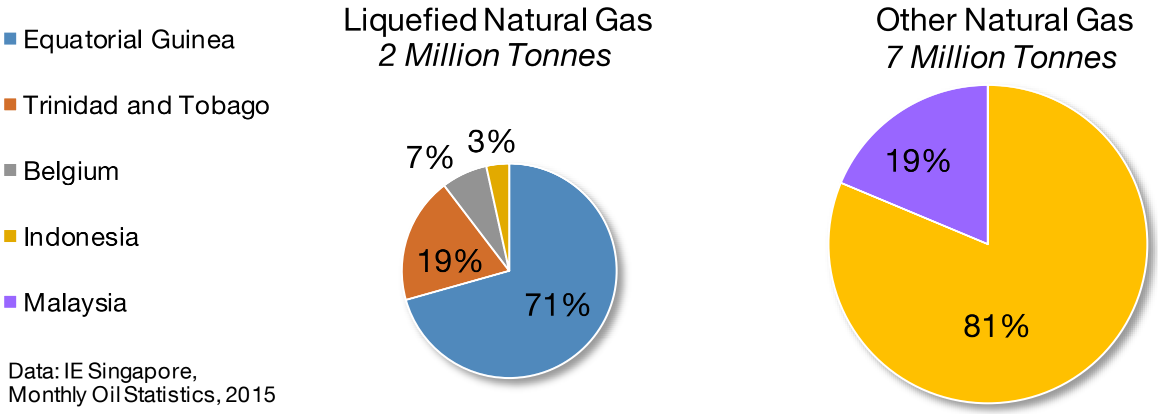


Data: IE Singapore, Monthly Oil Statistics, 2015

Figure 3-6: Fuel oil imports to Singapore by country of origin in 2014

Energy imports of other types of petroleum products were comparably smaller. 12 million tonnes of gasoline (Research octane number (RON) between 90 & under 97) were imported mainly from China (29%), Korea (20%), Taiwan (19%), and India (17%). Other types of motor spirits had only a minor share in gasoline imports. 14 million tonnes of automotive diesel fuels were mainly imported from Korea (40%), Malaysia (17%), Japan (9%), Taiwan (7%), and India (7%). 8 million tonnes of naphtha were mainly imported from the Middle East (47%), Malaysia (14%), and Thailand (10%). Further petroleum products with minor shares are included in Singapore Energy Statistics 2015. (IE Singapore 2015; Singapore EMA 2015)

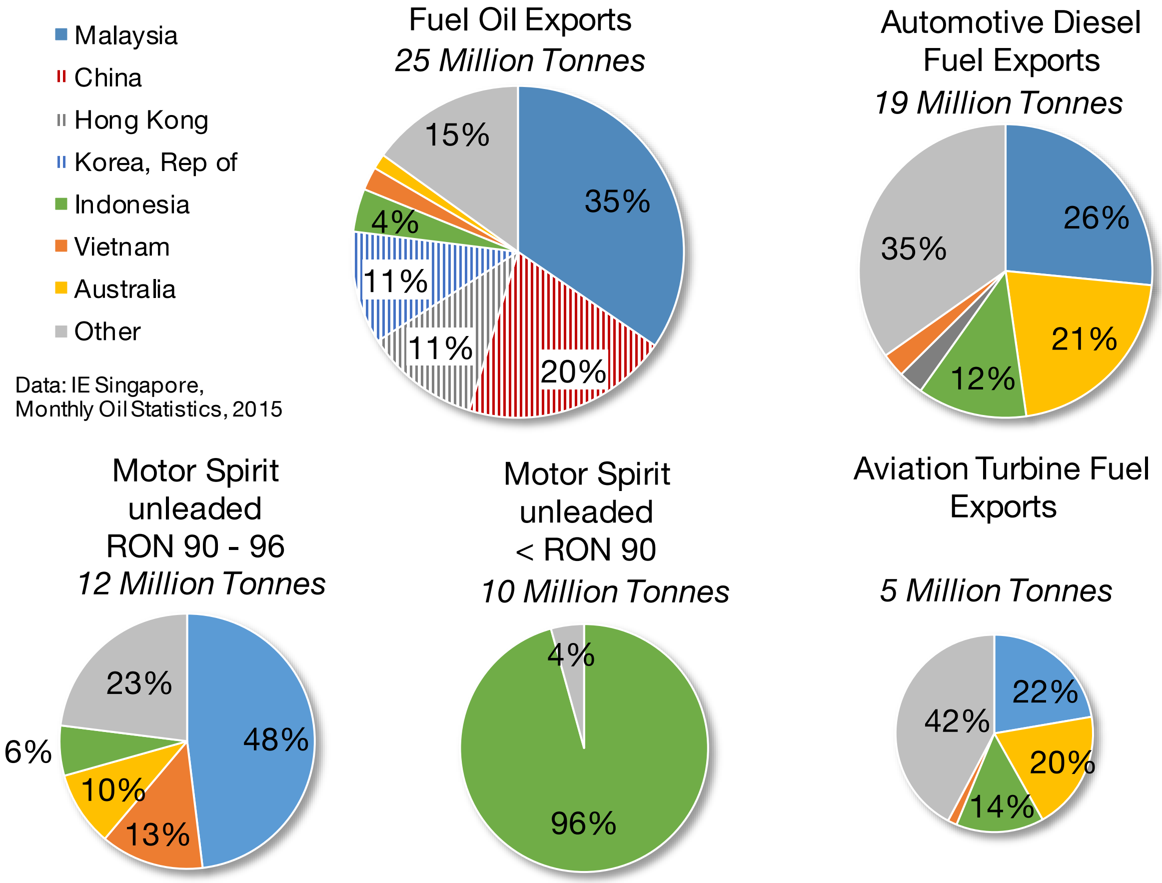
As visualised in Figure 3-7, nearly 2 million tonnes of liquefied natural gas were imported to Singapore in 2014. Countries of origin were Equatorial Guinea (71%), Trinidad and Tobago (19%), Belgium (7%), and Indonesia (3%). Other natural gas imports of 7 million tonnes were supplied by Indonesia (81%) and Malaysia (19%) via pipelines. (IE Singapore 2015)



Data: IE Singapore, Monthly Oil Statistics, 2015

Figure 3-7: LNG and natural gas imports by country of origin in 2014

But Singapore is not only a big importer of energy products. It is also a leading exporter and supplier of other Asian countries. Singapore Energy Statistics 2015 reports 3,608 PJ of energy exports in 2014. These consisted of 3,580 PJ petroleum products, 28 PJ of crude oil and marginal amounts of coal and peat. Domestic exports and re-exports can be distinguished. Most of Singapore's exports were domestic exports. Petroleum products exports can be further divided up into exports of fuel oil (1034 PJ, 97% domestic), gas and diesel oil (950 PJ, 65% domestic), gasoline (1057 PJ, 83% domestic), jet fuel (211 PJ, 78% domestic), naphtha (18 PJ, 96% domestic), and other petroleum products (310 PJ, 93% domestic). Countries of destination by the largest export commodities are visualised in Figure 3-8, which emphasises that besides the major fuel oil importers China, Hong Kong, and Korea, especially Malaysia, Indonesia, Vietnam, and Australia are important markets for Singapore's oil products. (Singapore EMA 2015; IE Singapore 2015)



Fuel Oil Exports
25 Million Tonnes

Automotive Diesel Fuel Exports
19 Million Tonnes

Data: IE Singapore, Monthly Oil Statistics, 2015

Motor Spirit unleaded RON 90 - 96
12 Million Tonnes

Motor Spirit unleaded < RON 90
10 Million Tonnes

Aviation Turbine Fuel Exports
5 Million Tonnes

Figure 3-8: Selected exports of products by country of destination in 2014

25 million tonnes of fuel oil were exported to mainly Asian countries: 35% to Malaysia, 20% to China, 11% to Hong Kong, 11% to Korea, 4% to Indonesia, 2% to Vietnam, 1% to Australia, and 15% to other countries. While Malaysia, Australia, and Indonesia

accounted for 60% of automotive diesel oil exports, the remaining share was evenly distributed to many countries. Singapore exported over 9 million tonnes of motor spirits RON 90 unleaded to Indonesia. 12 million tonnes of motor sprits RON 90-96 unleaded were mainly distributed to Malaysia (48%), Vietnam (13%), Australia (10%), and Indonesia (6%). Nearly 5 million tonnes of aviation fuels were exported to Malaysia (22%), Australia (20%), and Indonesia (14%). (IE Singapore 2015)

Storage of energy products decouples energy demand and energy supply. Singapore Energy Statistics 2015 reports storage changes of oil products for crude oil and natural gas liquids and for petroleum products (light distillates, middle distillates, and heavy distillates and residuum). In the period from 2010 to 2013, absolute storage changes were less than 38 PJ. However, grouping of multiple energy products might mask more significant changes in the case that products within the same group show opposing trends. (Singapore EMA 2015)

3.3.2 Energy balance

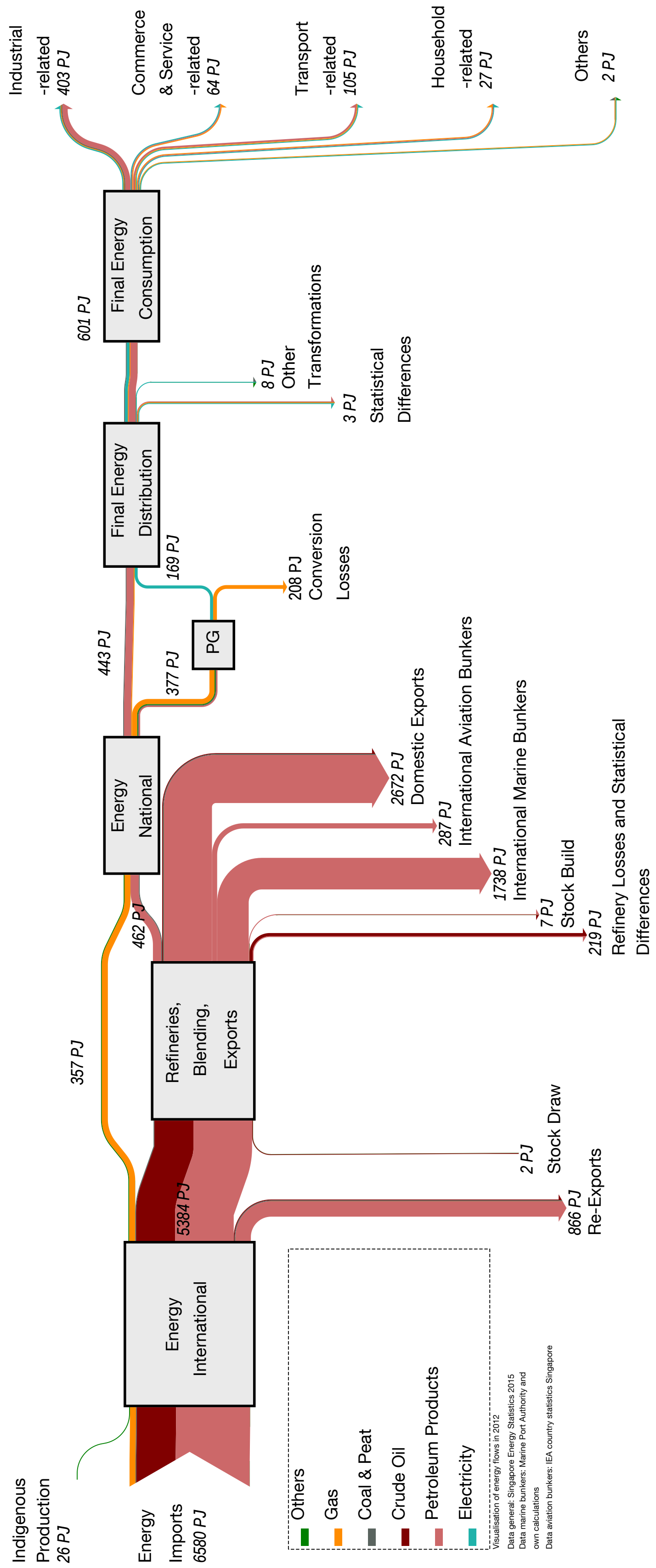
Above described energy flows show imports and exports of energy carriers to and out of Singapore. In the next step energy flows into and within Singapore are analysed in detail for the year 2012. Wherever possible, data of Singapore's official energy statistics (Singapore Energy Statistics 2015) is used and complemented by data from the Maritime Port Authority for marine bunker fuels and data from IEA for international aviation fuels (Singapore EMA 2015; Singapore MPA 2014; IEA 2015a). In divergence to Singapore Energy Statistics 2015, energy amounts of natural gas are reported based on the lower heating value in coherence with other energy carriers.

In order to analyse Singapore's energy system several sub categories were defined:

- *Energy international*, comprises all energy carriers that are imported and produced in Singapore indigenously.
- *Refining, Blending, Exports*, is required to restructure Singapore's crude oil, petroleum, and coal flows in order to divide their further energy use. This category is necessary in order to distinguish between energy that is imported as refinery input, for exports, bunkering, stock draw and build, and energy that is finally consumed within Singapore.
- *Energy national*, summarises all energy carriers that are consumed inside of Singapore.
- *Power generation (PG)*, comprises energy inputs into the power sector that are transformed into electricity. A certain amount of energy is lost during transformation.

- *Energy distribution*, combines outputs of power generation together with other quantities of energy such as gas and oil that are consumed within Singapore.
- *Energy consumption*, summarises all end use sectors and is equal to energy distribution reduced by statistical differences and other transformations such as power plant own use and losses. In line with Singapore Energy Statistics 2015, industrial -, commerce and services -, transport -, household -, and other -, related energy consumption is distinguished.

Energy flows, visualised by this structure, are shown in Figure 3-9.



Visualisation of energy flows in 2012

Data general: Singapore Energy Statistics 2015
Data marine bunkers: Marine Port Authority and own calculations
Data aviation bunkers: IEA country statistics Singapore

Figure 3-9: Energy balance of Singapore in 2012

Energy imports consisting of mainly petroleum products, crude oil, and gas with a total amount of 6,580 PJ are far higher than indigenous energy production, which adds up to 26 PJ and includes waste incineration, biomass, and PV. These numbers reflect the physically available energy in Singapore.

Energy products of the amount of 866 PJ, mainly comprising oil products, are re-exported. While natural gas imports of 331 PJ are used in Singapore locally, oil has to be further split up. Crude oil is mainly consumed in the refinery sector and used for petroleum products production. 20 PJ of crude oil are exported. The largest share with 2,652 PJ of petroleum products is exported, 287 PJ are used for international marine aviation bunkers, and 1,738 PJ are used for international marine bunkers. Owing to statistical differences between refinery inputs and crude oil imports, an amount of 85 PJ cannot be further assigned. This amount is summed up in the category 'refinery losses and statistical differences' together with refinery losses of 89 PJ and further statistical differences of 45 PJ arising from use of different data sources for marine and aviation bunkers. For both, petroleum products and crude oil products, minor changes occur owing to stock builds and stock draws.

Singapore's national energy use of 819 PJ consists of 461 PJ of petroleum products, 331 PJ of natural gas, 26 PJ of others and 1 PJ of coal and peat. 377 PJ based on 283 PJ of natural gas, 68 PJ of petroleum products and 26 PJ of other feedstock including waste, biomass, and PV are used for power generation. Electricity production accounts for 169 PJ. 208 PJ are lost in energy conversion to electricity. Electricity supply totals to 159 PJ. The gap between distribution and supply results from own use in power generation, losses, and statistical differences.

The industry sector uses most of Singapore's final energy with 403 PJ. More than two third is supplied by petroleum products. But the industry is also Singapore's largest consumer of electricity with a consumption of 67 PJ and gas with a consumption of 41 PJ. Further 1 PJ of coal and peat is consumed in the industry.

The energy consumption of the commerce & services sector is 64 PJ. With 58 PJ, electricity supplies the largest share of this amount. Gas and petroleum products contribute with 3 PJ each.

105 PJ of energy consumption within the transport sector splits up into 96 PJ petroleum products, 1 PJ natural gas, and 9 PJ electricity.

Consumption of household only amounts 27 PJ and is the smallest sector of energy consumption. Electricity with 24 PJ supplies most of this energy. Minor shares are supplied by gas (2 PJ) and petroleum products (1 PJ).

Remaining energy consumption of 2 PJ electricity and marginal shares of gas is allocated to the sector others.

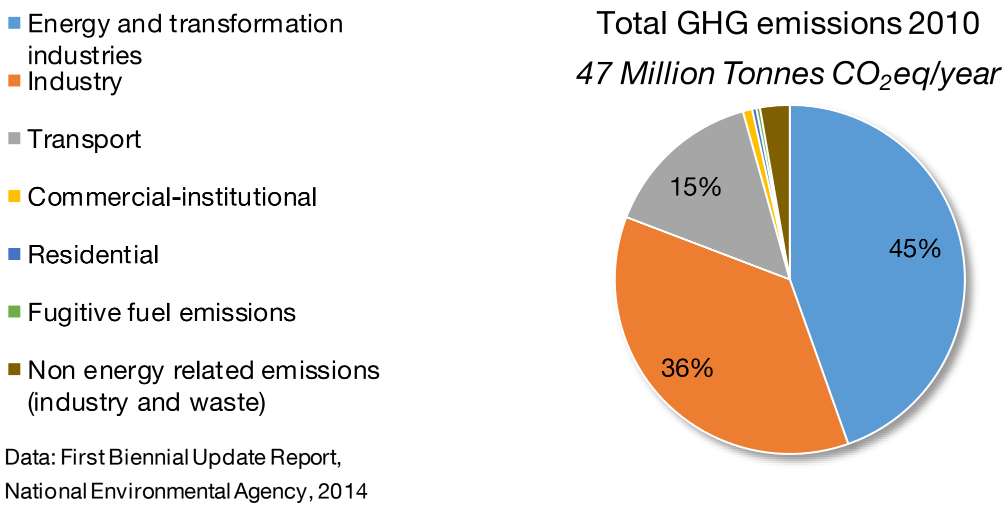
Detailed analyses of energy flows within Singapore were done by M. Wagner and K. Schönsteiner on basis of an energy model of Singapore (Wagner et al. 2012; Wagner et al. 2014). Within these studies local energy consumption for industry, commerce & services, transport, and households is analysed and forecasted in different scenarios. Interactions with different power generation mixes are discussed. Special focus is set on the transport sector and the investigation of feasibility and effect of electric vehicles in Singapore. Investigation shows that the impact of the transport sector is limited, compared to the total final energy consumption in Singapore.

Based on the energy balance, two general characteristics of Singapore's energy system are derived. First, most of the 6.6 EJ of energy supply is not used within the country's borders, but exported to mainly Asian countries (3.5 EJ) or used as bunker fuels (2.0 EJ). Only 0.8 EJ are used in Singapore itself. Second, Singapore is heavily dependent on energy imports.

High amounts of energy exports reflect Singapore's business model as a transshipment and refining hub. Petroleum products are transported to Singapore in large ships from far distances, unloaded to smaller ships and distributed to other countries. Crude oil is refined in Singapore. Products are used to supply especially Asian countries. Situated at the world's busiest shipping route, Singapore is an ideal spot for bunker sales. Supply of international aviation fuels and international marine fuels contribute significantly to Singapore's energy demand. While energy content of traded products does not necessarily increase local energy consumption, bunker fuels are supplied in Singapore and increase consumption of energy carriers. This additional energy demand more than triples total energy consumption in Singapore and makes a sustainable energy supply of Singapore more difficult. Future structural and technological developments are discussed in Chapter 4 to assess possibilities to mitigate effects of international transport on Singapore's energy system.

