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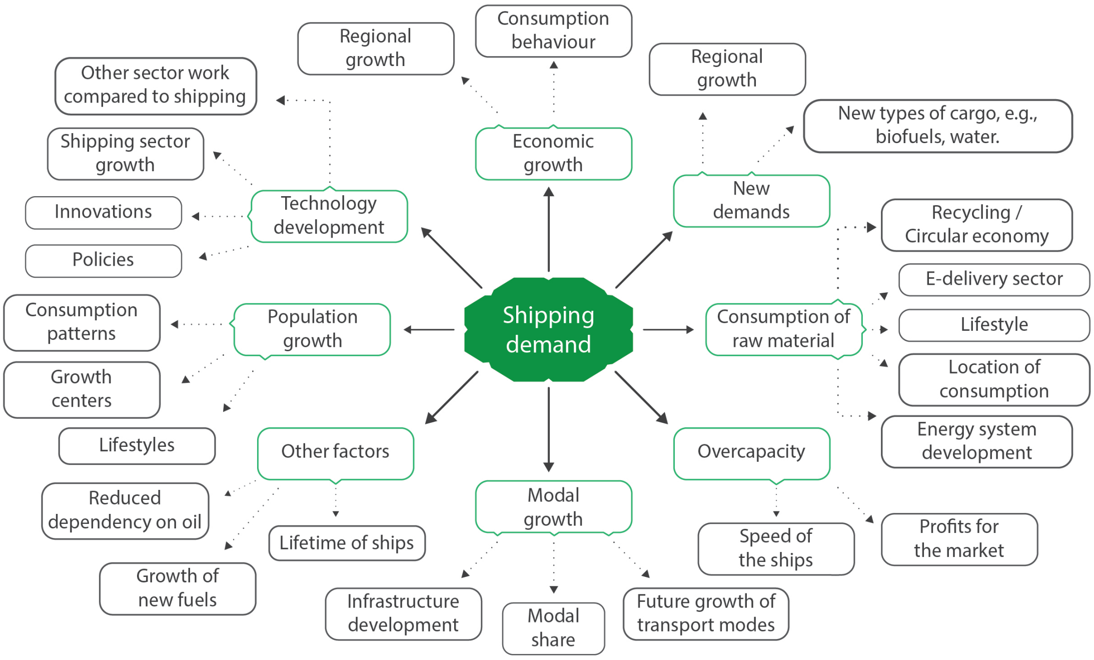

Cost-effective fuel choices for the future shipping sector

The effect of different demand scenarios in the updated energy systems model GET-RC 6.5

Master's thesis in Sustainable Energy Systems

Aniket Autade

Department of Energy and Environment
Chalmers University of Technology, Gothenburg, Sweden 2017
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Cover: Factors affecting shipping demand while reducing GHG emissions © Aniket Autade, 2017.

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Abstract

The impacts of climate change are a complex area. To avoid known as well as unknown impacts, there is a need to make transition towards non-GHG emitting energy system. Shipping transport sector, a part of global energy system, corresponds to 3.1% of global anthropogenic CO_2 emissions for the period 2007-2013. The aim of this thesis is to develop demand scenarios for the future shipping sector and evaluate the impact of demand scenarios on the cost-effective fuel choices in a carbon constrained world for the time period 2010-2100. The aim is further to deepening the understanding around what carbon tax that may be needed to fulfill the fuel scenarios. The purpose is to provide input to different shipping stakeholders and policy makers aimed at designing pathways for sustainable development in the shipping sector. Multi-variable linear function of shipping demand in terms of population and economic growth (in terms of GDP) has been established using regression analysis to calculate shipping demand until the year 2100. SSP2 scenario has been incorporated in Global Energy Transition (GET-RC 6.5) model. Not only the GET-RC 6.5 model became consistent with all demands from every sector but the shipping demand is calculated using population and economic growth values taken from IIASA database. This study is performed using the GET-RC 6.5 model which is a global linear progammed energy systems model and provides results over cost-effective fuel choices. The results obtained during this masters thesis include: 1) The cost-effective choices in a 400 ppm CO_2 concentration scenario suggest LNG as transitional fuel and hydrogen as the longer term alternative marine fuel for the shipping sector. 2) The level of shipping demand is very vital for the use of fuel cell technology coupled with hydrogen specifically for the shipping sector. 3) In case where hydrogen is not available as shipping fuel, the use of petrol based fuel(HFO/MGO) increases, alongside with the small but significant use of biofuels and electrofuels with fuel cells. 4) The role of natural gas becomes even more vital for the shipping sector if hydrogen is assumed not to be a shipping fuel. 5) The needed tax level for generating similar incentives as in a 400 ppm scenario and IMO discussed level show huge difference and hence, unclear incentives towards the shipping sector. The major recommendations suggest a need of policy which will create the needed incentives and creation of more niche markets for early diffusion of technologies. It would facilitate the fuel and technology transition if the IMO might provide more as well as clearer information towards shipping stakeholders about long term plans or expected regulations in the shipping sector.