3.3.3 GHG emissions

GHG emissions are an essential indicator for ecologic efficiency of an economy and strongly related to energy consumption. In its INDC, Singapore defines its binding emissions value for GHG emissions to 40.9 million tonnes CO_2eq, which was calculated for 2005 (Singapore 2015; Singapore NEA 2014). In 2010, the overall GHG emissions reached 47 million tonnes CO_2eq (Singapore NEA 2014). Figure 3-10 splits this amount into different subsectors.



Data: First Biennial Update Report, National Environmental Agency, 2014

Figure 3-10: National GHG emissions in Singapore by sector

Most of Singapore's national GHG emissions in 2010 were caused by energy and transformation industries (20.9 million tonnes CO_2eq). Industry consumed 42% of total electricity generated, followed by commerce & Service-related (36%), households (16%), transport-related (5%), and other sectors (1%).

17.0 million tonnes CO_2eq emissions are emitted directly in the industrial sector and were mainly caused by CO_2 emissions. The refinery and petrochemical sector contributed with over 52% to CO_2 emissions by the combustion of primary fuels. Other sources of CO_2 emissions were combustion of other fuels such as natural gas (16%), fuel oil (20%), diesel (10%), liquefied petroleum gas (0.5%), and gas works gas (0.1%).

Emissions of 7.0 million tonnes CO_2eq were emitted in the transport sector. Carbon dioxide emissions caused 6.7 million tons of these emissions. The combustion of diesel (54%), petrol (35%), and CNG (1%) in land transport caused 90% of CO_2 emissions. Remaining 10% of transport CO_2 emissions resulted from burning ship fuels used in the harbour and by pleasure crafts.

Direct emissions in the residential (0.2 million tonnes CO_2eq) and commercial sector (0.4 million tonnes CO_2eq) were mainly caused by use of LPG and Gas Works Gas for cooking and hot water. Further emissions of 0.2 million tonnes of CO_2eq resulted from fugitive fuel emissions. GHG emissions from industrial processes (1.1 million tonnes

CO_2eq) arose mainly from PFCs, SF_6, and HFCs. Wastewater-handling generated GHG emissions of around 0.2 million tonnes CO_2eq caused by CH_4 and N_2O. IEA reports 48.4 million tonnes CO_2 for 2010 and 49.8 million tonnes CO_2 for 2012 including only emissions from fuel combustion within Singapore (IEA 2015a). Other statistics including international marine and aviation bunkers report significantly higher values. EIA publishes values of 191 million tonnes CO_2 for 2010 and 208 million tonnes CO_2 for 2012 resulting from energy consumption (U.S. EIA 2016). BP calculates carbon dioxide emissions of 206 million tonnes for 2010 and 226 million tonnes for 2014 (BP plc 2015b).

4 Transport: Trends and technologies

Bunker fuels for ships and airplanes in transport hubs are identified as major consumers of energy locally and sources of GHG emissions globally. Chapter 4 summarises future trends in international transport. Caused by demographic and economic developments, there will be fast increasing transport requirements in the next decades. Advances in conventional technology, design, and operation procedures will not be sufficient to keep energy demand and GHG emissions at current levels. A switch in fuel technology from fossil fuels to low carbon fuels is the only option to decrease ship and airplane emissions in the long term.

In Chapter 4.1 different reports and outlooks are analysed that investigate the past and future development of marine transport. Forced by demographic and economic growth, there will be a strong increase in transport demand and consequently associated energy demand and air emissions. The impact of advanced technologies is expected to be limited. In Chapter 4.2 marine transport technologies are investigated in more detail. Current technologies, their optimisation potential, measures to reduce emissions and meet environmental goals are discussed together with improvements in operational procedures. Current technologies are highly efficient and relatively mature. They offer only small potential for further improvements. To further dampen the growth of emissions caused by increasing transport demand, alternative fuels are required. LNG is identified as the most promising alternative fuel. Advantages and disadvantages of conventional and promising alternative fuels for marine transport are summarised and introduced for further analysis in Chapter 5. Chapter 4.3 gives an overview over past developments and the current status of the aviation industries. Forecasts show that rapid growth in the aviation sector will continue. Especially fast growth of the aviation sector is expected in Asia. Environmental aims of the industry and international organisations for the airline industry are presented. In order to reach these goals, technological improvements and operational and infrastructure measures are required. Alternative fuels and Market Based Measures (MBM) have to contribute significantly in order to reach the targeted reduction of 50% of GHG emissions compared to 2005 levels. In Chapter 4.4, possible measures are summarised and assessed. Although technological, operational, and infrastructure improvements offer great potential for fuel savings, alternative fuels are required. Biofuels are identified as the most promising alternative fuels for future aviation. Hydrogen offers great potential, but will require extensive technical adjustments and new aircraft designs.

4.1 Marine trends and environmental targets

4.1.1 Current status and past developments

The International Maritime Organization (IMO) publishes a comprehensive outlook of current and future energy demand and emissions of marine transport. In 2012, 972 million tonnes of CO_2eq were emitted. 816 million tonnes of CO_2eq emissions were caused by international shipping, around 2.1% of global GHG emissions. Fuel consumption between 2007 and 2012 ranged from 250 to 325 million tonnes, of which 200 to 270 million tonnes were used for international shipping. (IMO 2014)

The Review of Maritime Transport 2014 offers a good impression of the past and current structure of seaborne trade. Figure 4-1 describes past development of world seaborne trade by type of cargo loaded on ships annually (UNCTAD 2014).

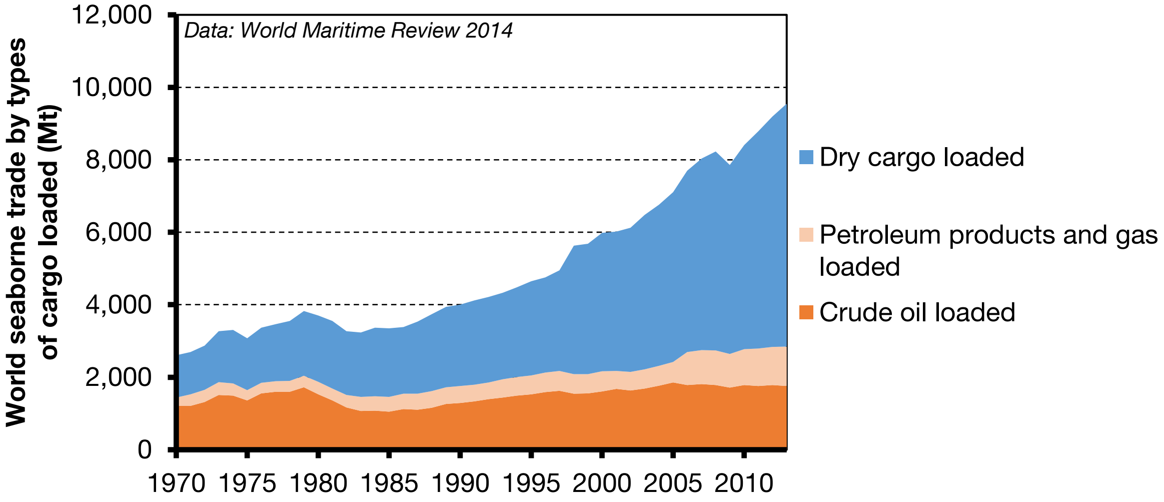


Figure 4-1: World seaborne trade by types of cargo loaded

Since the 1970's the share of crude oil in seaborne trade has been declining. The most recent decline is explainable with less crude imports into the US owing to unconventional fossil energy extraction (UNCTAD 2014). Trade of petroleum products became more important, as new refinery capacities are often export oriented, situated near to supply sources, and more distant to final consumers (Blas 2015). Share of dry cargo loaded was growing from 47% in 1970 to more than 70% in 2013. The five major bulks (iron ore, coal, grain, bauxite and alumina, and phosphate rock) contributed 42% to total volume of dry cargo in 2013 (UNCTAD 2014). During this period crude oil trade was growing by a factor of 1.4, while trade of petroleum products and dry cargo increased by factors of 4.7 and 5.8. Effects of the oil price crises in 1973 and 1979 affected especially trade of crude oil in the next years, while the world financial crisis in 2009 resulted especially in a reduction of dry cargo trades. Figure 4-2 visualises the total capacity of the merchant fleet by type from 1980 to 2015.

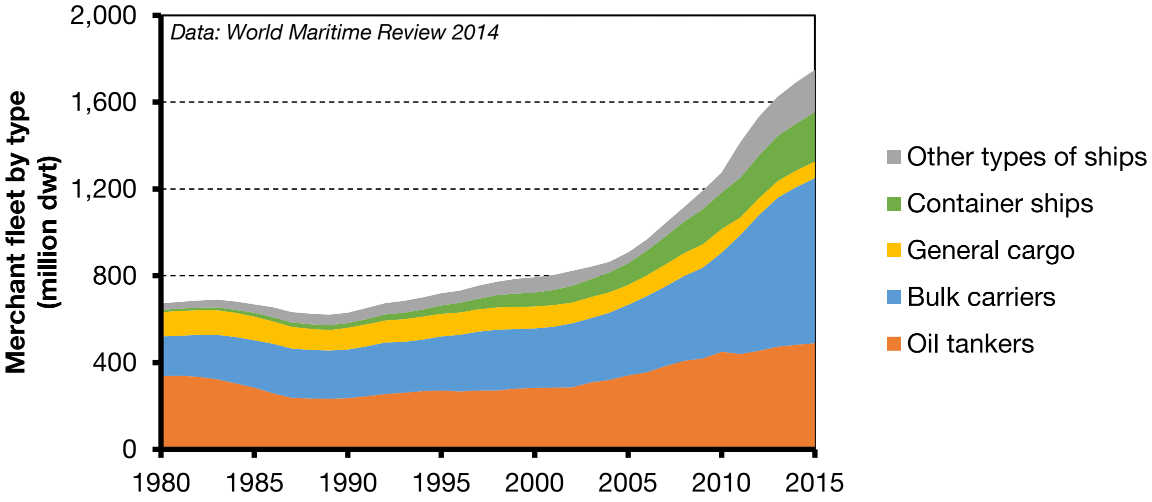


Figure 4-2: Merchant fleet by type

While the total merchant fleet was growing relatively slow compared to seaborne trade in the last two decades of the 20th century, growth accelerated significantly since 2000. Total merchant fleet capacity more than doubled in the last 15 years. Capacity of the container fleet was growing by a factor of 3.6, bulk carriers by 2.8, others by 2.7 and tankers by 1.7. Only the general cargo capacity declined by 24%. While container trade contributed by 1/6 to the amount (tonnes) of goods traded, it contributed by 50% to the value of goods traded (UNCTAD 2014).

4.1.2 Outlook

Outlooks for future seaborne trade predict a significant increase in transport demand, fuel consumption, and emissions in the next decades. The outcomes of three major studies are presented in order to show future trends in maritime transport.

The International Maritime Organization (IMO) gives an outlook till 2050. In different scenarios, GHG emissions are expected to rise between 50% and 250%. While efficiency improvements dampen the effect of more trade activity, effects of alternative fuels are limited owing to the enduring dominance of conventional fuels (IMO 2014).

I. Fang et al. forecast future expansions of marine transport and develop different scenarios, which are characterised by different levels of globalisation or localisation (Fang et al. 2013). Following issues are identified as main drivers and taken into account:

- Demography (population growth to 8 billion people in 2030, ageing population, continuing urbanisation)
- Economy (doubling or tripling of world GDP, growing importance of emerging economies, increasing purchasing power and middle class, doubling of intra-regional trade, more than doubling of seaborne trade, growing importance of cities)
- Resources (40% higher world energy demand with especially high growth in emerging economies, environmental challenges)

Expectations are summarised as follows: Crude oil trade will increase significantly especially on trade routes between the Middle East, China, South Asia, and Southeast Asia. Product oil trade will become more important, especially for Southeast Asia and other Asian countries. While LNG exports are dominated by Qatar today, Australia will become the largest LNG exporter in the future and lead to a reorganisation of trade routes. The overall LNG trade will at least double its volume till 2030. There will be much more coal, iron ore, grain, and containerised trade. Southeast Asia will continue to carry out most container tranship loaded lifts operations. Container trade between the Middle East and Far East is expected to have the strongest growth. In order to supply future transport demands, the merchant fleet has to grow. While the capacity of the tanker fleet is forecasted to increase by factors of 1.7–1.8, bulk capacity, container capacity, and LNG capacity is forecasted to grow by factors of 1.8–3. Especially capacity of large container ships (<7600 TEU) will increase by a factor of 6–6.5. (Fang et al. 2013)

Based on the publication of I. Fang et al. (Fang et al. 2013), Lloyd's Register investigates fuel use and carbon emissions on basis of the developed scenarios (LR 2014a). Fuel demand will double in all scenarios till 2030. Carbon emissions of shipping will significantly increase till 2030. Developments range from around 50% to nearly 100% and are heavily dependent on scenario. Conventional fuels will still dominate the fuel mix. Share of heavy fuel oil (HFO) will decline from over 80% to 47%–66% depending on scenario. Marine gas oil (MGO), low sulphur fuel oil (LSFO), liquefied natural gas (LNG), and alternative fuels, such as biofuels and hydrogen, will become more important for the global marine fuel mix. As 16 years are a relatively short period in a ship's life time, only slow changes are expected. Ship speed will decrease in all scenarios. Upstream emissions, which are of special importance for alternative marine fuels, are not included in this study. (LR 2014a)

4.1.3 Environmental goals

Besides increasing demand and emissions caused by additional transport demand, environmental standards will have an impact on future ship design, ship operation, and fuel use. Shipping is the most efficient mode of goods transport from an energy and economic point of view. However, the aim to minimise costs results in the application of the cheapest available fuels that make marine transport a major contributor to air pollution, especially in large ports and at highly frequented shipping lanes. The International Maritime Organization (IMO) formulated regulations to improve the environmental impact of marine transport.

In 1973, the International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted and has been further updated since then. MARPOL and its annexes provide rules, standards, and procedures to avoid water pollution with chemical substances or oil, to handle pollution incidents, to transport hazardous goods, to deal with waste and waste water, to reduce air pollution, and to increase the efficiency of ships. MARPOL has had significant impact on ship design and operations. (IMO 2011)

Especially regulations related to air pollution have the potential to change fuel use and applied technologies in the next years. Current regulations take emissions of SO_x, particulate matter and NO_x into account. Table 4-1 summarises environmental targets of the IMO.

Table 4-1: Emission reduction goals defined by IMO

year	Outside ECAs		Inside ECAs	
	NO_x	SO_x	NO_x	SO_x
2010	Tier I	4.5%	Tier I	1.0%
2011	Tier II		Tier II	
2012		3.5%		
2013				
2014				
2015				0.1%
2016			Tier III	
2017				
2018				
2019				
2020		0.5% or 3.5%		
:				
2025		0.5%		

From 1 January 2012 sulphur content of fuel oil is limited to 3.50% and reduced to 0.50% from 1 January 2020 (fuel availability could extend the 3.50% period to 1st January 2025 (IMO 2015b)). In defined Emission Control Areas (ECAs) even lower sulphur fuels are required. From 1 January 2015 only 0.1% sulphur content are allowed for fuels used in the ECAs (IMO 2015b). NO_x emissions are regulated globally and in certain ECAs. Marine diesel engines installed after 1 January 1990 (Tier I) have to reach a certain level of NO_x emissions depending on engine speed. Tier II limits NO_x emissions for marine diesel engines installed after 1 January 2011 and set 20% lower emission limits than Tier I (U.S. EPA 2010). Even stricter NO_x limits (Tier III) are set for engines installed after 1 January 2016, reducing emission limits to 80% of Tier I in North American ECAs (U.S. EPA 2010; LR 2014b). (IMO 2011; IMO 2015a)

CO_2 is identified as the most important contributor to GHG emissions. An additional chapter in MARPOL was added in July 2011 that defines 'mandatory technical and operational measures to reduce GHG emissions from international shipping'. From 1 January 2013, energy efficiency of new ships should be increased by technical improvements (Energy Efficiency Design Index (EEDI)) and energy consumption of the whole fleet should be reduced by operational practices (Ship Energy Efficiency Management Plan (SEEMP)). New built ships must meet certain efficiency criteria in gCO_2/t.nm related to ship type, size (dwt), and year of construction (Bazari & Longva 2011). This approach leaves the choice of technology and measures to the ship building industry and operators. The SEEMP mandates to document and monitor energy consumption for larger ships. Possible reduction potentials should be planned, implemented, monitored, self-evaluated, and improved. (IMO 2011; MPEC n.d.)

The IMO states that *"technical and operational measures will not be sufficient to satisfactorily reduce the amount of GHG emissions from international shipping in view of the growth projections of human population and world trade"* and suggest additional Market Based Measures (MBM) to accelerate investments in more efficient shipping. (IMO 2011)

Current and possible future ECAs are especially challenging for current marine transport technologies. The North American ECA encompasses an area up to 200 nautical miles from coasts of the United States, Canada, and the French Territories (U.S. EPA 2010). Areas subject to sovereignty or jurisdiction of other countries are excluded from the ECAs (U.S. EPA 2010). The US Caribbean Emission Area sets the same requirements since January 2014 (U.S. EPA 2011). Two more ECAs are established in Europe reducing only SO_x emissions in the Baltic Sea and the North Sea (IMO 2015b). More ECAs are discussed for Mexican coastlines, the Mediterranean

Sea, Norwegian coasts, Japanese coasts, Hong Kong and Guangdong Area, and Singapore (Mohn 2014).

4.2 Marine technology in transport

4.2.1 Technology of marine transport

To show the current status of marine technology a short introduction about technical developments of drive trains in commercial shipping is given. While sail ships had dominated oceans for thousands of years, steam ships had begun to challenge this supremacy in the early 19th century. Coal fired steam engines made these ships independent from wind. While the first steam ships were propelled by paddle wheels, soon propellers became the more efficient solution. Demand for larger ships and higher weights of propulsion technology made iron and steel the preferred choice to build the hull. At the end of the 19th century and the beginning of the 20th century, steam turbines, which were using smaller space, causing less vibrations, and requiring less maintenance, had started to replace steam engines in ships. As the growing power demand of ships required even more man power and fuel storage at a greater extent, oil firing became attractive and began to replace coal firing. In the beginning of the 20th century, diesel engines started to substitute less efficient steam turbines in smaller ships, but till 1970 these were used for very large ships with high requirements for propulsion power. With the first oil crisis in 1973, fuel efficiency and fuel price became important aspects for ship owners. Increasing power of diesel engines, their higher efficiency, power density, and improving ability to run with low quality fuel led to a substitution of steam engines for large ships. (Brennecke 1981; Kemp 2000; Röder 2008; U.S. EPA 2008)

Mainly two types of ship engines are used today:

- *Medium speed 4 stroke diesel engines* are built for small and medium sized ships, trade ships, passenger ships, and military applications. Higher speeds can be reached. (Vergara et al. 2012)
- *Slow speed 2 stroke diesel engines* are built mainly for large container vessels, bulk carriers, and tankers (Vergara et al. 2012).

Ships powered by nuclear reactors were first built in the second half of the 20th century. However, this technology is limited to some special applications such as aircraft carriers, submarines, or ice breakers. (Kamei 2013)

In order to improve energy consumption of international shipping and reach environmental requirements set by policy regulations, three areas are identified: technological advancements and potentials, operational improvements, and alternative fuels and drive trains.