Keywords: Renewable Marine Fuels; Shipping Demand, Global Energy System, Alternative Marine Fuels, SSP2 Scenario, Global Energy System Model(GET-RC 6.5)

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Aniket Autade, Gothenburg, June 2017

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Acronyms and Abbreviations

BTL	Biomass-to-Liquids
CTL_GTL	Coal-to-liquids and gas-to-liquids
GHG	Greenhouse Gas
H2	Hydrogen
HFO	Heavy Fuel Oil
LNG	Liquified Natural Gas
MGO	Marine Gas Oil

0/ICE	Internal Combustion Engines
BEV	Battery Electric Vehicle
FC	Fuel Cells
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
BAU	Business-as-usual
CCS	Carbon, Capture and Storage.
CO_2	Carbon dioxide
EJ	10^{18} joules
IPCC	International Panel on Climate Change
GDP	Gross Domestic Production
AFR	Africa
CPA	Centrally planned Asia(mainly China)
EUR	European Region
FSU	Former Soviet Union
LAM	Latin America
MEA	Middle East
NAM	North America
PAO	OECD Countries in Pacific Ocean
PAS	Other pacific Asia
SAS	South Asia (mainly India)
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
SSP	Shared Socio-economic pathways
OPRF	Ocean policy Research Foundation
ECA	Emission Control Area

1

Introduction

Human activities, from the beginning of industrialization, have dominantly contributed towards GHG emissions. The cumulative built-up of GHG emissions by the recent and older generations have lead towards climate change[1]. The impacts of climate change are a complex area. More evident consequences are likely to be seen by future generations to a great extent. Climate change, hence, is said to have a global, an intra as well as an inter-generational dimension in its causes and consequences. More collective efforts like transition towards alternative and renewable energy sources are need of the hour. Such efforts are expected not only to cease future cumulative built-up of GHG emissions in the atmosphere but also reduce overall GHG concentration [2].

Marine shipping is one of the key sectors in global transport and deals with more than 80% of the global trade by volume and contributes with GHG emissions. Even though the shipping sector is the least CO_2 intensive sector (in terms of CO_2 emissions/kg transported), in total shipping corresponds to 3.1% of the global anthropogenic CO_2 emissions for the period 2007-2012[3].

Historically the shipping sector has been lagging behind, compared to road transportation sector, in reduction of GHG emissions. However in recent years more shipping companies have shown increased commitment to sustainable development[4]. Recent shipping policy interventions are focused on reducing sulphur oxides (SO_x) and nitrogen oxides (NO_x) emissions as well as energy efficiency measures. In order to contribute to the wider decarbonization needed, these efforts are not enough. It is expected that the GHG emissions from the marine sector will increase its share of global emissions from 3.1% to 17% by 2050[4]. This implies that there is a need for urgent actions in the shipping sector aiming at more clean and sustainable operations.

However, investment decisions in the shipping sector are made through long term investments planning. So, if the shipping industry must make progress towards decarbonizing efforts, it is important to understand how the shipping demand will be in the future as well as what kind of fuel and associated technologies that might be available for this sector. Modelling of long-term scenarios incorporating different parameters has become a common approach to discuss aforementioned problems and the insights can be used to design a sustainable pathway[5]. This thesis will contribute to the understanding of cost-effective choices for fuels in the marine shipping sector using such a modelling approach. The model used particularly in this thesis is a global linear programmed energy systems model, the Global Energy Transition (GET6.5 version) model which generates scenarios over fuel choices that meets the exogenously given energy demand at lowest cost to the society. Furthermore, such exercises offer new insights to understand the possible future role of alternative fuels.

1.1 Aim and Purpose

The aim of this master's thesis is to develop demand scenarios for the future shipping sector and evaluate the impact of demand scenarios on the cost-effective fuel choices in a carbon constrained world. Sensitivity analyses will be done based upon scenario arguments eg. decarbonisation due to global carbon tax implementation, demand variation that depend on economic growth.

This master's thesis will address the following specific research questions:

- How may the future shipping demand develop? What change in trade commodities is expected?
- How may different shipping demand scenarios influence the long term and cost-effective fuel choice in the shipping sector in a carbon constrained world?

The hope is to provide input to policy makers and shipping stakeholders aiming at designing pathways for sustainable development in the shipping sector. The purpose is to assess the role of future alternative and renewable marine fuels and provide support to different stakeholders in decision making about future renewable marine fuels and its corresponding propulsion technology.

1.2 Limitations

The future shipping demand will depend on many different variables. But not all the factors will be considered in this study due to the limited amount of time available. The focus will be on the factors considered most important. In addition, the GET-RC 6.5 model does not considers other GHGs except CO_2[1]. The thesis does not aim to predict future development of global energy system, as this is not the aim of the model tool used. Any future changes in the development of global energy system might affect the result of marine transport fuels. It is hard to predict upcoming disruptive technologies in the long-term future. Hence, the results are more limited by the virtue of present knowledge in the marine shipping sector as well as in the entire global energy system.

Apart from limitations in the modelling tool (GET-RC 6.5) applied, emission factors and size of ship are generalized to calculate the number of ships required using average power inputs and average annual cargo movements (see section 3.1 for brief information).

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[1] Equivalent CO_2 emissions due to methane leakage in case of liquified natural gas combustion has been considered while calculating aggregated CO_2 emissions

2

Scenarios

Demand scenarios in the shipping sector form a part of the global energy system scenarios. The assumptions made while modelling part of the transport sector or the whole global energy system are supposed to be consistent. For a better understanding of scenario approaches, it is important to know how models are generated at a system level or a sector level. Hence, a literature review of different approaches carried out while modelling global energy system or a sector of a global energy system, in this case it is the shipping sector, is carried out. In addition, the second half of this chapter provides relevant information about different CO_2 reduction strategies possible in the shipping sector and detailed information on Socio-economic Shared Pathway(SSP) approach.

2.1 Previous Global Energy System Scenarios

There is still a limited understanding of the complex interactions between Earth's climate system and influences due to human activities. From the time the issue of climate change was realized, significant progress has been done in modelling the future impacts of climate change to reveal future impacts on socio-economic, technological, and environmental conditions of global society.

There has been significant effort into climate change modelling from 1896 when Arrhenius estimated CO_2 induced warming of earth's atmosphere[6]. The Intergovernmental Panel on Climate Change (IPCC) published the scenarios IS92 in 1992, focusing on energy system development and economic growth scenarios for different regions[7]. These scenarios forecasted anthropogenic emissions until year 2100. As many weaknesses were found in the IS92 modelling exercise there was soon a need for in-depth modelling to get a clearer picture of climate change impacts. The set of SRES scenarios were published in year 2000 to overcome the weaknesses found in IS92[8]. These scenarios were recognized as four storylines based on 1) Global, 2) Economic, 3) Regional, 4) Environmental factors. It was assumed that the future will be shaped by population, economy, technology, energy, and agricultural (land use) factors. But Moss et al. (2010) argues that all the scenarios so far were fixated towards generating impacts and did not consider the fact that climate change impacts will shape socio-economic, technological conditions of the future society as well[9]. This has led towards a novel approach of scenario modelling based on capability of human society towards climate change mitigation and adaptation.

Socio-economic shared pathways (SSP) are the most recent set of scenarios that describe future changes in demographics, human development, economy, lifestyle, policies and institutions, technology, and environment and resources[10]. These scenarios contain a set of five different scenarios with combination of high or low challenges to mitigation and adaptation, where the fifth is described as moderate challenges to both.