4.2.2 Technological advancements and potentials

Optimisation of the existing technology offers further potentials for fuel and emission reductions. Table 4-2 clusters different technologies into five main areas and shows their potential for fuel savings. It summarises the results of ABS (ABS 2013).

Table 4-2: Potentials of ships to reduce fuel consumption and emissions (ABS 2013)

Area	Technology/Measure	Potential
Resistance	Air lubrication	10%
	Hull design	5-8%
	Fouling control and care	7-9%
	Silicon coating	3-4%
	Hull surface texturing	5-10%
	Higher strength steel	<0.5%
Propulsor	High efficiency propellers	3-10%
	Cleaning/polishing propeller	6%
Engine	Main engine performance measures	1-2%
	Waste heat recovery for propulsion	11%
Drive train	Wake equalising and flow separation sys.	0-5%
	Post swirl devices	2-6%
	Pre swirl devices	2-6%
	Trim/draft optimisation	1-2%
Alternative propulsion	Alternative concepts (sky sales, Flettner rotor)	30%

The smaller the resistance of the ship, the lesser the demand of fuel for propulsion. Multiple measures are possible to reduce the resistance. The resistance between ship and water can be reduced by fouling control and maintenance of hull and propellers, increased skin smoothness (e.g. air lubrication reducing friction, silicon coating, or other surface types), reduced wave resistance by bulbous bows, stern bulbs, lift modes, or advanced hull designs. Resistance could be further decreased by minimising the resistance between ship and air and reduce the weight of the ship by new and lighter materials. (Vergara et al. 2012; ABS 2013)

Highest efficiency of the propulsors is reached with the largest propeller and the slowest rotation, which results in minimum slip and fluid perturbation. However, ship design, physical limits of components, and operational aspects set limits to propeller size. Propellers could be further optimised by boss cap fins, vanes, tip fins, or advanced blade profiles. Further improvements are possible by supercavitating propellers, surface piercing, or ventilated propellers. Complex screw arrangements such as contra rotating propulsion (CRP), hybrid CRP, or free wheels offer potential for fuel savings in combination with certain applications. (Vergara et al. 2012; ABS 2013)

Engines for marine propulsion reach very high efficiencies today. Only small improvements in optimising the combustion process are possible. A reduced engine size could lead to more cargo space and consequently higher efficiencies. However, waste heat recovery and use for additional propulsion or for on-board electricity generation offer large potentials up to 11% to further reduce fuel consumption. (Vergara et al. 2012; ABS 2013)

Overall drive train and tuning of the main components hull, propulsor, main engine, and auxiliary engine could further reduce fuel consumption. Technologies, such as advanced controlled electric transmission, fixed pitch propellers, optimisation of water flows and wake fields, and pre and post swirl devices, have the potential to further improve fuel efficiency. Further electrification of the ship and improvement of components, e.g. pumps, compressors, HVAC, ventilation, lights, insulation, and water production reduce energy demand (Vergara et al. 2012; DNV GL n.d.; ABS 2013)

By reducing propulsion augments, which describe a category of new technologies that support conventional propulsors, propulsion or on-board electricity demand is lowered. Use of wind power is a promising option to reduce fuel consumption. Either wind power could be used by wind turbines, e.g. Darrieus Rotor or Savonious Rotor, to produce electricity for on-board power demand. Fins or flaps could be used to harvest wave energy. Alternatively, wind power could contribute to supply additional propulsion power by sky sales or Flettner Rotors. The effect of solar PV on fuel savings is very limited. (Vergara et al. 2012; ABS 2013)

4.2.3 Operational improvements

Besides improvements of ship technology, operational measures can significantly reduce energy consumption and environmental impact. Operations and processes in ports offer further potential of emission reductions. Communication, precise knowledge about ship movements, and times of arrival and departure depending on e.g. weather, traffic, and delays enable ports to reduce time spent in ports. The use of onshore electricity or decentralised electricity supply based on natural gas or other efficient energy carriers, instead of on-board engines will help to decrease local emissions. Cleaning and maintenance of ships, e.g. anti-fouling measures, will reduce fuel consumption on the onward journey. (Vergara et al. 2012; DNV GL n.d.; DNV GL 2014; ABS 2013)

General management and organisation methods enable more economical and environmental transport operations. Typical elements, identified by J. Vergara, DNV, and ABS, comprise (Vergara et al. 2012; DNV GL n.d.; DNV GL 2014; ABS 2013):

- *Operation:* Dynamic route planning, weather avoidance, use of sea currents, and trim and draft optimisation to reduce resistance and increase fuel efficiency.
- *Logistics Management:* Intermodal planning to identify the most energy efficient solutions and enable adequate processes for arrival and further transport of goods including selection of optimal sizes of vessels and vehicles
- *Energy Management/Optimisation:* Permanent monitoring of energy consumption – Assessment of efficiency measures and implementation of further measures

Speed management and slow steaming enable disproportionately high fuel savings at reduced speeds. ABS analyses that speed reduction by 1 knot for container ships with more than 4,500 TEU capacity results in fuel savings of 12-15% (ABS 2013). Besides significant fuel savings, typical benefits of slow steaming are a higher capacity utilisation and potential savings in new built ships by smaller engine sizes and associated optimised cargo space and costs. (Rodrigue 2015)

Economies of scale in transport lead to larger ship sizes. This trend is especially apparent for container vessels. While typical container vessels carried only around 1,000 TEU at a length of 130 m in the 1960's, container ships today reach a capacity over 19,000 TEU and a length of around 400 m. Ultra large container vessels use less than half of the specific fuel consumption per container compared to feeder vessels at normal shipping speed. ABS calculates fuel savings per TEU of 25% if the ship size increases from 4,500 to 8,000 TEU. 10% improvements are realised if the ship size grows further to 12,500 TEU. (Diekmann & Rosenthal 2013; ABS 2013)

Infrastructure measures, such as improvements of port infrastructure, reduce waiting times and improve port processes. The extensions of canals enhance capacities and enable more direct routes for larger ships.

4.2.4 Conventional and alternative fuels and drive trains

Two main groups of fuels for marine transport can be distinguished. Heavy fuel oil (HFO), in line with Singapore's nomenclature referred to as marine fuel oil (MFO), and marine gas oil (MGO). MFO supplied 77% of ship fuel worldwide (McGill et al. 2013) and its market share has increased to more than 95% since 2010 in Singapore's port (Singapore MPA 2015). Remaining demand was mainly satisfied by MGO. Other fuels, such as LNG used in LNG carriers or niche applications, play only a minor role. So do nuclear fuels, which are used in aircraft carriers, submarines, and ice breakers.

Table 4-3 sets the main characteristics of selected fuels into comparison and highlights advantages (green), impairments (yellow), and severe obstacles (orange) for implementation.

Table 4-3: Comparison of characteristics of selected fuels

Criteria	MFO	MGO	Biodiesel	LNG	LH_2
Engine type	Diesel	Diesel	Diesel	Diesel	Diesel/FC
Fuel storage & treatment	tank + heater + purifier	tank	tank	cryo tank	cryo tank
Req. storage volume	normal	normal	normal	times 1.8	times 4.7
Sulphur regulation	LSFO or scrubber	LSMGO or scrubber	fulfilled	fulfilled	fulfilled
NO_x regulations	SCR / EGR	SCR / EGR	SCR / EGR	fulfilled	fulfilled
PM regulations	scrubber	scrubber	scrubber	fulfilled	fulfilled
Fuel costs	low	medium	high	low	high
Safety requirements	normal	normal	normal	increased	increased
Spills	severe	severe	degradable	methane	vanish

MFO. Marine fuel oil is the cheapest available fuel. It is produced from heavy refinery distillates. Upgrading of certain shares of these to higher value fuels is either economically or technically not feasible. Therefore, MFO contains high levels of sulphur, phosphor, and heavy metals. (Singapore MPA 2015)

Different grades of MFO are distinguished on basis of its viscosity. Typical grades are MFO 180, which is characterised by a kinematic viscosity of lower than 180 centistokes at 50 degrees Celsius. The most traded fuel in Singapore is MFO 360 with a kinematic viscosity lower than 360 centistokes. Fuels with higher viscosity are cheaper. Therefore, with improvements in engine design, even heavier fuels such as MFO 500 have been used more often in recent years. In Singapore, share of MFO 500 in total sales volume increased from 13% in 2007 to 19% in 2014. The density of MFO in Singapore is usually higher than 980 kg/m^3 and increases further with higher viscosity of fuel types. (Singapore MPA 2015)

Before MFO can be burned in diesel engines it has to be heated and purified. Heated tanks, centrifuges, and filters are used to reach the required specifics for the combustion process. (U.S. EPA 2008)

Current MFO grades sold in Singapore, are compatible with the current IMO sulphur regulation outside of the ECAs (< 3.5%) (Singapore MPA 2015). However, stricter regulations with sulphur levels below 0.5% are planned for 2020 (IMO 2015b). Stricter levels for NO_x emissions and particulate matter might also reduce the attractiveness to use MFO in regulated ECAs.

There are two possibilities to improve air emissions of MFO:

First, emission can be reduced during and after the combustion processes: while sulphur emissions are proportional to the sulphur content in the fuel, NO_x emissions and particulate matter emissions can be partly influenced during combustion processes. Engine improvements, such as direct injection, optimisation of chamber geometry, valve timing, and optimised airflow, could therefore reduce parts of NO_x emissions. In addition, exhaust gas treatment will be necessary to further reduce emissions. Selective catalytic reduction (SCR) can be used to remove NO_x from the exhaust gas. NO_x is separated by a catalyst into N_2 and H_2O. SCR technology could reduce emissions up to 90%. An alternative to SCR is exhaust gas recirculation (EGR). After cooling and cleaning, part of the exhaust is recirculated into the combustion chamber. Heat capacity of the scavenging air is increased and peak temperatures during combustion are reduced. By this, NO_x emissions are avoided but particulate matter emissions increase. Exhaust gas cleaning (EGC) scrubber technologies clean the exhaust to the required SO_x levels. Dry and wet scrubbing can be distinguished. While dry scrubbers use chemicals to remove the SO_x emissions from the exhaust, wet scrubbers use sea water to reduce SO_x emissions from the exhaust. Afterwards the sea water is cooled, filtered, and released back into the sea. The high alkalinity of sea water and its naturally high sulphur content make this a feasible solution. Besides SO_x also particulate matter is removed from the exhaust gas. A combination of EGR and EGC scrubbers allows to use MFO in 2 stroke engines and at the same time to comply with the strictest IMO regulations. (Hansen et al. 2014; MAN Diesel & Turbo 2015; McGill et al. 2013; U.S. EPA 2008)

Second, emissions can be reduced before fuel combustion by using fuels with altered fuel properties. Low sulphur fuel oil (LSFO) has a reduced sulphur content compared to MFO. Sulphur content can be reduced to less than 0.5% and is therefore applicable for future use outside of ECAs (Brynolf 2014). LSFO is very similar to today's fuels. Therefore, use in current engines or even fuel switching is possible. However, increased refining efforts lead to higher prices as conventional fuels and engine systems have to be improved by reason of slightly different fuel characteristics – e.g. other lubricants with different alkalinity are required, injection and pumps have to adjust to different viscosity, and fuel switching when entering ECAs might cause the formation of sludge and block filters (McGill et al. 2013). Alternatively, also fuel switching to MGO is possible.

MGO. Marine gas oil is more expensive than MFO. It is a lighter fuel and has a reduced viscosity and sulphur content. Tier III NO_x emission requirements can be met if SCR systems are used (Brynolf 2014). Low sulphur marine gas oil (LSMGO), which is mandatory in European ports, reaches especially low sulphur levels of below 0.1% and is compatible to the strict emission regulations in ECAs. MGO sold in Singapore has an average tested sulphur content of 0.28% (Singapore MPA 2015).

A detailed summary of different studies that investigate the usability of alternative bunker fuels is given in Chapter 5.1. The most promising alternatives to conventional bunker fuels are presented in the following:

Biofuels. Owing to their very similar fuel properties to conventional fuels, biofuels can be used as drop-in fuels. Biodiesel as a replacement to MGO and crude vegetable oil as a substitute to MFO are the most promising options (Opdal & Hojem 2007). Biofuels have very low sulphur contents and accordingly low SO_x emissions. NO_x emissions are comparable to conventional fuels. Additional exhaust treatment (SCR) is necessary to reach NO_x Tier III requirements. Spills of biofuels are less harmful than spills of conventional fuels, owing to their biodegradability. Higher acidity of biofuels requires improved materials or coatings in engine, fuel storage, and seals. The largest obstacles to introduce biofuels are sustainable feedstock availability and production costs. (Brynolf 2014; McGill et al. 2013)

LNG. Liquefied natural gas (LNG) is one of the most promising future fuels for marine transport (McGill et al. 2013). Advantages compared to MFO are:

- Around 20-25% lower carbon emissions per unit of energy depending on fuel composition (Burel et al. 2013; DNV Germany 2011; Brynolf 2014; McGill et al. 2013)
- Nearly negligible sulphur content (DNV Germany 2011; McGill et al. 2013)
- Significantly reduced NO_x (-85%) and particulate matter emissions (-95%) (McGill et al. 2013)

Therefore, no exhaust gas treatment is required to operate in ECAs and all future regulatory requirements are fulfilled (Brynolf 2014). LNG can be used in dual fuel engines, which offer the potential to switch between LNG and conventional fuels (Brynolf 2014). Different studies show that LNG has been economical competitive to conventional fuels. (Burel et al. 2013; Brynolf 2014; McGill et al. 2013; DNV Germany 2011)

However, there are some drawbacks of LNG use as a fuel for marine transport:

- The current LNG fuelling infrastructure is very limited compared to conventional fuelling infrastructure (McGill et al. 2013).
- While the gravimetric energy density of LNG is higher, its volumetric energy density is only around half of MFO, resulting in 1.8 times higher storage space (Vogler & Sattler 2016). This characteristic and the required low temperatures of below -163 degrees Celsius for storing LNG at liquid state require larger and costlier on board storage systems. (Abe 1998; McGill et al. 2013; Brynolf 2014)
- Costs of new built ships are increased and retrofitting of ships is comparably expensive, as LNG is not compatible with existing engine and fuel system technologies. (McGill et al. 2013; Brynolf 2014)
- Methane losses, which might occur during storage, when heat intake transforms LNG into a gaseous state, or in the engine have to be avoided as methane is a very potent greenhouse gas. (McGill et al. 2013; Brynolf 2014)
- Furthermore, the safety standards compared to MFO have to be increased. (McGill et al. 2013)

H_2. Hydrogen is another potential fuel for marine transport. There are two possibilities to convert hydrogen into power for propulsion:

- Combustion in an internal combustion engine, similar to today's diesel engines, as a single fuel or in a mixture with conventional fuels. Pure combustion of hydrogen causes emission of water and NO_x in small quantities. (Verhelst 2014; Szwaja & Grab-Rogalinski 2009)

- Conversion of hydrogen in a fuel cell system into electricity and water. In this process only vapour emissions are caused (DNV 2013; Luckose et al. 2009).

However, there are several disadvantages that hinder the introduction of this technology. First, hydrogen occurs only in compound form. Therefore, it has to be produced, either from hydrocarbons or from water electrolysis. Both processes require much energy. Hydrogen has an extremely low energy density. In order to make its transport economically viable it has to be compressed (CGH_2) or liquefied (LH_2). However, volumetric energy density remains low and resulting storage space of LH_2 compared to HFO is 4.7 times higher (Vogler & Sattler 2016). Extremely low temperatures below -253 degree Celsius for storing liquid hydrogen challenge materials and require special storage systems and components (Abe 1998). This increases costs compared to conventional systems. Fuel cell technology has to improve significantly considering weight per power output, volume per power output, lifetime, durability, and costs per power output (Vogler & Sattler 2016). New safety standards and increased safety measures are necessary to enable safe processes for hydrogen use, transport, bunkering, and fuelling. (Vogler & Sattler 2016)

However, in order to assess energy efficiency, GHG emissions, and costs on a global scale, the individual pathways to produce alternative and conventional fuels have to be taken into account. A detailed pathway analysis that takes into account the particularities of Singapore in terms of geographic position, access to energy carriers, and transformation and distribution technologies is carried out in Chapter 5.

4.3 Aviation trends and environmental targets

4.3.1 Current status and past developments

Air transport has been playing an important role to facilitate globalisation. In 2013, over 3.1 billion passengers were scheduled and over 49 million tonnes of cargo were transported. This translates into 6 trillion USD of goods traded, which is equivalent to nearly 35% of international trade value. Since 1994 the number of unique connections has doubled while transport costs have halved. (IATA 2015a) In the last 14 years, air traffic, measured in revenue passenger kilometres (RPK) has been growing by 85% to over 6.2 trillion RPK in 2014 (Leahy 2015). In 2013, 705 million tonnes of CO_2 were emitted by flights. This quantity is in the same order of magnitude as CO_2 emissions caused by international shipping. Fuel efficiency of aircraft improved significantly. Today, passenger aircraft are 70% more fuel efficient than in 1960 by means of fuel consumption per seat kilometre. (ATAG 2015; IATA 2013)

4.3.2 Outlook

Boeing and Airbus, the leading manufacturers of aircraft, are predicting future air transport demand and fleet development in order to improve product strategies, strategic planning, and to inform customers, suppliers, and stakeholders. Both reports forecast ongoing strong growth in air transport demand.

The ‘Airbus Global Market Forecast’ predicts future developments in the period from 2014 to 2034. In this period RPK will grow from 6.2 trillion to 15.2 trillion by a factor of 2.5 (4.6% p.a). The passenger aircraft fleet (≥100 seats) will increase from 17,354 to 35,749 by a factor of 2.1. The number of dedicated freighters (≥ 10 tonnes) will rise from 1,633 to 2,687 by a factor of 1.6 (Leahy 2015).

The ‘Boeing Current Market Outlook’ investigates the period from 2015 to 2034. RPK will grow from 6.2 trillion (2014) to 16.2 by a factor of 2.6 (4.9% p.a.). The global passenger fleet will more than double from 19,880 to 40,630, while global freighter fleet will increase from 1,720 to 2,930 aircraft by a factor of 1.7 (Boeing 2015).

In both reports the aircraft fleet is growing at a lower annual rate as the number of passengers and the air transport demand. Increase of GDP and a growing middle class is a strong driver of transport growth. Accordingly, growth in emerging economies, especially in Asia, is even stronger than in other parts of the world (Leahy 2015; Boeing 2015).

Both reports diverge considering the future importance of large (wide-body) aircraft. Boeing argues that recent growth was only slightly driven by an increase in airplane size and capacity and much more influenced by additional non-stop links and a higher frequency in the existing network (Boeing 2015). Average airplane size (total available seat kilometres per total available airplane kilometres) has been declining since the mid-1990s. It is predicted that smaller (single aisle) aircraft will substitute wide-body aircraft on short and medium haul trips. Large wide-body aircraft will be substituted by medium and small wide-body aircraft and large wide-body shares will decline till 2034. Only in the Middle East large wide-body aircraft will have a significant market share of 9% in 2034. The market share of wide-body aircraft in 2034 is forecasted to be 48%, and will be dominated by single aisle aircraft. In contrast, Airbus predicts a market share of single aisle aircraft of 45%, twin aisle aircraft (small and medium wide-body) of 43%, and very large (large wide-body) aircraft of 12% (Leahy 2015). Airbus Global Market Forecast shows that yearly offered seat per aircraft has increased by 46% since 1980. Very large aircraft are mainly concentrated on big airport hubs or aviation megacities. Their number will nearly double till 2034. 39 of today's 47 aviation megacities have problems with congestion and capacity (Leahy 2015).

Summarising both reports, it is common consensus that air transport demand will double in the next two decades. This is in coherence with other expectations derived from literature (Mensen 2013; ICAO 2013). Growth in Asia will be especially strong. This will result in further extensions of airports, airline networks, and capacity of routes (by frequency or larger aircraft).

4.3.3 Environmental goals

In recent years, air transport has often been confronted with environmental concerns. The aviation industry and international organisations are still in the process of defining obligatory international climate goals and appropriate measures to reach these. The International Civil Aviation Organization (ICAO) is a UN created organisation to promote *"safe and orderly development of aviation"* worldwide. It has 191 member states. ICAO pursuits three environmental goals (ICAO 2013):

- Limit or reduce the number of people affected by significant aircraft noise
- Limit or reduce the adverse impact of aviation emissions on local air quality
- Limit or reduce the impact of aviation greenhouse gases on the global climate

On the 37th ICAO general assembly (2010), member states set the aim for global aviation to improve fuel efficiency by 2% p.a. and limit emissions at 2020 levels (ICAO 2013). In close proximity to these aims, leading members of the aviation industry signed a declaration to define aims for a sustainable aviation (ATAG 2012):

- Increase of fuel efficiency of aircraft fleet (fuel use by RPK): 1.5% p.a. by 2020
- Cap of aircraft CO_2 emissions from 2020 and carbon neutral growth
- Reduction of total aircraft net carbon emissions by 50% till 2050 based on 2005 levels

Four main pillars are identified to reach these aims: new technologies, operational efficiency, infrastructure improvements, and economic measures (ATAG 2013; ICAO 2013). These are further discussed in the next Chapter. The efficiency targets of the aviation industry were met during the first years (IATA 2015a). Figure 4-3 displays the International Air Transport Association's (IATA's) strategy to reach the established goals of CO_2 reduction.

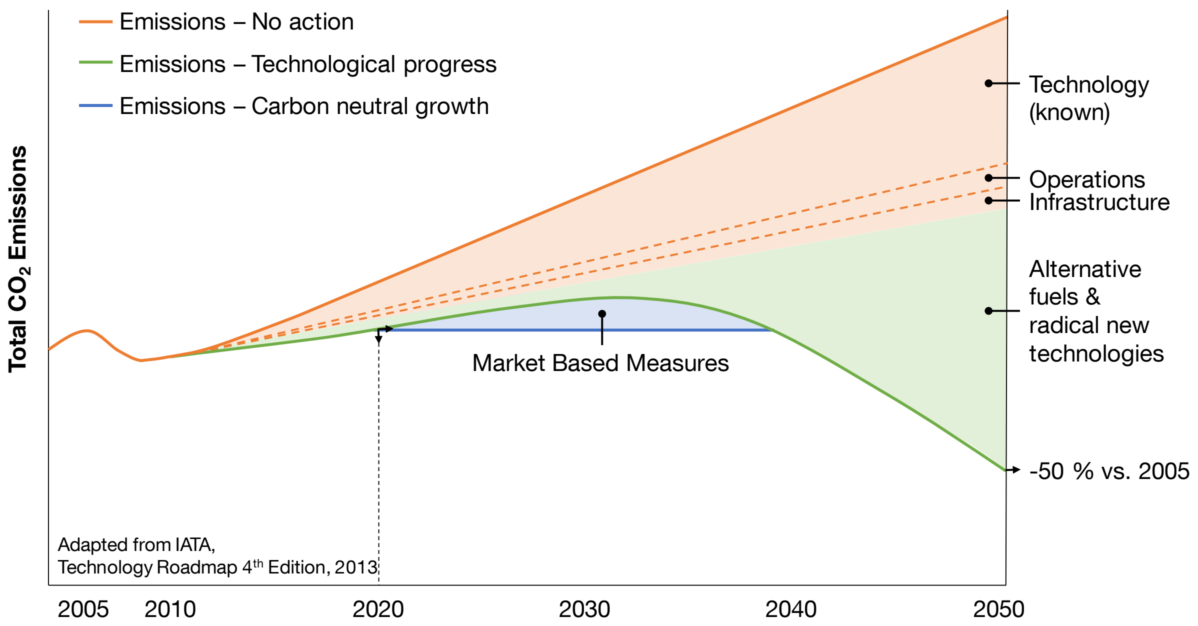


Figure 4-3: CO_2 emission goals IATA

However, with respect to a doubling of air transport demand, technological and operational improvements are not sufficient to cap CO_2 emissions in 2020 and the next decades. Before new technologies are available and economically feasible, a gap is expected. This gap should be bridged by economic mechanisms (ATAG 2010). Market Based Measures (MBMs) should create incentives to use alternative fuels and other promising, but without incentives, not economically feasible technologies. MBMs should only support market integration of alternative fuels and innovative technologies from 2020 to further decades, until economies of scale and technological advances make alternative solutions more reasonable than conventional fuels and technologies. At the 38th (ICAO) General Assembly in Montreal (2013), the road map for an implementation of MBMs was agreed. Till the 39th ICAO General Assembly (2016), ICAO will prepare a proposal for MBMs to achieve the expected emission cap and reductions (ATAG 2013; ICAO 2013). According to ATAG, carbon offsetting is the preferred industry solution (ATAG 2013). This means that CO_2 emissions produced by aviation could be balanced by opposing CO_2 emission reductions in other areas. Other key elements of 38th ICAO General Assembly were reaffirmation of climate goals proposed at 37th ICAO General Assembly (see above), improvement of GHG monitoring and measurement, development of CO_2 emission standards for aircraft for adoption by 39th ICAO General Assembly, and various other actions to support sustainable development of aviation. (ICAO 2013; IATA 2014; ICAO 2012)

Aviation’s role in mitigating climate change is only one environmental hurdle. Aircraft noise and local emissions are further challenges for future aviation. (ICAO 2011)

Thus, measures and technologies that contribute to unite environmental goals and future growth are presented in the next Chapter.

4.4 Aviation technologies in transport

4.4.1 Technology in civil aviation

The history of aviation technology started in 1783 with first attempts of Montgolfier to fly with balloons filled with hot air or gas. In 1903, the first motor propelled flight was done by the Wright brothers. In the coming decades developments in aviation were driven by military applications. In 1939, the first flight with an aircraft powered by a jet engine was performed and jet engines became a solution for military and civil aviation. This new engine type allowed the construction of bigger and faster aircraft. Further improvements in engine design led to the development of turbofan engines. Since the end of the 1960's turbofan engines have powered most aircraft for civil aviation. Since then, technological improvements have reduced fuel consumption of aircraft significantly. Today, turbofan engines are mainly used for large passenger aircraft and enable high cruise speeds. Owing to their higher energy efficiency, turboprop engines are often used in small aircraft or transport aircraft with lower cruise speeds and often shorter cruise distances (Engmann 2013). (Engmann 2013; Mensen 2013; ATAG 2010)

According to H. Mensen future development of aircraft will be determined by reducing drag, weight, and emissions while requirements for economic efficiency, safety, operability, and comfort of passengers increase (Mensen 2013). In addition, assistance systems will more and more enable autonomous flying on most economical routes in reorganised and monitored airspaces. Various technologies and measures offer the potential to reduce emissions of air transport.

4.4.2 Future technological developments

IATA publishes a roadmap to show the impact of future technological developments on fuel consumption. The results are derived from the TERESA (Technology roadmap for environmentally sustainable aviation) project, which was carried out by IATA in cooperation with the German Aerospace Center (DLR) and the Georgia Institute of Technology (Georgia Tech). Engines and airframe are identified as key research areas to reduce fuel consumption. The airframe is further subdivided into aerodynamics, lightweight materials and structures, equipment systems, and new configurations. A broad range of different aircraft technologies for airframe and engines, their current development status, fuel reduction benefit, and forecasted availability is assessed in the IATA Technology Roadmap (IATA 2013). Radical new technologies for new aircraft and engine designs are presented. Sixteen of the most relevant technologies are compared in an airplane simulation model. Benchmarking with other studies shows similar results. According to IATA, the most important technologies to reduce fuel consumption of current aircraft are: (IATA 2013)

1. Natural or hybrid laminar flow control: Energy consumption of airplanes could be significantly reduced, if laminar characteristics of the air flow around parts of the airplane is kept as long as possible and turbulent air flows are delayed. By this friction is reduced. Natural laminar flow could be achieved with special geometries of airplane parts. However, profiles that enable natural laminar flow are often not suitable for large airplanes. Therefore, hybrid laminar flow technologies are used to force air flows as long as possible in laminar characteristics by sucking in parts of the air flow or influencing it by blowing. ICAO assesses that potential reductions of drag with hybrid laminar flow control are 10%. Therefore, it is assumed to be one of the most promising technologies to reduce energy consumption of airplanes. (TUHH - IFS n.d.; Engmann 2013; IATA & GIT ASDL 2009; ICAO 2013)
2. Active load alleviation and variable chamber: Active load alleviation describes active measures at the wing surface to reduce or distribute aerodynamic loads at the wing of the airplane. Further technological advancements will reduce weight and improve aerodynamics. Variable chamber describes the continuous adoption of the wing to the current flight phase in order to optimise aerodynamics and reduce weight. The main advantage is an increased efficiency under ’off-design’ conditions, which could occur when the aircraft is forced to fly faster and higher or on changed height owing to other air traffic. (IATA & GIT ASDL 2009)
3. Winglets and riblets: Winglets are mounted at the wing tip and reduce induced drag and thus fuel consumption. Different types and designs of winglets can be installed on aircraft. Further advances in winglet design are expected. Riblets are coatings at the aircraft surface that support natural laminar air flow. By this, drag is reduced and efficiency increased. (Engmann 2013; Airbus et al. 2014)
4. Structural health monitoring: Instead of using fail-safe design, aircraft are designed towards a low probability of failure. Permanent monitoring of the status of structures and materials by sensors offers benefits for adjusted maintenance. By switching from fixed maintenance intervals, e.g. based on flight hours or take-off and landing cycles, to health status adapted intervals of parts and components safety margins at airplane construction can be reduced. This

leads to weight reductions resulting in higher range and reduced fuel consumption of aircraft. (Balageas 2006; Khan et al. 2014)

5. Composite structures for wing and fuselage: Further weight reductions, and thus associated reductions of fuel consumption, can be achieved by use of composite materials in the main body (fuselage) and wings of the aircraft. Composite materials are part of modern aircraft. For example, composite materials account for 25% of total weight in the A380. In the B787 or the A350, lightweight materials account for more than 50% of the total weight. (ICAO 2013)
6. New engine architectures: The optimisation of engine weight and efficiency offers further potentials for fuel savings. Three main technological improvements can be distinguished:

   The existing turbofan technology could be further improved by achieving higher bypass ratios, use of new materials, improved coatings and aerodynamics, higher efficiency of components (compressors, combustion process, turbines, mechanical parts, and cooling) and an improved integration into airplane design. Besides aims to reduce fuel use and weight, also reduction of noise and emissions is an essential part of current research. (ATAG 2010; Mensen 2013; ICAO 2013)

   Geared turbofan technology offers additional advantages: Noise reductions and efficiency improvements in various flight situations are achieved by geared operation that enable the fan section to operate at a lower speed than the low-pressure compressor and the turbine. (IATA & GIT ASDL 2009; ATAG 2010)

   The open rotor concept or prop fan offers the possibility to increase engine efficiency by reaching even higher bypass ratios. Fuel consumption could be reduced by 10-15% compared to advanced turbofan engines. However, the propellers mounted at the outside of the nacelle of the turbine cause higher noise levels than turbofan engines and result in a reduced cruise speed. (Engmann 2013; ICAO 2013; ATAG 2010; IATA & GIT ASDL 2009)

Besides the presented innovations, there are more developments such as 'more-electric-aircraft', more efficient auxiliary power units (APUs), fuel cell APUs, use of lighter paint, use of lighter cabin equipment, etc.

IATA clustered technologies into four categories (IATA 2013):

- Retrofit: Variable chamber, riblets, winglets, lightweight cabin interiors, structural health monitoring, Laminar flow drag coatings, Al-LI alloys
- Production upgrades: Active load alleviation, advanced materials
- New aircraft types before 2020: Geared turbofan, advanced turbofan
- New aircraft types after 2020: Natural laminar flow control, hybrid laminar flow control, fuel cell for secondary power

Based on IATA's roadmap, Figure 4-4 visualises potential CO_2 reductions for the investigated technologies according to the IATA roadmap. (IATA 2013)

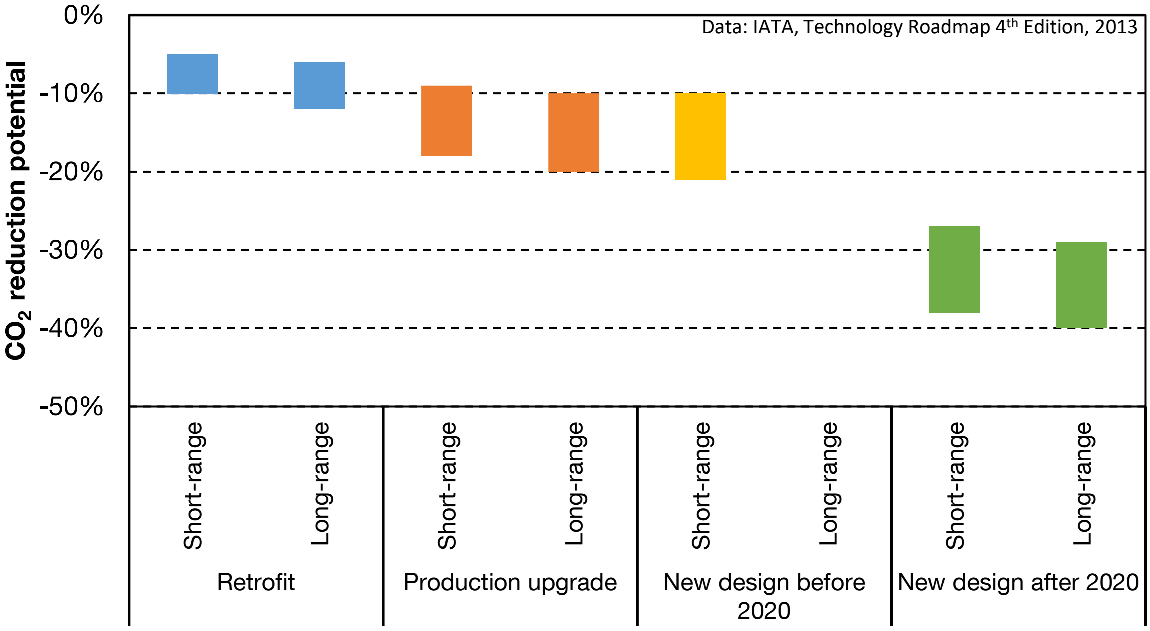


Figure 4-4: CO_2 reduction potentials of technological improvements

The visualised reductions are shown in reference to a baseline aircraft with 2005 technology. While retrofits could reduce CO_2 emissions by 5-10% for short-range aircraft (SR) and 6-12% for long-range aircraft (LR), production upgrades could further reduce fuel consumption by 9-18% for SR and 10-20% for LR. New designs for 2020 include only SR, as no prediction is done for LR aircraft in this timeframe. Carbon emissions of new designs of SR will be reduced by 10%-21%. New airplane types after 2020 will reduce fuel consumption by 27-38% for SR and 29-40% for LR.

Radical new concepts beyond 2030 could further reduce fuel efficiency up to 50% and are necessary to reach the target to cut the overall GHG emissions in the aviation sector by 50% compared to 2005 levels till 2050 (IATA 2013). A number of new aircraft designs, presented in literature, comprises blended wing design, spiroid winglets and actively controlled winglets design, multi-fan engines design, and box wing design. (ATAG 2010; Mensen 2013; IATA & GIT ASDL 2009)

According to H. Mensen, all current future concepts are based on optimisation and further development of the established technology (Mensen 2013). Radical new concepts of high speed transport are not in the focus of current research.

4.4.3 Efficient operations and infrastructure

In order to reach the ambitious goals in fuel savings, improvements of aircraft technology are not sufficient. Advances in airplane operation and of infrastructure offer further fuel savings.

Increases of operational and infrastructure efficiency of air transport already start at the airport. While 95% of fuel is used during flight, 5% of fuel is consumed at the ground (ATAG 2010). After landing, aircraft have to drive to the terminal to board passengers. After ground operations and boarding of passengers, aircraft have to drive back to the landing strip for departure. These procedures are called taxiing. Minimal engine use, single engine use or electric taxiing could reduce fuel consumption (ICAO 2013; ATAG 2010). When the aircraft is standing at the airport, use of electrical ground power instead of the electrical power unit decreases amount of fuel consumptions and local emissions (ATAG 2010). Effective communications, intelligent schedules, and forecasting have the potential to avoid queuing of aircraft at the ground before departure or additional congestion in the air before landing (ATAG 2010). Simple operational measures like cleaning of aircraft engines could further reduce fuel consumption and weight by removing debris and deposits (ATAG 2010). Furthermore, adaption of airport infrastructure to actual demand contributes to avoid congestion.

Several ’in the air’ measures will improve the efficiency of air transport. Advances in monitoring, positioning, and communication technology enable new airspace infrastructures and flight operations. Today airspace is determined by national borders and regulations. Therefore, it is often not possible for airlines to fly direct routes. Lufthansa reports, that European flights are in average 42 km longer than compared to a direct route (Lufthansa Group 2015). In the European Union, the ‘Single European Sky ATM (air traffic management) Research’ (SESAR) will reorganise the airspace and its regulations, design, and management to increase efficiency, capacity, and safety and reduce costs. (Mensen 2013) Similar objectives will be achieved in the US with the ‘Next Generation Air Transport System’ (NextGen) (IATA 2013). Elements are e.g. uniting today’s fragmented airspace into one larger airspace, flexible use of military and commercial airspace, advanced flight planning and management systems, performance based traffic management, and use of most economical efficient routes in dependence of weather and air traffic (ATAG 2010). Further fuel reductions could be achieved by use of efficient aircraft that fit actual air transport demand; for instance, by flexible use of different aircraft sizes in the fleet (ATAG 2010).

New take-off and landing procedures can increase efficiency by using the potential of very accurate navigation systems of modern aircraft (ATAG 2010). Measures are e.g. dynamic airspace configuration, denser terminal area operations, performance based navigation, better traffic flow management, time-based metering, and trajectory-based operations (ICAO 2013).

Radical new operations and network design of airline networks also influence energy efficiency. Economic efficiency of hub networks is challenged by increased comfort and faster connections of direct flights (point-to-point). In order to assess energy efficiency of the two network types, efficiency advantages of larger aircraft and airports in hub-and-spoke networks have to be compared to reduced fuel consumption caused by less mileage and less departure and landing operations in point-to-point networks. Individual network characteristics, technology of aircraft, and passenger flows will influence possible outcomes. While low-cost and holiday carriers prefer direct point-to-point connections, network carriers often use a combination of hub-and-spoke networks to feed their main hub and direct connections between airports with high air transport demand.

4.4.4 Alternative aviation fuels

Aviation industry postulates use of alternative fuels as an essential part of its long-term strategy to reduce energy consumption and GHG emissions of aviation by reason of insufficient gains in efficiency, which will not be able to offset additional fuel consumption caused by increasing transport demand in the coming decades (ICAO 2013).