2.1.1 Different Emission Scenario Modelling Approaches for the Shipping Sector

For the shipping sector, many researchers have modelled future emission scenarios for the shipping sector until 2050[3, 11, 12, 13, 14, 15].

Eyring et al. (2005) used correlation between GDP and shipping demand to generate emission scenarios varying global GDP rates and assumptions over efficiency improvements [11]. Calculated emissions in Eyring et al. (2005) under different scenarios are illustrated in table 2.1.

Table 2.1: Projected International Shipping Emissions under different scenarios in 2050 [11]

Scenarios			**CO2 Emissions (Giga tonnes of Emissions)**		
Growth			**2001**	**2020**	**2050**
2.30%	DS1	TS1-3	0.28	1.11	1.109
2.80%	DS2	TS1-3		1.138	1.232
3.10%	DS3	TS1-3		1.156	1.321
3.60%	DS4	TS1-3		1.188	1.501
2.30%	DS1	TS4	0.28	1.11	1.478
2.80%	DS2	TS4		1.138	1.643
3.10%	DS3	TS4		1.156	1.762
3.60%	DS4	TS4		1.188	2.001

Where DS represents demand scenario and TS represents technology scenario(see [11] for detailed information).

Buhaug et al. (2009) developed scenarios based on maritime transport drivers and efficiency trends to model energy demand which then was multiplied with emission factors to get GHG emission scenarios[12]. These scenarios were based on the IPCC SRES scenarios(see [8]), the most recent at that moment. Also Endresson et al. (2008) developed emission scenarios, along the lines with IPCC SRES storylines, based on growth in GDP, policy developments in environmental sector and speed of technology development[13].

Another study conducted by Ocean policy Research Foundation (OPRF) calculated sea cargo volume by each type using GDP, population, energy consumption data etc. Along with these calculations and cargo movement data, emission scenarios were designed. The study, by ORPF, also internalized offshore-waiting time, energy related infrastructure movement and global warming countermeasure assumptions[16]. Offshore-waiting time involves assumptions where oligopoly situation of for example iron ore suppliers results in higher waiting time for ships at the coast. This increases GHG emissions for this specific commodity. Energy related infrastructure demand such as future LNG pipelines between countries are evaluated until 2050 considering construction in progress. Recycling assumptions of iron was considered to adjust the calculations. The major argument OPRF study considers is the global warming countermeasure ability. It is assumed that there will be counter actions from the future global society to combat global warming impacts. A part of shipping demand is assumed to be satisfied locally in the ORPF model.

Chang et al. (2012) studied the close relationship between marine energy consumption, GDP and GHG emissions. It is found that different parts of the world have different feedback relationship in the short-run as well as in the long-run. But there existed some relationship in between these three factors. The relationship in the regions was either unidirectional i.e. A caused B or bidirectional i.e. A causes B and B causes A, a mutual feedback relationship[17].

Vergara et al. (2012) discussed strategies for reduction in emissions for the passenger and freight maritime sector using projected emissions based on IPCC SRES scenarios. The study discusses the capability of new fuels in the maritime sector to reduce emissions. This study estimates that 22% i.e. approximately 370 Million tons of CO_2/year could be saved using alternative fuels[18]. The pointed-out strategies were not enough to reach the reduction target, assuming that the maritime sector is held responsible for its reduction share of the overall emission target. Author asserts that only 62% target was possible to achieve i.e. 1Gt/yr reduction was possible if all the strategies are adopted at the same time. This analysis emphasized the need of more international rules and policies under IMO to reach such a reduction target.

The latest GHG study performed by IMO (the third) highlights different GHG emission scenarios based on the mix of SSP+RCP scenarios[15] (for more detailed information on SSP and RCP scenarios see [19]and [20] respectively). This study projects the maritime demand for cargo types using correlation between GDP and demand. The analysis done by Ebi et al. (2014) showed no saturation in overall demand as it is strongly coupled to economic growth (in terms of GDP). Overall projected emissions in the shipping sector are presented in the table 2.2.