Biofuels. Biofuels, used as drop-in fuels, are seen as the most promising alternative energy source (ICAO 2013). In contrast to other possible substitutes, such as hydrogen, natural gas, or electricity, drop-in biofuels could substitute jet fuel without changing engine technology and without requiring radical new aircraft designs. Biofuels are derived from biomass or waste. The GHG emissions compared to conventional fuels are reduced, as carbon emissions occurring at fuel combustion have been bound prior during growth of the feedstock plants.

In 2009, ICAO member states endorsed alternative jet fuels as a measure to limit the carbon footprint of aviation. In the same year, Fischer-Tropsch (FT) fuel was certified by ASTM International as a drop-in fuel in blends up to 50% with conventional jet fuel. In 2011, hydroprocessed esters and fatty acids (HEFA) or hydrotreated renewable jet fuel (HRJ) was certified in blends up to 50%. The latest addition of possible pathways to supply biofuels for aviation is synthetic iso-paraffin from fermented hydroprocessed sugar (SIP) and was approved by ASTM International in 2014. Further approvals that allow the use of other possible pathways to produce alternative fuels for aviation are expected. (IATA 2014)

Two major challenges for alternative aviation fuels are distinguished: The fuel costs and the sustainability of alternative fuels. (ICAO 2013)

As fuel costs are the highest operational costs for airlines, reasonable fuel costs are vital in this highly competitive business area. As of now, there is still a big price gap between conventional jet fuel and alternative aviation fuels derived from biomass. In this context, scale up of technologies to produce alternative jet fuel in significant quantities is often difficult. Increases in process efficiency and reduction of feedstock and process cost is mandatory to produce alternative jet fuels economically. (IATA 2014; ICAO 2013)

While reduction of costs is certainly the near term challenge for introducing aviation biofuels, the long term challenge is to supply these fuels in a sustainable way. This concerns in particular the feedstock availability and the impact of biofuel production. (IATA 2014; ICAO 2013) In this context, first and second generation biofuels are distinguished. First generation biofuels are made from sugar, starch, or vegetable oil. Typical examples are: biodiesel from palm oil in Southeast Asia, ethanol from sugarcane in the US, or biodiesel from rape in Europe. While first generation biofuels contribute to reduce GHG emissions and import dependency, and increase energy supply security and support of agricultural industries, there are several negative aspects associated. Land use conflicts with food production or woods lead to higher food prices and deforestation. Production in water scarce regions may lead to environmental and economic pressure. Sustainable production and GHG reductions of palm oil fuels, particularly in the context of land use change, is at least questionable. (Sims et al. 2008)

Second generation biofuels try to avoid most of these critical issues. These fuels are produced from agricultural or urban by-products or from plants cultivated on land areas that are not suitable for the production of food or other products. Direct competition with food production, alternative land use, and water consumption should be avoided. Therefore, second generation biofuels are more sustainable than first generation biofuels. However, the resource potential is limited. Second generation biofuels for aviation could be produced from Camelia, Jatropha, Halophytes, and household and municipal waste. Algae, often described as third generation biofuels, could solve problems with the limited availability of feedstock in the future. More research and technological progress is needed to make biofuels derived from algae an economic solution. (IATA 2014; Sims et al. 2008; ATAG 2011)

H_2. Hydrogen can be used as an alternative aviation fuel and offers the potential of zero carbon aviation. There had been several testing programs in the past to use hydrogen as fuel for turbofan engines or fuel cells (IATA & GIT ASDL 2009; Godula-Jopek & Westenberger 2016).

While the gravimetric energy density of hydrogen is nearly three times higher than that of jet fuel, lower volumetric energy density in compressed or liquid form will increase required storage space compared to kerosene by a factor of 15 or 4, respectively. Owing to these characteristics, new aircraft designs are required. (Godula-Jopek & Westenberger 2016)

The Cryoplane study shows that hydrogen as an aviation fuel is technically possible for commercial aircraft. The study investigates a rise in energy consumption ranging from 9% for long range aircraft to 14% for small regional aircraft owing to an enlarged area in contact with external airflow. Storing hydrogen in liquid form is assessed to be the best solution for storing hydrogen on-board of large commercial aircraft for propulsion purposes (Airbus 2003). The emitted vapour by hydrogen combustion is not seen as a severe contribution to global warming, as emissions remain only a few days in the troposphere.

Technical challenges for powering commercial aircraft with hydrogen are (Godula-Jopek & Westenberger 2016; IATA & GIT ASDL 2009):

- Reduction of size, weight, and costs of the hydrogen storage system
- Adoption of combustion process (turbofan) or radical change to fuel cell technology
- Redesign of fuelling infrastructure
- Minimisation of heat intake and associated boil-off losses of hydrogen

Besides implications, caused by technical requirements, sustainability of hydrogen as a fuel is highly influenced by its energy source. While most hydrogen is produced by steam methane reforming today, electrolysis powered by renewable energy sources offers the potential to significantly reduce carbon emissions and improve sustainability.

A detailed study on biofuel and hydrogen pathways and the required process steps to supply bunkers for marine and aviation transport in Singapore is given in Chapter 5.

5 Process chain analysis for alternative energy carriers in Singapore

Chapter 5 presents alternative fuel pathways in order to cover Singapore's energy demand for marine and aviation fuels. Specific energy demand, emissions, and costs are assessed for conventional fuels, LNG, biofuels, and liquid hydrogen.

This Chapter contains parts of the article "*Sustainable transport by use of alternative marine and aviation fuels–a well-to-tank analysis to assess interactions with Singapore's energy system*", which was published in the Journal of Renewable and Sustainable Energy Reviews. The relevant parts of this article are cited in the remaining parts of Chapter 5 in order to enable a sound interpretation of the results that are discussed in Chapter 6.

/extract from article (Schönsteiner et al. 2016)/

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' (Edwards et al. 2014) and Argonne's GREET life cycle analysis (Argonne 2015) 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 (Bengtsson et al. 2011; Chryssakis 2013; Verbeek et al. 2011; Bengtsson et al. 2012; Brynolf 2014) and alternative aviation fuels (Elgowainy et al. 2012; Stratton et al. 2010; Saynor et al. 2003; Pereira et al. 2014). These studies, however, were based on data from Europe or the US.

Singapore and its surrounding countries, 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 the following, 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. The derived results for conventional and alternative process chains to supply fuels to international transport services are assessed in Chapter 5.5. Typical energetic factors, GHG emission factors, and costs are derived for each fuel type. Indicators derived from related literature are compared.

5.1 Review of related literature

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.

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 5.1.1. The results of selected WTT and WTW studies focusing on marine transport or aviation technologies are summarised in Chapters 5.1.2 and 5.1.3.

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 5.2. In Chapter 5.6, specific results presented in related literature sources are compared to the results derived in this paper.

5.1.1 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 5.2). 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. (JEC n.d.; Edwards et al. 2014)

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 ongoing 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 a 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. (Argonne 2015)

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. (IINAS 2015; UBA 2016; ecoinvent n.d.)

Other process specific literature sources used to adapt the investigated pathways to Singapore's energy system and related upstream processes are presented in Chapter 5.4.

5.1.2 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 (Bengtsson et al. 2011; Bengtsson et al. 2012; Verbeek et al. 2011; Chryssakis 2013; Brynolf 2014). 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. (Bengtsson et al. 2011)

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. A 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. (Bengtsson et al. 2012)

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. (Verbeek et al. 2011)

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. (Chryssakis 2013)

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. (Brynolf 2014)

An inspection of the literature related in this Chapter makes it clear that current research is mainly focussed on Europe (Chryssakis 2013; Bengtsson et al. 2012; Bengtsson et al. 2011; Brynolf 2014; Verbeek et al. 2011). 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 (Chryssakis 2013; Bengtsson et al. 2012; Bengtsson et al. 2011; Brynolf 2014; Verbeek et al. 2011). Hydrogen may become an energy carrier in the long term if costs can be reduced significantly (Chryssakis 2013). 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.

5.1.3 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 a LCA on basis of the GREET model presented in Chapter 5.1.1. 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, Fischer-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. (Elgowainy et al. 2012)

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. (Stratton et al. 2010)

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 only took into account the utilisation phase of each process 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. (Saynor et al. 2003)

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. (Pereira et al. 2014)

Summarising the results of the above literature, it is clear that drop-in biofuels are seen as the most promising options (Elgowainy et al. 2012; Stratton et al. 2010; Saynor et al. 2003). Hydrogen might become a possible alternative fuel for aviation in the long term (Saynor et al. 2003; Pereira et al. 2014). The pathways examined for supplying these fuels, however, focus on Europe and North America (Elgowainy et al. 2012; Stratton et al. 2010; Saynor et al. 2003; Pereira et al. 2014), 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.

5.2 Definition of methodology

The developed methodology identifies key indicators that describe energy efficiency, GHG emissions, and costs of the investigated fuels. Figure 5-1 visualises the applied terms and definitions.

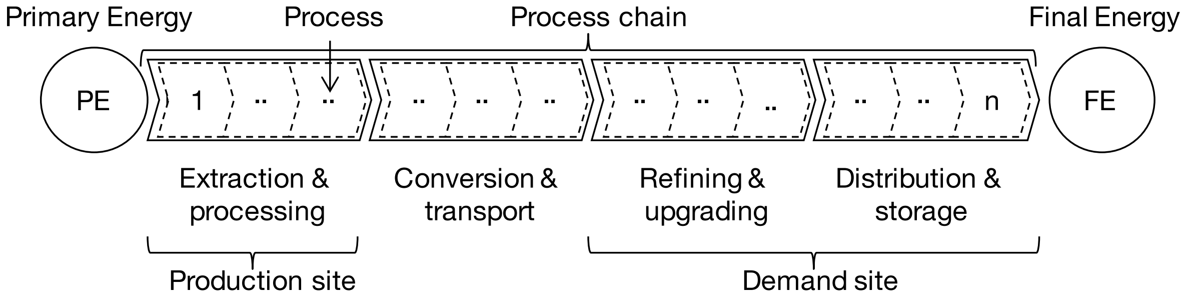


Figure 5-1: Conversion of primary energy to final energy – Applied terms and definitions

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 $\boldsymbol{E}_{\boldsymbol{In,i}}$ equal energy outputs $\boldsymbol{E}_{\boldsymbol{Out,i}}$ plus energy losses $\boldsymbol{E}_{\boldsymbol{L,i}}$.

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

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

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

$$E_{In,i} = E_{Prod,i} + E_{Uti,i} + E_{Disp,i} \tag{2}$$

$E_{Uti,i}$ 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.

$$E_{Uti,i} = E_{Main,i} + E_{Aux,i} \tag{3}$$

Figure 5-2 displays the energy balance for process i and defines the relevant terms.

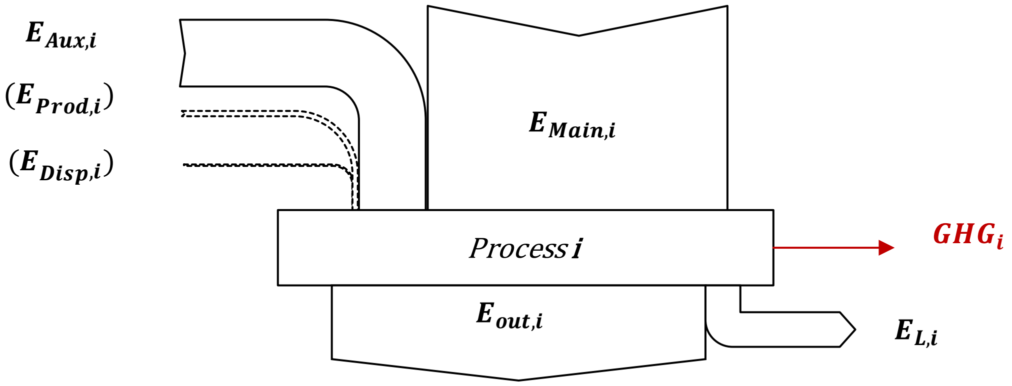


Figure 5-2: Energy balance of a single process

In accordance with other studies investigating well-to-tank (WTT) pathways presented in Chapter 5.1, 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 are 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 $\boldsymbol{E}_{\boldsymbol{Out,i}}$ of each process describes the energy of the target product. Energy losses $\boldsymbol{E}_{\boldsymbol{L,i}}$ are the difference between $\boldsymbol{E}_{\boldsymbol{In,i}}$ and $\boldsymbol{E}_{\boldsymbol{Out,i}}$ that occurs in transformation from inputs to outputs.

$$\boldsymbol{E}_{\boldsymbol{L,i}} = \boldsymbol{E}_{\boldsymbol{In,i}} - \boldsymbol{E}_{\boldsymbol{Out,i}} = \boldsymbol{E}_{\boldsymbol{Main,i}} + \boldsymbol{E}_{\boldsymbol{Aux,i}} - \boldsymbol{E}_{\boldsymbol{Out,i}} \tag{4}$$

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. (Verein Deutscher Ingenieure (VDI) 2012; Dreier 2000; Edwards et al. 2014):

- *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 ($\boldsymbol{E}_{\boldsymbol{Main,i}}$) is equal to the energy output of process $i-1$ ($\boldsymbol{E}_{\boldsymbol{Out,i-1}}$):

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

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:

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

Whereas the energy of the final fuel is included in the 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 5-3 visualises the simplified methodology we use to calculate primary energy and emissions.

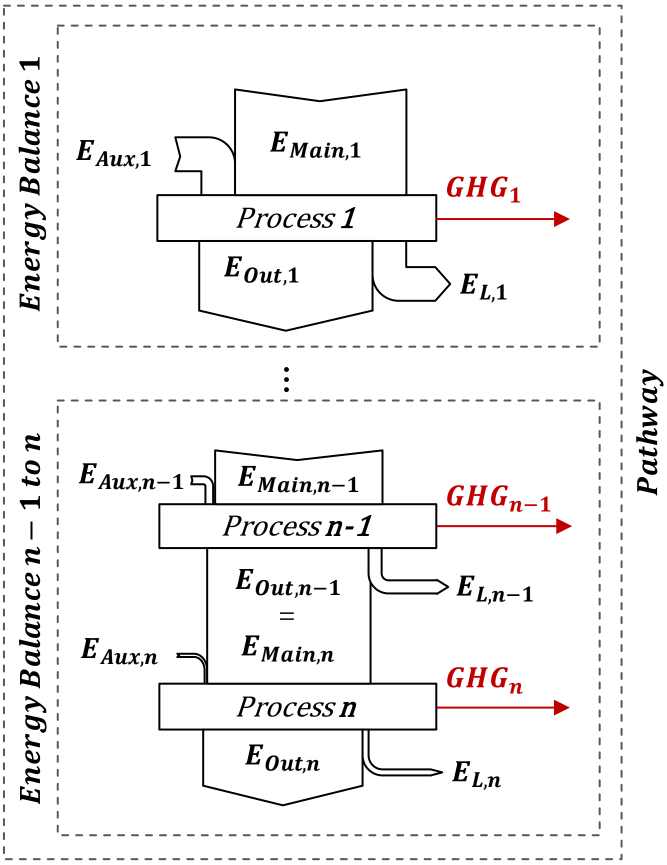


Figure 5-3: Methodology to set up process chains and calculate energy and GHG emissions

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

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

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:

$$\boldsymbol{EROI} = \frac{\boldsymbol{E_{Out,n}}}{\boldsymbol{E_{Main,1}} + \sum_1^n \boldsymbol{E_{Aux,i}} - \boldsymbol{E_{Out,n}}} \tag{8}$$

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

$$\boldsymbol{GHG_i} = \boldsymbol{c_{GHG,i}} \times \boldsymbol{E_{Out,i}} \tag{9}$$

$\boldsymbol{GHG_i}$ 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 $\boldsymbol{E_{Main,i}}$ within a process. Upstream emissions caused by the consumption of $\boldsymbol{E_{Main,i}}$ are allocated to previous processes through an increase of $\boldsymbol{E_{Main,i}}$. As $\boldsymbol{E_{Aux,i}}$ is expressed in terms of primary energy, upstream emissions have to be included for each process separately.

The upstream emissions $\boldsymbol{GHG_{Path}}$ of the total pathway, also referred to as WTT emissions, result from the sum of emissions emitted in every process $\boldsymbol{i}$. 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.

$$\boldsymbol{GHG_{PATH}} = \sum_{\boldsymbol{i}}^{\boldsymbol{n}} \boldsymbol{GHG_i} \tag{10}$$

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 $\boldsymbol{c_{Costs,i}}$ per unit of process output are multiplied by $\boldsymbol{E_{Out,i}}$ to calculate $\boldsymbol{C_i}$ for every process:

$$\boldsymbol{C_i = c_{Costs,i} \times E_{Out,i}} \tag{11}$$

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

$$\boldsymbol{C_{PATH} = \sum_{i}^{n} C_i} \tag{12}$$

5.3 Scenarios

Before chances and challenges caused by international bunker fuels in Singapore can be assessed in Chapter 6, key indicators must be derived for existing and alternative bunker fuels. Applying the methodology described in Chapter 5.2, 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 5.5.2.

Based on the literature presented in Chapter 5.1 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 5-1.

Table 5-1: 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

5.4 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.

Table 5-2 summarises the input data of processes with regard to the methodology presented in this Chapter.

Table 5-2: 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

5.4.1 Conventional fuels

Supply of MFO, MGO, and Jet in Singapore requires a complex supply chain. The essential processes are listed in Table 5-2 and described in the following paragraphs.

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 (OGP 2014; OGP 2013) and shares of crude oil and condensate imports from different world regions according to IE Singapore (IE Singapore 2015). 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 (IE Singapore 2015) and typical fuel consumption of crude oil transport (Smith et al. 2013), 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 (IE Singapore 2015) and resulting average crude quality, complexity data of Singapore's refineries, and heavy product yield (ENI spa 2013; ENI spa 2014) are taken into account. Based on these data, a regression formula for calculating efficiencies of refineries (Cai et al. 2013) 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 (ENI spa 2014; ENI spa 2013), 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 (IE Singapore 2015). 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 (OGP 2014; OGP 2013) 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 5-2, 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 (IE Singapore 2015) and specific fuel consumption for product transport (Smith et al. 2013), 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.

5.4.2 Liquefied natural gas

A description of input data for the LNG pathway shown in Table 5-2 is given in this Chapter.

NG extraction and processing. The energy required to supply the energy for the processes of extraction and processing is highly variable and dependent 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 (Turner & Barker 2013).

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} (Edwards et al. 2014; ARB California & US EPA 2009; OGP 2014; IEA ETSAP 2010; Skone 2012; Lowell et al. 2013; Verbeek et al. 2011; Shell 2010; BG Group plc 2015; Kannan et al. 2005). 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 (Qatargas n.d.). 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 (Edwards et al. 2014), 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) (Attah & Bucknall 2013; Edwards et al. 2014). Usually, insulation in modern LNG carriers is designed so that the energy requirements at the ship's design speed equals BOG (Wang et al. 2014; Aldous & Smith 2012). 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 (IE Singapore 2015). 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 (Edwards et al. 2014). 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 (Edwards et al. 2014; Lowell et al. 2013; Verbeek et al. 2011; Chryssakis 2013), 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. (GL 2013) 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}.

5.4.3 Biofuels

A description of input data for the biofuel pathways in Table 5-2 is given in this Chapter.

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 (U.S. DA 2015b) and high oil yields per area (Kurki et al. n.d.). 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 5.5.3. 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 (Choo et al. 2011; Argonne 2015; Edwards et al. 2014; Uusitalo et al. 2014; Schmidt 2007).

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 (Uusitalo et al. 2014; Schmidt 2007; Edwards et al. 2014; Lee & Ofori-Boateng 2013; Choo et al. 2011). In this simple model, it is assumed 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, surplus heat or electricity produced from fibres and hulls is not taken 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 Southeast 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 (Neste Oil 2014). 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 (Stratton et al. 2010; Edwards et al. 2014; ifeu 2006). 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}.

5.4.4 Liquid hydrogen

A description of input data for the liquid hydrogen pathway in Table 5-2 is given in this Chapter.

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 (Hamacher 2014).

Electricity generation. The WTT approach does not take into account energy demand or emissions for manufacturing, installation, and disposal. 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 (Fred Farchmin 2014). As the efficiencies for both electrolysis technologies are similar (Felgenhauer & Hamacher 2015), 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 (Edwards et al. 2014; Hamacher 2014; Felgenhauer & Hamacher 2015; Simbeck & Chang 2002; Ruth et al. 2009; Ball & Wietschel 2009; Acar & Dincer 2014; Argonne 2015). 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. (Amos 1999) In this paper, an electricity demand for liquefaction of 0.280 MJ_{ele}/MJ_{out} in a range from 0.210–0.300 MJ_{ele}/MJ_{out} is assumed. Literature values show an even broader range with more extreme values (Edwards et al. 2014; Ohlig & Decker 2014; Stolzenburg & Mubbala

2013; Barckholtz et al. 2013; Simbeck & Chang 2002; Ruth et al. 2009; Ball & Wietschel 2009; Argonne 2015).

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 (Barckholtz et al. 2013; Abe 1998; Ball & Wietschel 2009). LH_2 transport has also been investigated in recent publications and projects (Oyama et al. 2012; Mortimer et al. 2013). 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.

5.4.5 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 5-3 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 (Ship & Bunker 2015). 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 (Theo 2015; IATA 2015b), 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 (Walker 2015), and a 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 (IEA ETSAP 2013). 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 5-3: 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 (IEA 2014c) 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 costs 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 (Timera Energy 2013). As with LNG shipping, costs would be highly dependent on fluctuating charter rates and distance travelled (Timera Energy 2015; Timera Energy 2013). 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 (Timera Energy 2015). 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.

5.5 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.

5.5.1 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.

Conventional fuels

Figure 5-4 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.

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 $MJ/MJ_{\text{final fuel}}$ of energy lost and 6.2 $gCO_2eq/MJ_{\text{final fuel}}$ 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$_{\text{final fuel}}$ for both pathways, while GHG emissions of the MGO and Jet fuel pathways total 9.1 gCO$_2$eq/MJ$_{\text{MGO}}$ and 9.2 gCO$_2$eq/MJ$_{\text{Jet}}$, respectively.

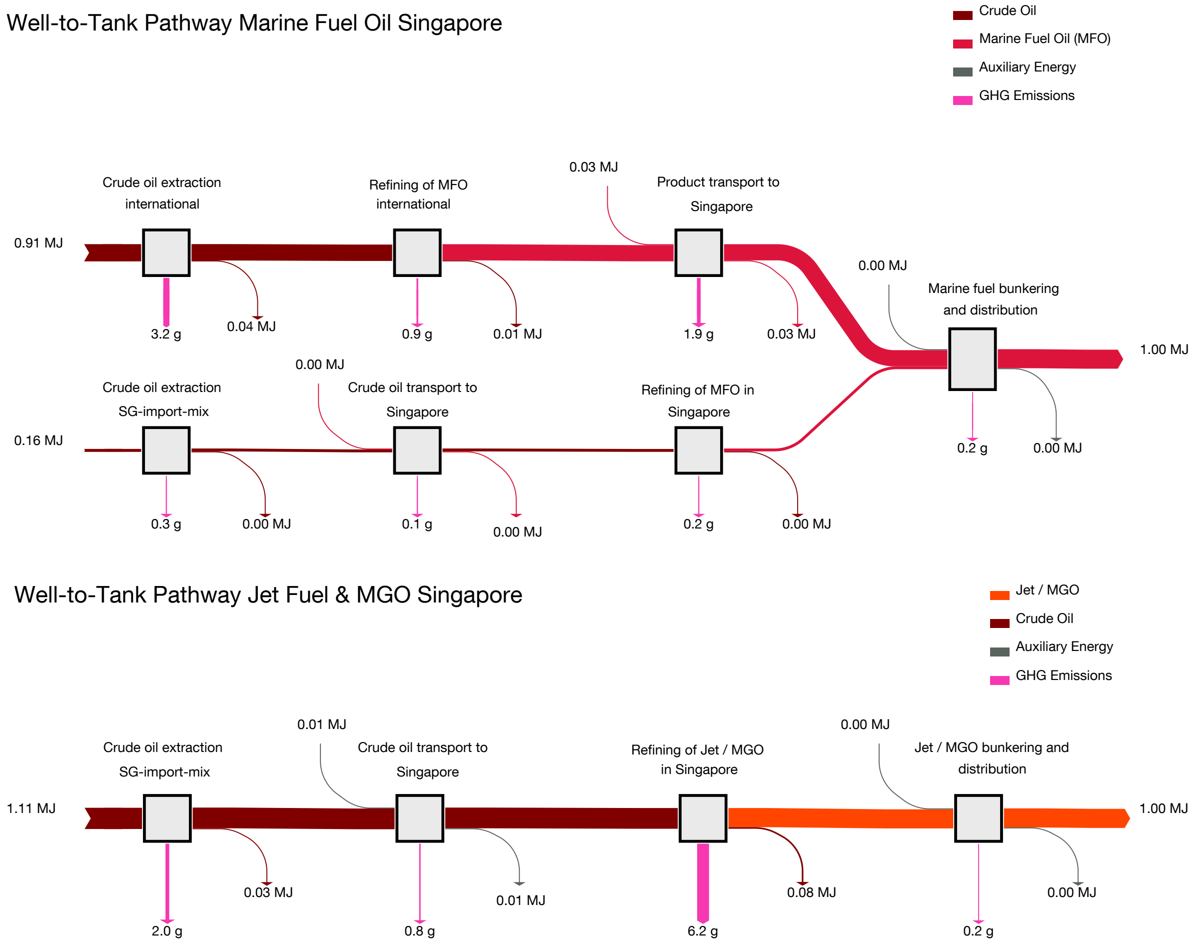


Figure 5-4: Energy flow and GHG emissions for MFO, MGO, and Jet fuels in Singapore

Liquefied natural gas

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

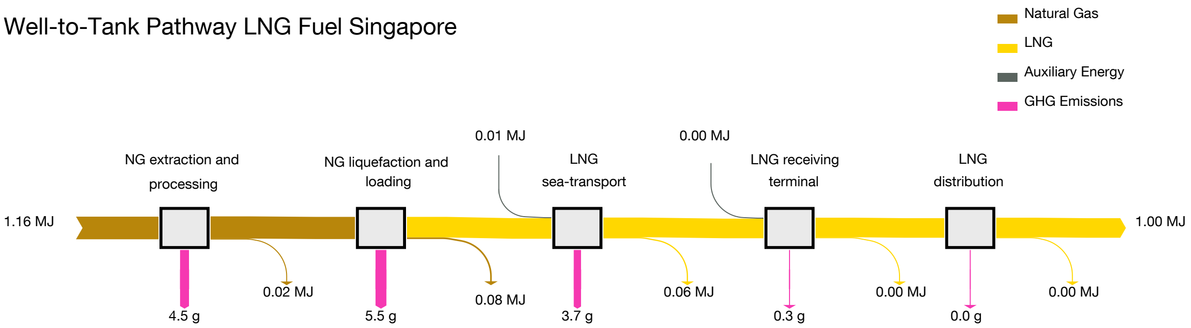


Figure 5-5: Energy flow and GHG emissions for LNG as a bunker fuel for ships in Singapore

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 NG 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. NG liquefaction and loading (5.5 gCO_2eq/MJ_{LNG}) has the highest GHG emissions within the process chain, followed by NG 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}.

Biofuels

Figure 5-6 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.

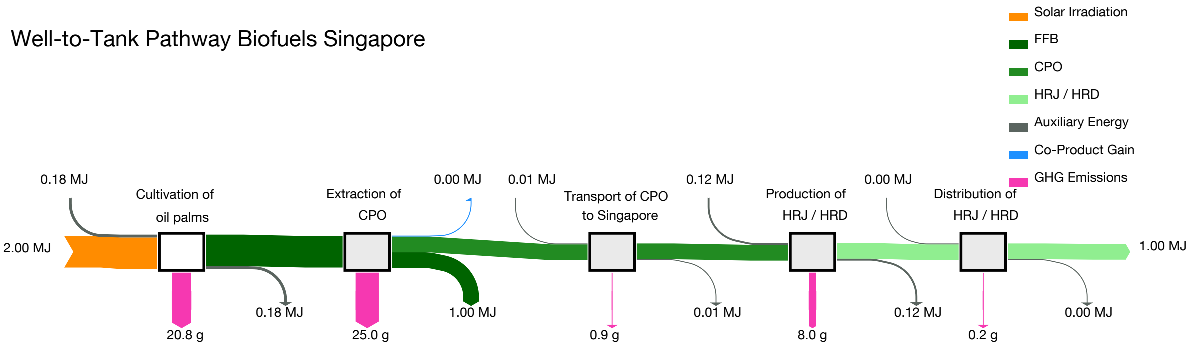


Figure 5-6: Energy flow and GHG emissions for hydrogenated renewable jet fuel and diesel in Singapore

The overall CED is particularly affected by the extraction of crude palm oil (CPO) (1.00 MJ/MJ$_{\text{final fuel}}$). Cultivation of oil palms (0.18 MJ/MJ$_{\text{final fuel}}$) and production of hydrogenated fuel (0.12 MJ/MJ$_{\text{final fuel}}$) cause significant energy losses. Transport of CPO (0.01 MJ/MJ$_{\text{final fuel}}$) and fuel distribution contribute only marginally to the overall CED (2.31 MJ/MJ$_{\text{final fuel}}$). GHG emissions are highest for extraction of CPO (25.0 gCO$_2$eq/MJ$_{\text{final fuel}}$), cultivation of oil palms (20.8 gCO$_2$eq/MJ$_{\text{final fuel}}$), and production of fuels (8.0 gCO$_2$eq/MJ$_{\text{final fuel}}$). Transport of CPO (0.9 gCO$_2$eq/MJ$_{\text{final fuel}}$) and distribution of fuels (0.2 gCO$_2$eq/MJ$_{\text{final fuel}}$) have little impact on pathway emissions. The overall upstream emissions in the hydrogenated diesel and jet fuel pathways add up to 54.8 gCO$_2$eq/MJ$_{\text{HRD}}$ and 54.9 gCO$_2$eq/MJ$_{\text{HRJ}}$, respectively. Technological improvements and handling of co-products can have a high influence on CED and GHG emissions. Impacts are further discussed in Chapter 5.5.2.

Liquid Hydrogen

Energy flow for liquid hydrogen as a zero emission fuel in Singapore is visualised in Figure 5-7.

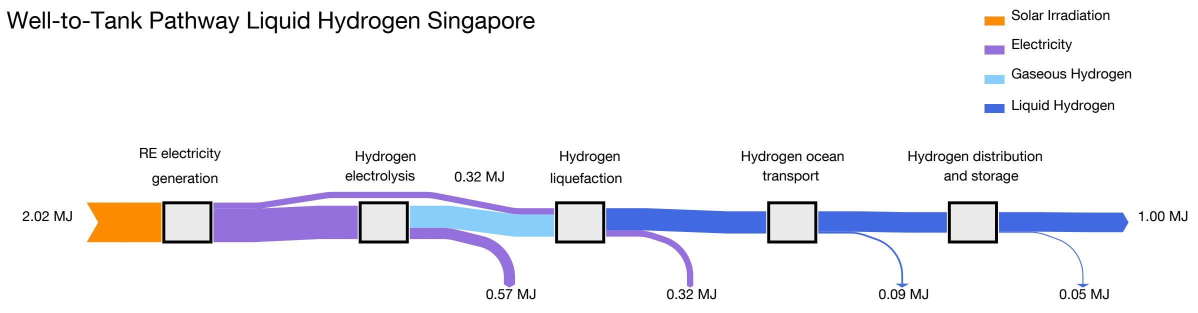


Figure 5-7: Energy flow and GHG emissions for liquid hydrogen as zero emission fuel in Singapore

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$_{\text{LH2}}$), followed by hydrogen liquefaction (0.32 MJ/MJ$_{\text{LH2}}$) and ocean transport (0.09 MJ/MJ$_{\text{LH2}}$). Owing to leakage, energy losses in LH$_2$ distribution (0.05 MJ/MJ$_{\text{LH2}}$) are significant. The overall CED of the process chain is 2.02 MJ/MJ$_{\text{LH2}}$. Technological improvements and future capacity to handle hydrogen leakage losses will have a big impact on overall energy efficiency of this pathway.

5.5.2 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 5-4. Sensitivities of process chains are investigated by substituting **ave** parameters with **min** and **max** values according to Table 5-2.

Table 5-4: 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	=	=	=	=

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 **ave** to **max** values 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 5-2, 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 5-2, 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 **ave** to **max** values 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 5-2 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).

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** values would reduce total energy demand by 7% and GHG emissions by 16%. The **max** values would increase process chain energy demand by 20% and GHG emissions by 24%. Higher liquefaction efficiencies could reduce the 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.

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.

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%.

5.5.3 Comparison of pathways

Cumulative energy demand

Figure 5-8 compares the CED of the investigated pathways by allocating the energy losses occurring in single processes to the four main groups described in Chapter 5.2.

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.

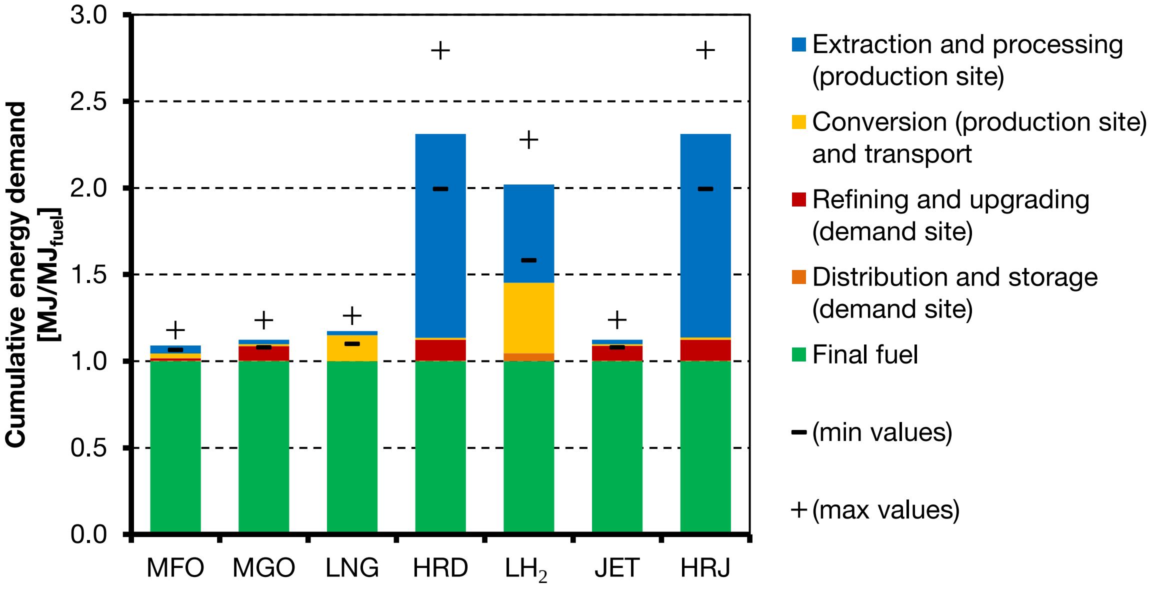


Figure 5-8: Cumulative energy demand of fuel process chains by process stage

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}. $(EROI_{min} = 1.7,\ EROI_{ave} = 1.0,\ EROI_{max} = 0.8)$

GHG emissions

In Figure 5-9, 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.

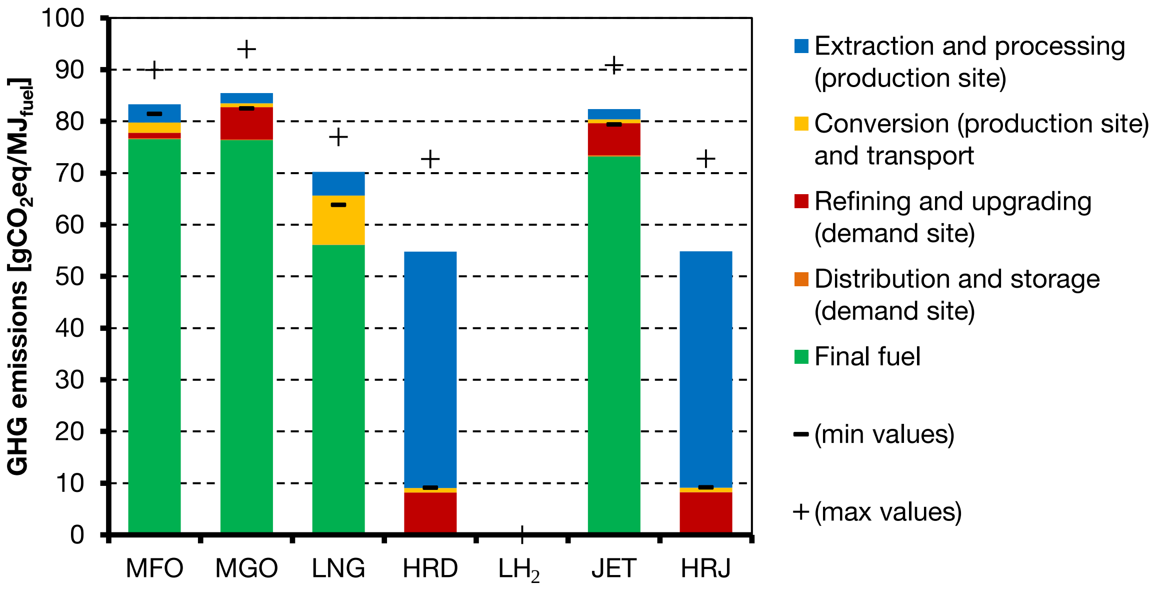


Figure 5-9: GHG emissions of fuel process chains by process stage

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} (Stratton et al. 2010)), 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 have 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_{HRJ} 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 (Edwards et al. 2014) 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).

Costs

The costs of final fuels resulting from our modelled process chain of hydrogen and taken from market data are displayed in Figure 5-10. Prices for fuels are determined by markets; as there is no market for hydrogen, its costs are assessed based on the underlying process chain.