Table 2.2: Projected shipping emissions by 3rd GHG study

	CO2 Projections (Million Tonnes)								
Scenarios	**Base Year**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Scenario 1	810	800	890	1000	1200	1400	1600	1700	1800
Scenario 2	810	800	870	970	1100	1200	1300	1300	1400
Scenario 3	810	800	850	910	940	940	920	880	810
Scenario 4	810	800	850	910	960	1000	1000	1000	1000
Scenario 5	810	800	890	1000	1200	1500	1800	2200	2700
Scenario 6	810	800	870	970	1100	1300	1500	1700	2000
Scenario 7	810	800	850	910	940	1000	1100	1100	1200
Scenario 8	810	800	850	910	960	1100	1200	1300	1500
Scenario 9	810	810	910	1100	1200	1400	1700	1800	1900
Scenario 10	810	810	890	990	1100	1200	1300	1400	1400
Scenario 11	810	800	870	940	970	980	960	920	850
Scenario 12	810	810	870	930	990	1000	1100	1100	1100
Scenario 13	810	810	910	1100	1200	1500	1900	2400	2800
Scenario 14	810	810	890	990	1100	1300	1600	1800	2100
Scenario 15	810	800	870	940	970	1000	1100	1200	1200
Scenario 16	810	810	870	930	990	1100	1300	1400	1500

Agnolucci et al. (2015) presented the relationship between transport distance or transport cost and material flows using statistical approach along with SSP1 and SSP2 climate change scenario. The study found that 10% increase in surcharge fee for iron ore reduces export flows by 54.1%. Also 10% increase in the transport distance increases the cost by 3.4% for iron ore[21].

Traut et al. (2016) discussed climate change impacts on the shipping sector, focused on expected fluctuations in grain demand of Egypt and Nigeria due to climate change[22].

Schuitmaker et al. (2016) emphasized on urgency of action in shipping sector and forecasts that emissions will increase by a factor of 2.73 in 2050 compared to 2010 in business-as-usual (BAU) scenario[23]. Projected shipping emissions in Schuitmaker et al. (2016) are presented in table 2.3. A study performed by Lloyd's register discusses the uncertainty of GHG emission control policy timescale and states that required rate of decarbonization will be higher with more delay in implementation[24]. The total amount of shipping emissions by the authors under different scenarios are presented in table 2.4.

Table 2.3: Projected Shipping Emissions under Different Scenarios[23]

	Carbon Emissions (million tonnes)	
Year	2012	2050
BAU	615	1937
2DS	615	710

Table 2.4: Projected Shipping Emissions in Low Carbon Pathways[24]

Scenario	Emissions(Million tonnes)
BAU	1400
High Hydrogen	700
High Bio mix	600
High Offsetting	1000

Taljegård et al. (2014) asserts that the transition in the use of marine fuels i.e. from HFO to alternative and renewable fuels will start from 2020 and natural gas based fuels such as Liquified natural gas and methanol during the time-period 2020-2050[5].

As seen in the most studies mentioned above, the focus is to either model future emission scenarios with assumption over technologies and/or economic growth. The projected shipping emissions vary among different scenarios ranges in between 700 to 2800 million tonnes. There seems a limited discussion on the transition of fuel technology and infrastructure needed in order for the global shipping industry to reduce its GHG emissions. This, despite that, is important to understand which fuels will be cost-effective options for the marine shipping industry when the expected more stringent carbon constraints are implemented.

2.2 Shipping Demand

Shipping demand is said to be a derived demand[1][25]. It is dependent on the growth in other sectors which increase the need for commodities which are transported by ships. There are a large number of parameters that affect the shipping demand. This section briefly discusses the vital parameters that effect the shipping demand directly. Scientific literature concludes the principal parameters affecting the shipping demand in present and future trends shown in the fig.2.2. Such parameters include:

- Economic Growth
- Population
- Modal Growth
- Technology Development
- Consumption of Raw Materials
- Overcapacity
- New Demands

2.2.1 Economic Growth

Economic growth results in an increase in personal income. This increases the ability to use more goods and services. So, economic growth can be said to have a direct impact on consumption patterns in the region and in short, can define the need of trade in the region. The shipping sector satisfies a part of that demand in case some commodities are not manufactured in the same region or country.