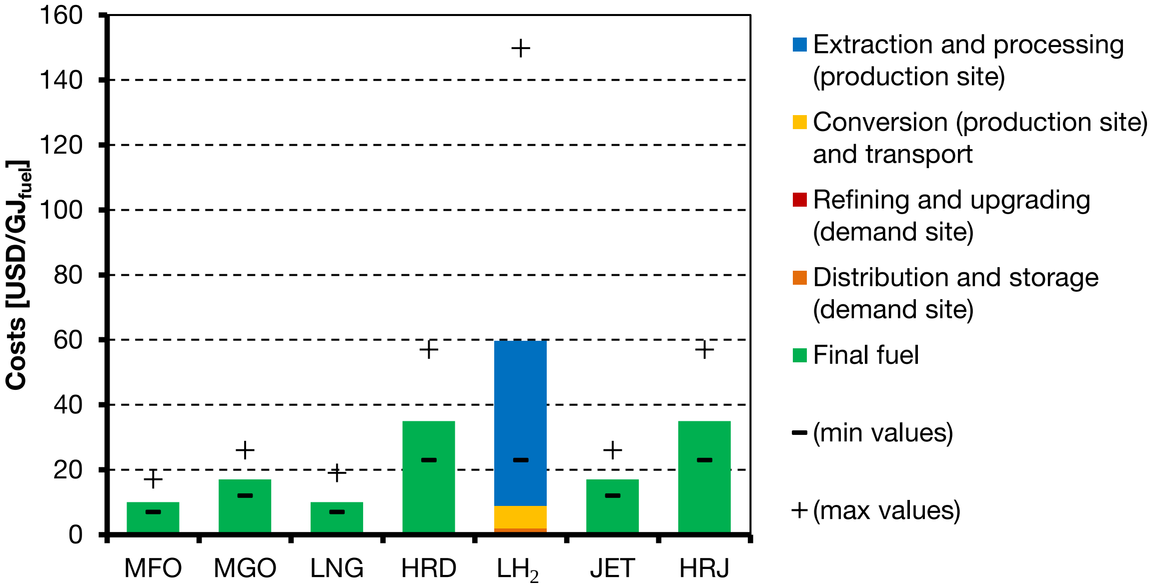


Figure 5-10: Costs of fuel process chains by process stage

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 have been 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.

5.6 Comparison of results with related literature

Results of the WTT analysis of Singapore's pathways were compared to the outcomes of the other studies discussed in Chapter 5.1. 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 5-5.

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

Related Literature	MFO	MGO	LNG	HRD	LH$_2$	JET	HRJ
JEC	HFO	COD1	GRLG1	POHY1a	WDEL1/ LH1		
Bengtsson	HFO	MGO	LNG	BTL			
Verbeek	HFO	MGO	LNG Qatar				
Chryssakis	HFO	MGO	LNG Qatar	Biodiesel	H2 RE		
Brynolf	HFO	MGO	LNG	BTL$_W$			
Stratton						Crude to conv. jet fuel	Palm oils to HRJ (LUC-P0)
Saynor					H_2 OSW		Biodiesel

Figure 5-11 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.

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 5.4). 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 JEC WTT study.

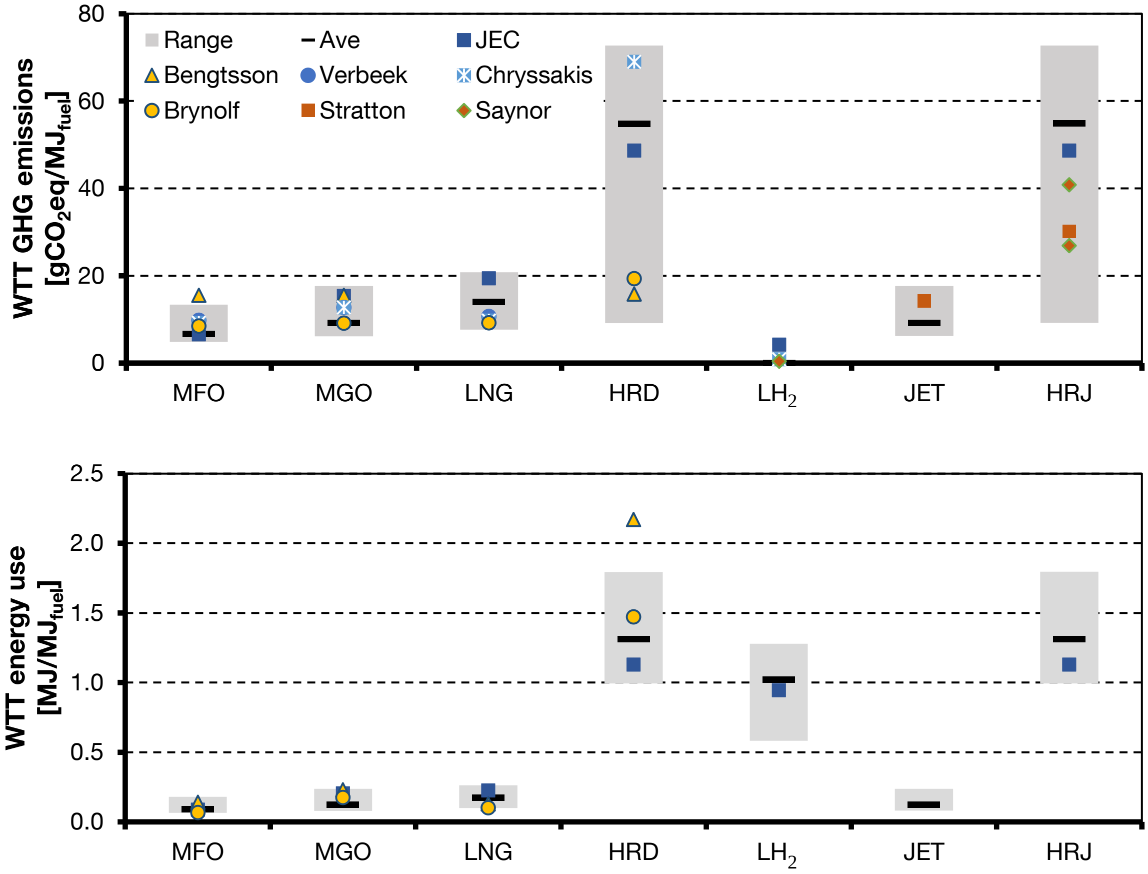


Figure 5-11: Comparison of Well-to-Tank GHG emissions and WTT energy use with other studies

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.

6 Effects of a sustainable energy supply on hub cities

Chapter 6 discusses opportunities and challenges for Singapore that arise from the interplay between globalisation and sustainable development. In a short outlook, applicability and transferability of the results to other hub cities are discussed.

Chapter 2 shows that forces of trade and globalisation led to the emergence of hub cities. A detailed analysis of Singapore's economic activity and energy consumption shows that there is a high import dependency of fossil fuels (Chapter 3). The energy consumption in Singapore is dominated by bunker fuels. In Chapter 4, an assessment of future trends and technologies shows that fuel consumption is unlikely to decline in the future. Technological alternatives to conventional fuels for ships and aircraft are presented. On this basis, a Well-to-Tank analysis is done to assess the impact of alternative fuel pathways (Chapter 5). The impacts on energy efficiency, greenhouse gas emissions, and costs are analysed.

Chapter 6 draws conclusions based on the results of previous Chapters. It is divided into four parts.

Chapter 6.1 analyses the resource potentials and availability of alternative energy carriers to supply bunker fuels for international transport in Singapore. While the fast growing LNG market is likely to satisfy new demands in Singapore, vegetable oil potentials in the region are limited and not sustainable to develop. Hydrogen might become a long term alternative, if prices and transportability make a large scale global supply chain a feasible solution. In the future, it seems likely that a mix of different fuels will evolve in contrast to the current situation in which most of fuel demand is satisfied by petroleum based fuels.

Opportunities and challenges for Singapore that would arise if supply of bunker fuels became more sustainable, are discussed in Chapter 6.2. A diversification of energy carriers will not be able to reduce the import dependency of Singapore, but will contribute to broaden the range of possible energy sources and lessen the focus on petroleum fuels. While Singapore's local potential to decrease GHG emissions is limited, substitution of bunker fuels could lead to significantly less global emissions caused by trade. By introducing alternative bunker fuels, Singapore's petroleum focussed energy hub could transform into a multi energy hub. Synergies of alternative fuels with petroleum fuels outweigh possible competition, as a relatively slow substitution is expected.

Chapter 6.3 discusses the transferability of the results investigated based on Singapore for other hub cities. Owing to other types of specialisations resulting in less specific energy consumption, it is often easier to supply other hub cities with sustainable energy. However, a change from the existing fossil fuel based to a more sustainable energy supply will affect places with higher energy demands.

Chapter 6.4 highlights that a sustainable energy supply questions the structure of the globalised world economy and increases the pressure towards regionalisation. However, it is uncertain if higher energy costs and fundamental changes in energy supply will limit growth or even lead to a declining importance of hub cities. In order to assess the impact of a sustainable energy supply on the future development of hub cities, their overall economic benefit has to be opposed to additional costs arising from their high local energy demand.

6.1 Potentials of alternative energy carriers

There are a couple of studies that investigate sustainable energy supply in Singapore. M. Wagner et al. investigated impacts of different power plant technologies on the future power system of Singapore. Only fuels and energy consumed within Singapore's land area were taken into account. Electricity imports from the surrounding countries were not investigated. Owing to Singapore's high population density, small land area, and scarce renewable potentials, Singapore's energy consumption will be highly dependent on energy imports. A future reduction of GHG emissions from current levels appears unlikely to happen in the case that electricity is generated within Singapore. (Wagner et al. 2014)

J. Stich and T. Massier investigate the possibility of a transnational ASEAN (Association of the Southeast Asian Nations) power grid to supply growing energy demand in Southeast Asia and integrate renewable energy sources. The paper proves that an inter-country grid could reduce costs of renewable energy supply and therefore contribute to climate change mitigation. It has to be emphasised that current political situation and tensions hinder the development of an interregional grid and strengthen tendencies to national electricity autarky based on fossil energy carriers. (Stich & Massier 2015)

The energy balance of Singapore for 2012, which is presented in Chapter 3, shows that bunker fuel supply for ships and aircraft in Singapore require more than 2 EJ while roughly 0.8 EJ are supplied to satisfy domestic energy demand in Singapore. The investigations in Chapter 4 predict that fuel demand for international transport services will further increase. Therefore, a sustainable bunker fuel supply will be a key issue for a sustainable energy supply of hub cities. In the following paragraphs, resource and market potentials of the presented alternatives (Chapter 5) to conventional energy carriers are analysed.

6.1.1 Liquefied natural gas

Natural gas is the cleanest fossil energy carrier as its combustion results in lower GHG emissions than oil or coal. Natural gas supplied about 22% of the world's energy demand in 2012 (IEA 2014a). Gas markets are still dominated by piped natural gas, which supplies around 90% of global demand. The remaining 10% are supplied by LNG, whose share is forecasted to increase in the next years. In 2014, LNG trade was 241.1 million tonnes per annum (MTPA), which is equivalent to around 11,809 PJ assuming a LHV of 49 GJ/t (Schönsteiner et al. 2016). Total liquefaction capacity was 14,759 PJ and is expected to increase to over 21,036 PJ till 2020. At the moment, Qatar (3,763 PJ) has the largest market share, followed by Malaysia (1,229.9 PJ), Australia (1,141.7 PJ), Nigeria (950.6 PJ), and Indonesia (784 PJ). Till 2018, liquefaction capacity in Australia is forecasted to increase to 3,964 PJ. With new liquefaction capacity of 2,161 PJ till 2020, the US will become third largest LNG exporter. Regasification capacity was 35,476 PJ in 2014. Japan (4,356 PJ), South Korea (1,862 PJ), China (980 PJ), and India (715 PJ) were the largest importers. Total LNG fleet consisted of 373 carriers with a cumulated capacity of 55 million m^3 (24.75 Mt, 1,213 PJ). (IGU 2015)

BP forecasts a strong demand growth for natural gas accompanied by a more than doubling of global LNG demand till 2035 (BP plc 2015a). Demand in the Asia-Pacific region will triple. Exxon Mobil predicts a tripling of global LNG trade till 2040 (Exxon Mobil 2015). Both studies emphasise that the fastest growth of demand will take place in the Asia-Pacific region.

Resources and reserves of natural gas are plentiful compared to oil. Availability and statistical reach is higher compared to oil reserves. With respect to IEA's demand forecasts for 2040, BGR assess future availability of oil and gas to be *"relaxed"* as estimated cumulated production is much lower than available reserves (BGR 2014).

Summing up, even a complete substitution of Singapore's bunker fuels by LNG seems possible. Expected LNG production in 2020 is more than ten times higher than energy demand for conventional bunker fuels in Singapore today. Even a projected doubling or tripling of bunker fuel demand in the next decades could be supplied by LNG in principle, as LNG production and trade will experience significant growth.

6.1.2 Biofuels

As shown in Chapter 4, biofuels can be produced based on different feedstock. Vegetable oils are identified as most promising alternatives for conventional fuels. The U.S. Department of Agriculture reports a production of 176 million tonnes of major vegetable oils for the report year 2014/2015 (U.S. DA 2015a). Palm oil with a production of 61 million tonnes and soybean oil with a production of 48 million tonnes accounted for more than 60% of global vegetable oil production. Rapeseed and sunflower seed added 27 million tonnes and 15 million tonnes to this amount. Palm kernel oil, which is also produced from oil palms, increased annual production by 7 million tonnes. The remaining amount was supplied by other types of oil. In 2014/2015, major palm oil producers were Indonesia (33 million tonnes), Malaysia (20 million tonnes), and other countries with accumulated 9 million tonnes (U.S. DA 2015b). Singapore, as a direct neighbour to Malaysia and Indonesia, is situated in close geographical proximity to oil palm production. Assuming a LHV of 37 GJ/t (Schönsteiner et al. 2016), palm oil production in Indonesia and Malaysia would add up to 2.0 EJ, which is in the order of magnitude of bunker fuel supply in Singapore. As shown in Chapter 4, energy consumption of international transport is likely to increase significantly in the future. In order to meet Singapore's fuel needs, cultivation area would be required to multiply. Considering resulting upstream GHG emissions (compare Chapter 5.5, land use change) and competition with food production, these developments would be unsustainable.

6.1.3 Hydrogen

Hydrogen from renewable energy sources might become a long term option to supply hydrogen as bunker fuels for ships and aircraft in Singapore. In this investigation, hydrogen is supplied from remote areas with high renewable energy potentials and use of deserted areas.

Future demand of renewable energy to supply hydrogen is depending on fuel economy of future transport technologies, transport demand, and energy losses during Well-to-Tank provision. Therefore, estimations of demand and potentials are subject to various assumptions and high uncertainties.

Based on above described pathways and an assumed efficiency increase of 15%, K. Schönsteiner et al. estimate an energy demand of 3.5 EJ to supply current demand of marine and aviation bunkers in Singapore (Schönsteiner et al. 2016). Assumed land use factors for solar PV and typical capacity factors require an installed PV capacity of 508 GW covering an area of 16,000 km^2. Globally, IEA estimated 177 GW of installed PV capacity in 2014 (IEA PVPS 2015). A completely new supply chain for energy would be required to enable such a supply of new fuel, but potentials are technically available. An implementation is subject to future costs of renewable electricity and possible alternatives.

6.1.4 Limited energy availability

The analysis above shows that the potentials of alternative fuels are limited. For marine bunkers, LNG is the only fuel that is available in sufficient quantities to allow a complete substitution of conventional fuels. Biofuels may become an interesting alternative as drop-in fuels for the aviation industry. However, huge energy requirements would probably force an extension of palm oil plantations and question sustainability and life cycle emissions of these fuels. For a significant reduction of GHG emissions, hydrogen generated from renewable energy sources is the only available option in the long term. Currently costs for LH_2 as fuel are not competitive (Schönsteiner et al. 2016). Therefore, a fast replacement of fossil fuels by one dominating technology seems unlikely. Instead, a piecewise substitution of conventional energy carriers by different alternatives, similar to current developments in the road transport sector, seems more likely.

6.2 Opportunities and challenges for Singapore

Three major areas of emerging opportunities and challenges are identified that may result from the transformation of Singapore's bunker market towards a more sustainable energy system:

- Diversification of energy carriers
- Climate change mitigation
- Transformation of economic model

These issues are discussed in the following Chapters.

6.2.1 Diversification of energy carriers

The energy balance in Chapter 3.3 shows, that Singapore's energy imports are dominated by crude oil and petroleum products. Current trade, refining, petrochemical, and bunkering industry force a high import dependency on associated inputs. There are two negative consequences:

- Strong import dependency on single regions or countries: while Singapore is heavily dependent on the Middle East as crude exporter, its sources of petroleum products are diverse (compare Chapter 3.3).
- The Concentration on crude oil and petroleum products causes heavy reliance on oil price and market developments as cheaper imports of energy are opposed to reduced prices for exported petroleum products and bunker sales. In addition to lower feedstock prices, low oil prices tend to stimulate global consumption and therefore benefit some of Singapore's export products. However, manufacturing companies that are integrated into oil supply chain, such as rig builders or offshore supply companies, may suffer in a low oil price environment.

IEA forecasts increasing crude oil imports into Southeast Asia in the next three decades, caused by growing demand and more refining capacity in the region. This will increase further dependency on countries in the Middle East (IEA 2015b).

Owing to Singapore's limited land area, scarce renewable potentials, and high energy consumption, there are no options to significantly lower Singapore's amount of energy imports, besides reductions in energy consumption or trade volumes.

By substituting conventional bunker fuels by alternative fuels, dependencies on crude oil and petroleum products would decline.

Compared to oil exports, which are dominated by the Middle East, LNG trade will become a much more diversified market in the future with Australia, USA, Qatar, and countries from Africa as major exporters.

The origin of biofuels to serve as bunker fuels in Singapore will depend on the type of feedstock. Indonesia and Malaysia offer large potentials of palm oil. However, it is doubtful that the huge quantities required could be supplied without significant land use changes in these countries. Second-generation biofuels, made of waste and residues, or tertiary biofuels, produced from algae, are additional options but not yet implemented in significant scales.

So is hydrogen production from renewable energy sources. In principle, all countries with low costs of renewable energy generation and corresponding potentials could become possible exporters of hydrogen. Future business models and energy markets will be decisive if hydrogen trade becomes a feasible solution.

Summing up, a substitution of conventional bunker fuels by the above mentioned alternatives would reduce dependency on petroleum based fuels and broaden the range of fuel sources to supply Singapore's energy needs. Its dependency on energy imports will continue.

6.2.2 Climate change mitigation

Potentials within Singapore. As shown in Chapter 3, Singapore's economic growth has been closely linked to rising energy consumption. Owing to a lack of adequate renewable energy sources within the country and its high share of very efficient electricity production from natural gas, Singapore will not be able to significantly reduce carbon emissions within its borders.

M. Wagner et al. discuss the integration of photovoltaics, coal, and nuclear power plants into Singapore's gas dominated electricity generation (Wagner et al. 2014). Future energy consumption, GHG emissions, and installed capacity is forecasted till 2050. Different scenarios for future developments of the road transport sector are presented. Bunker fuels and energy exports are not taken into account. Results of the scenarios predict that only integration of nuclear power plants could hinder an increase of emissions from 2010 levels.

Singapore's national goals to reduce carbon emissions reflect these circumstances. In its "intended nationally determined contribution" (INDC), which was published in connection with the 2015 United Nations Climate Conference, Singapore declares its intended measures to contribute to climate change mitigation. The INDC comprises two main goals (Singapore 2015):

1. Reduction of GHG emission intensity by 36% in 2030
2. Limitation of total GHG emissions to *"around"* 65 million tonnes in 2030 based on current projected growth

Fuels for international marine transport and aviation are not included in these targets.

Potentials of bunker fuels. Detailed analysis of GHG emissions in Singapore is carried out in Chapter 3.3, which discusses the impact of the treatment of international bunker fuels in Singapore's Energy Statistics on its GHG emissions. Current emission levels reported by different organisations publish GHG emissions around 45-50 million tonnes (IEA 2015a; Singapore NEA 2014) without allocation of international bunker fuels to national energy use and up to 226 million tonnes (BP plc 2015b) with allocation of international bunker fuels to national energy use.

A rough estimation of the emission reduction potential is discussed by K. Schönsteiner et al. and shows the effects on global emissions if Singapore's current bunker fuel demand is substituted by alternative fuels (Schönsteiner et al. 2016):

- Fuel amounts are based on data of IEA for consumption of international marine bunkers and international aviation bunkers reported for 2012.
- Well-to-Tank GHG emissions are calculated for the pathways presented in Chapter 5. The MFO pathway is used for international marine bunkers and the Jet pathway for international aviation bunkers. Slightly higher emissions of MGO are not taken into account, as IEA does not distinguish between these fuel types and most of the bunker fuels sold in Singapore are heavier fuels.
- GHG emissions of bunker fuels are calculated to 140–155 million tonnes GHG for international marine bunkers and 23–26 million tonnes GHG for international aviation bunkers. (If data from the energy balance presented in Chapter 3.3 are used, total emissions of marine bunkers are slightly higher by around 1% taking into account the exact amounts of MGO and MFO)
- Total substitution of conventional marine bunker fuels using LNG could lower GHG emissions by 22–30 million tonnes. Biofuels could reduce GHG emissions of marine and aviation bunker fuels by 35–144 million tonnes. Use of LH_2 would result in complete avoidance of GHG emissions caused by international bunker fuels.

Summing up, Singapore's potential to reduce GHG emissions is limited on a local scale. However, as the world's biggest bunkering port and a leading aviation hub, Singapore's influence on fuels for international transport is high. GHG reduction potentials by substituting international bunker fuels are much higher than its local potentials, which are limited to increasing energy efficiency.

Singapore will not be able to implement measures on its own, as it is dependent on a cost efficient transport system (Chapter 6.4). However, its big market shares on bunker sales and its unique position in the network of international trade make Singapore an important key player to shape future developments towards sustainable transport.

6.2.3 Transformation of economic model

Singapore – Petroleum hub. Energy conversion and trading, accompanied by industries for oil and gas exploration, has been playing an important role in Singapore's economic development (Ng 2012), which is described in Chapter 3: Singapore imports large amounts of crude oil and petroleum products for refining and distributing products for Asian countries and supplying bunker fuels for international transport such as marine fuels for ships and jet fuels for aircraft. Its domestic demand for industry, transport, and other sectors is comparably small. Its unique geographical position between the major crude exporting countries and the locations of high demand, especially Southeast Asia and Oceania, favour this business model. A big local bunker fuel market reduces dependency on export markets of other Asian countries. Its excellent infrastructure, trade finance, and energy media supported Singapore to become the pricing centre for refined fuels in the Middle East and Asia (Ng 2012; Platts 2014). Singapore has developed itself to one of the most important energy hubs, dominated by oil and petroleum products.

Challenges caused by alternative bunker fuels. A substitution of conventional bunker fuels by alternative fuels raises the question how Singapore's local oil industry would be affected by such developments. In order to assess possible challenges, future trends and the current situation have to be taken into account:

- A rising energy demand for crude oil and oil products is forecasted in Southeast Asia. According to IEA, demand of crude oil and condensate imports will more than triple to 5.5 million barrels per day owing to increasing refinery capacities and declining regional production. Trade of petroleum products will decline from 1.5 million barrels per day to 1.3 million barrels per day in 2040. Total oil demand will increase by 2.6 million barrels per day to 8.5 million barrels per day in the same period. The Middle East will remain the most important supplier of crude oil. As a consequence, East-West flows of oil and gas in the Strait of Malacca are forecasted to grow from 18 million barrels per day to 25 million barrels per day in 2040. Even in scenarios that favour alternative routes a small growth of energy flows is expected from today's levels (less than 3 million barrels per day). (IEA 2015b)
- As presented in Chapter 3, refineries in Singapore focus on production of petroleum products, such as gasoline, diesel, or jet fuel for Asian markets – not on bunker fuels. Most of Singapore's fuel oil is imported, split into smaller quantities, and supplied to ships as bunker fuels or distributed to other Asian countries.
- As presented in Chapter 4, the economic development and population growth will lead to increasing demands of marine and air transport. Owing to limited technological improvements, these demands will translate into higher energy requirements. For both, air transport and marine transport, a doubling of

transport demand is forecasted within the next two decades. In contrast to fast increasing energy demands, only a slow substitution of marine fuels or aviation fuels is expected. As the technology assessment of Chapter 4 shows, long lifecycles of ships and aircraft, lack of available zero emission technologies, and costs of alternative technologies hinder a faster adoption of the investigated substitutes.

Analysing these trends leads to the conclusion, that Singapore will remain at a central position of future oil and product trade. However, there might be rising competition from refineries in other Asian countries. As future demand of oil and oil products is expected to be high and a possible substitution of bunker fuels with alternative energy carriers is presumed to be slow, no immediate negative effects on local industries are expected in the mid-term.

Synergies with established businesses. Alternative bunker fuels will profit from synergies with the existing petroleum industry and related services. Advantages arise when alternative fuels become an integral part of Singapore's energy system. Consequently, Singapore can offer these at more competitive prices than other ports.

Economies of scope, as described in Chapter 2.1, will affect use of alternative bunker fuels in Singapore. These fuels will profit from supporting services, which are well established and available in Singapore owing to the existing bunkering and conventional petroleum businesses:

- Expert knowledge and workforce in bunkering business, trade, and finance
- Excellent infrastructure and a reputation for transparent markets, procedures, and quality of fuel supply
- Linkages to consumers
- Huge demand for marine and aviation fuels

In addition, different substitutes will profit from specialised businesses. Singapore's LNG terminal offers the possibility to trade and regasify LNG for domestic use. P. Turner and A. Barker forecast a rapid development of Singapore's LNG demand starting with the opening of Singapore's LNG terminal in 2013 from zero to over 10 million tonnes in 2025, as piped natural gas from Indonesia and Malaysia will start to deplete in 2018 (Turner & Barker 2013). The existing LNG terminal and available quantities offer an excellent basis for additional developments towards LNG bunkering. Hydrogen and biofuels could profit from other businesses in Singapore as well. Refineries require large quantities of hydrogen for hydrocracking processes. Accordingly, it is an established market for hydrogen products. Specialised companies, such as Linde and Air Liquide, produce hydrogen in Singapore. In the start-up phase, regional knowledge and established businesses will certainly help to introduce hydrogen as a fuel for bunkering. Singapore is home to several biofuel companies and biofuel production. Besides Neste Oil's biofuel refinery, agribusiness company Wilmar International, one of the largest owner of palm oil plantations in Malaysia and Indonesia and an integrated biofuel company, has its headquarters in Singapore and is listed on the Singapore stock exchange.

But synergies with existing businesses will also lead to economies of scale (compare Chapter 2.1): for instance, the substitution of bunker fuels can support ambitions of Singapore to become the price giving hub for LNG (SLNG 2015; Turner & Barker 2013). The IEA and H. Rogers and V. Stern stress that the LNG market in Asia is dominated by the large importing countries Japan, South Korea, and China (IEA 2013; Rogers & Stern 2014). Increasing local demand by e.g. LNG bunkering to ships would increase the relatively small local gas demand for power generation and industry use in Singapore. The resulting higher quantities of LNG would result in a larger throughputs and a higher frequency of LNG carriers. Consequently, price setting and market conditions would be supported by a higher number of transactions and more market participants. Further, a strong local demand would decrease dependency on other countries, which import LNG for own consumption.

Future – multi energy hub. The recent integration of Singapore's first LNG terminal shows that its petroleum hub is transforming into a multi energy hub. Substitution of conventional bunker fuels for marine and aviation by alternative fuels can support this development. Synergies with existing industries outweigh possible competition and offer advantages for an integration of alternative fuels compared to other ports.

6.3 Transferability to other hub cities

The presented energy balance in Chapter 3.3 visualises, that Singapore being the leading port for marine bunkering and a major airport hub is certainly an extreme example for energy consumption in hub cities.

However, also other cities experience increased energy demands, caused by their central position in national and international networks. Besides fuel supply for international marine and aviation transport, other specialisations are characterised by strong hub-and-spoke network behaviour and lead to high local energy demands.

Two further examples highlight how specific specialisations increase local energy demand in other hub cities:

Being home to the largest airport in Germany, Frankfurt am Main is a major hub for passenger and goods transport. But, it is also Germany's most important financial centre and the world's most important internet exchange point (DE-CIX Management GmbH 2015). Data centres consume more than 20% of electricity consumed in Frankfurt, which is equivalent to private household consumption (Trauthig 2014). Further growth of electricity demand of data centres is forecasted (Trauthig 2014). This example shows that also transfer, storage, and processing of information results in high local energy demand. In this context, it has to be emphasised that large virtualised data centres tend to be more efficient than decentral solutions (Herzog & Poguntke 2013). Consequently, the overall efficiency of IT systems increases with higher local demands at selected places.

The combination of early venture capital and high tech industry contributed significantly to the development of Silicon Valley to the world's most important information and communication cluster. It is home to companies such as Apple, Google, and Intel. Entrepreneurship and innovation have led to a highly successful knowledge society and forced the settlement of many international companies such as Nestle, Siemens, and Volkswagen. Knowledge created is transferred to companies and does not necessarily require large amounts of energy to be produced or distributed, but the supply of internationally required knowledge services increases local energy demand.

Owing to their higher share of interregional services, hub cities are characterised by increased energy demands, which often exceed local availability. Depending on the type of specialisations, the overall energy demand is strongly linked to local circumstances. The characteristics of hub cities related to energy demand, caused by economic activity and availability of land and sustainable energy potentials, have to be assessed for each hub city individually. Although hub cities with significantly lower specific energy requirements per land area or per capita are easier to supply than others, a sustainable energy supply will lead to rising difficulties to supply these energy sinks.

6.4 Regionalisation

In the previous Chapters, the effects of a sustainable energy supply on hub cities as isolated systems are discussed. This Chapter focuses on the question, if a sustainable energy supply could lead to more regionalisation and a declining importance of global trade, global division of labour, and global networks.

This question arises from the contrary characteristics of the formation of global hub cities and of the limited local availability of sustainable energy. As introduced in Chapter 2.1, hub cities result from economic advantages. Diversity and economies of scale lead to the formation of specialised hub cities. Different theories describe the formation and development of cities. Advances in technology and availability of energy have led to the emergence of networks with highly interconnected nodes supplying specialised products and services to global markets. On the contrary, a sustainable energy supply shows strong diseconomies of scale. As explained in Chapter 2.3, sustainable energy potentials are limited locally. Harvesting of renewables, such as wind, solar, or biomass, requires land area. Usually, the most economic locations for harvesting of renewable energy are used first. This results in increasing costs with rising capacities. If energy demand exceeds local economically feasible availability of renewables, energy has to be imported from remote places with an excess of energy production. Further, transport of energy leads to higher costs.

Impacts of a sustainable energy supply. The current economic network has been formed out of the equilibrium of changing globalising and regionalising forces. As shown in Chapter 2, recent decades were determined by increasing attractiveness of globalisation. A shift from a conventional energy to a sustainable energy supply has the potential to alter comparative advantages and to limit or even invert the process of globalisation. Negative and positive aspects of a sustainable energy supply on globalisation can be distinguished:

A sustainable energy supply might lead to rising costs of energy and at the same time of transport and production of goods and services. As shown in Chapter 5.5, costs of the investigated conventional fuels, LNG, biofuels, and hydrogen are different. While MFO and LNG are the cheapest fuels, the costs for MGO and Jet are higher. Even more expensive are biofuels and hydrogen in the investigated pathways. With improving technologies, these fuels become more attractive from an economic point of view. Considering historic developments, prices of conventional fuels are likely to increase in the long term. However, as recent price drops of energy carriers, caused by unconventional extraction, resulting redistribution of global fossil energy production, and strong competition of energy exporting countries, prove, a prediction of future price developments is highly uncertain. Besides direct costs of energy, transport costs, and costs of products and services are affected by a shift in energy supply towards sustainability. Accordingly, the existing networks of energy supply, supply chains, and regional and political dependencies will change.

However, the harvesting of sustainable energy sources and enabling of a sustainable energy supply could also solve some of the problems that occurred together with the industrialisation and globalisation. For example, air pollution, political or regional dependencies, and damage to the climate could be reduced.

Consequences of a sustainable energy supply will be different for every network structure of transport, production, or services and for every individual hub city. Challenges for the existing structures increase along with the amount of energy that has to be supplied. Accordingly, a sustainable energy supply questions the structure of the globalised world economy, which is often organised by hub-and-spoke networks, and increases the pressure to realise decentralised solutions. However, it is uncertain if higher energy costs and fundamental changes in energy supply will limit the growth or even lead to a declining importance of hub cities.

Resulting policy implications. Today's hub cities, require global markets and networks. Regionalisation would result in less collaboration between distant countries and lead to less global exchange of goods and information. This is a threat for hub cities. Sustainable energy supply based on renewables and alternative energy carriers is a potentially regionalising force that restructures energy supply networks towards more localism and increases energy and transport costs. In this context it has to be highlighted that there are more influencing factors that will be decisive for the further existence of a hub city, such as type of the network (transport, knowledge, finance, production, etc.), position within the hub network, and further exogenous and indigenous factors. To decrease risks, policies in hub cities should:

- Increase energy efficiency
- Maximise economic benefit
- Concentrate on less energy intensive technologies
- Establish systems that allow cheap energy and affordable transport

Further research required. In order to assess the impact of a sustainable energy supply on the future development of hub cities, their overall economic benefit has to be opposed to additional costs arising from their high local energy demand. Influencing factors are:

- Development of energy costs and impact on costs of production and transport of goods and services
- Increasing costs of energy with increasing amount of energy consumption
- Positive effects of a sustainable energy supply on hub cities (air pollution, dependencies, and damage to the climate could be reduced)
- Losses in economic efficiency caused by decentralised solutions (smaller scales)

7 Summary and future work

The objective of the thesis is to investigate the impact of a sustainable energy supply on global hub cities. On the example of Singapore, a detailed analysis is performed to study its energy system, possible sustainable transport fuels, and emerging opportunities and challenges. Transferability to other hub cities and induced trends towards regionalisation are discussed. In the following Chapters, results of this thesis are summarised and an outlook on future research is provided.

7.1 Summary

World energy demand is unevenly distributed. Hub cities emerged because of economic benefits. They structure international networks as central nodes by specialising on production, trade, distribution of particular products and services, and the creation of knowledge.

Based on a cheap fossil energy supply, transport costs, and technological improvements, globalisation has shaped current structures of the world economy. Some especially successful hub cities have been dominating the world economy for decades. A sustainable energy supply and the resulting changes with regard to sources, technologies, locations, distribution systems, and costs will affect hub cities.

Global demand of energy has been rising in the last centuries driven by growth of the global economy, population, and improving standards of living. Recent developments show that energy intensity of GDP and even total primary energy demand have been decreasing in developed countries. In the same period, total primary energy demand of hub cities, such as Singapore and Hong Kong, has been increasing.

Singapore’s past and future developments highlight that it is a highly specialised country in various areas such as transport, petroleum refining, distribution of petroleum products, finance, and knowledge. Singapore is a typical hub city and supplying international markets. Energy flows are visualised from energy imports to energy consumption. Local energy consumption is dominated by fuels for international marine and aviation transport, which lead to a high dependency on energy imports and fossil fuels.

An analysis of future developments of transport demands and future improvements of existing technologies suggests that these dependencies will continue. The most promising solution to reduce imports of fossil fuels and reduce associated greenhouse gas emissions is a substitution of conventional bunker fuels.

Consequently, alternative fuels to supply marine and aviation services are investigated in a Well-to-Tank analysis. Possible fuel pathways are defined to distribute petroleum based fuels, liquefied natural gas, biofuels, and hydrogen in Singapore. Fuels are compared by energy efficiency, greenhouse gas emissions, and costs. Specific indicators for specific energy demand, greenhouse gas emissions, and costs are developed. The robustness of the results and the impact of uncertainties in single processes are studied in a sensitivity analysis. While the energy efficiency of conventional fuels and liquefied natural gas is higher than of the compared alternatives, greenhouse gas emissions could be slightly decreased with the use of liquefied natural gas and significantly reduced if the proposed renewable hydrogen or biofuel pathways are investigated. However, also costs are likely to increase for these fuels.

The resource potential of fuel alternatives is limited. While current bunker demand could be easily supplied with global liquefied natural gas production, biofuels would require huge additional cultivation areas in the surrounding regions. It is very doubtful that these areas could be cultivated without additional burning of forests. Liquid hydrogen supply by ship from remote regions is highly dependent on future technological developments.

In the future, it is very likely that a mix of alternative fuels and conventional fuels will supply energy demand for international transport. These developments imply new opportunities and challenges for Singapore and its current business model.

- Singapore will never be able to supply its energy need indigenously, but diversification of energy carriers will reduce its dependency on oil and broaden the range of possible energy sources.
- Synergies of alternative energy carriers in processing, trading, distribution, and financing with conventional energy carriers outweigh possible disadvantages related to additional competition. Therefore, Singapore is in an advantageous position to transform its petroleum into a multi-energy hub.
- Potential domestic reduction of Singapore's greenhouse gas emissions is limited on a local scale. However, interactions with international bunker markets offer the possibility to affect and reduce greenhouse gas emissions of international transport significantly.

Singapore is certainly an extreme example for a hub city. However, investigation shows that also other hub cities, which supply global markets with specialised services, such as IT, finance, or knowledge creation, experience additional energy demands, although their incremental increase is comparably smaller than in the case of transport hubs. A sustainable energy supply will therefore affect these cities. It is not possible to generalise the specific results for Singapore as there are too many different manifestations of hub cities with unique characteristics. Further research has to be done for every individual case.

It is concluded that a sustainable energy supply questions the structure of today's world economy and strengthens forces towards regionalisation. Hub cities will continue their dominance if their benefit, caused by specialisation, is higher than the additional costs, caused by sustainable supply. However, more research is required for a final assessment under which precise conditions a sustainable energy supply will force global networks to regionalise.

7.2 Future work

The conducted research in this thesis discusses impacts of a sustainable energy supply on hub cities. A detailed analysis on basis of Singapore shows the precise design of its current energy system and the characteristics of possible renewable energy sources. Opportunities and challenges for Singapore caused by sustainable energy supply are derived. Mainly owing to its limited availability and higher costs, sustainable energy supply is identified as a regionalising force. This general characteristic is transferable to other hub cities.

However, more research is required to finally answer the question how regionalisation caused by a sustainable energy supply will look like. Therefore, three fields of research are identified:

> **Different hub effects in other cities and delineation.** Although Singapore comprises hub effects in different fields, its energy system is dominated by transport and trade of energy carriers. Therefore, transport fuels are in the focus of this study. Other hub cities are not necessarily transport hubs. Detailed analyses of other dominating hub cities will therefore extend the scope of this research and offer other valuable insights about effects of various hub networks. The separation of businesses essential for the hub network and businesses belonging solely to the local economy of a city is identified as a major challenge. Another one is the interdependency of different hub effects. For instance, Singapore's financial hub has developed out of the need for trade finance that in return supported the further growth as a transport hub.

Sustainable energy supply networks. This thesis discusses pathways in which hydrogen is supplied by a centralised source similar to conventional fuels. Alternatively, regional energy supply networks could be used to supply the energy demand of a city with renewable energy harvested in the surrounding regions. Further research has to be done about cost differences of renewables at different locations and their impact on energy supply networks. The decisive forces will be cost differences, diseconomies of scale at locations, and transportability of energy.

Economic modelling of hub networks. Another essential step, in order to get an impression how the process of regionalisation could develop, is to model and optimise hub networks. Economic benefits gained by hubs have to be opposed to additional costs and availability boundaries of renewable energy sources. The impact of different parameters should be analysed in an equilibrium model with an underlying cost-benefit analysis.

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