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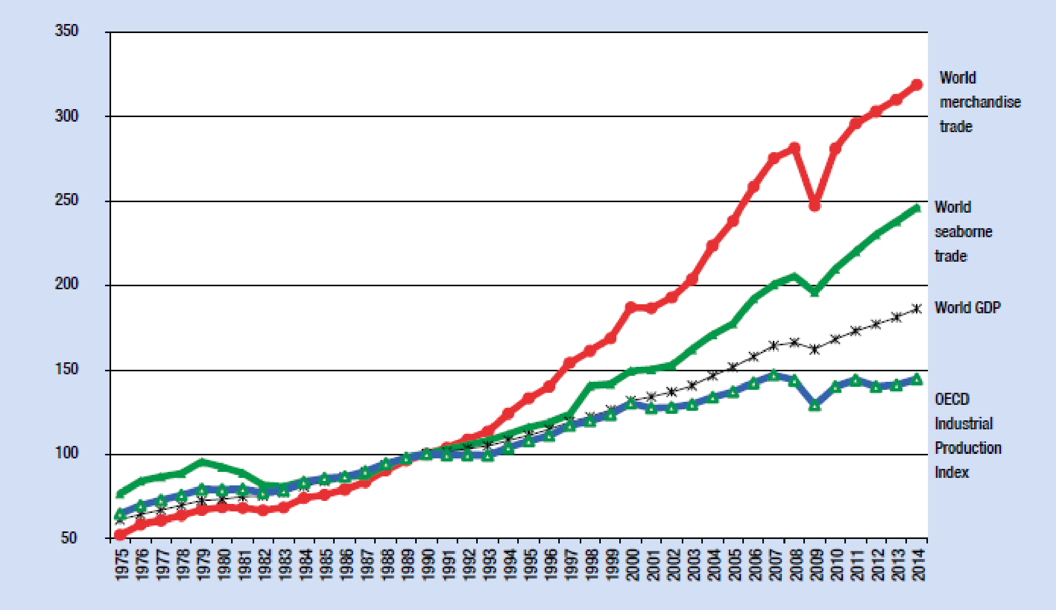
[1] The demand derived from the demand of another good. In this case, shipping demand changes as the demand of goods transported through ships changes.

Figure 1.1. The OECD Industrial Production Index and indices for world GDP, merchandise trade and seaborne shipments (1975–2014) (base year 1990 = 100)



Sources: UNCTAD secretariat, based on OECD Main Economic Indicators, June 2015; United Nations Department of Economic and Social Affairs, 2015; LINK Global Economic Outlook, June 2015; UNCTAD *Review of Maritime Transport*, various issues; WTO, appendix table A1a, World merchandise exports, production and gross domestic product, 1950–2012; WTO press release 739, 14 April 2015.

Figure 2.1: Relation between the development of economic growth and world seaborne trade for the time period 1975-2014[26]

Fig. 2.1 shows the plots for economic growth in terms of global GDP, merchandise growth and world seaborne trade growth annually[26]. As seen from fig. 2.1, there is a relationship between growth in terms of GDP and world seaborne trade growth. Especially in recent years, there seem to be a stronger relationship illustrating how economic growth in terms of GDP influences the growth of shipping demand. This master's thesis has exploited this relationship to generate future shipping trade (in terms of weight). A brief explanation on how the total shipping demand is calculated in the scenarios in this thesis is given in chapter 3 and section 3.2.

2.2.2 Population

Population along with urbanization directly correlates with the need of resources and type of resources[27]. The consumption of resources/services directly affects the trade in a specific region. So, population growth along with urbanization will influence the shipping demand in the future. Africa as well as many countries in other continents is still underdeveloped. For example the expected rise in new consumers in these regions will put more pressure on the resources. The influence on the need of resources will continue and become stronger as the population increases with time.

2.2.3 Modal Share

Currently, all the transport modes are undergoing decarbonization in all possible ways. So, future development of other transport modes will affect the shipping demand, the shipping demand will increase if the other transport modes remain more expensive compared to the shipping and if shipping is still a possible choice then the shipping demand is expected to increase. Policy interventions in different transport sectors can be one of the reason to drive such transformation from one type of transport to another. The shipping demand is expected to decrease when carbon offsetting cost becomes less expensive for other transport modes compared to marine shipping mode. A reduced demand in this case could be positive from a climate perspective. In addition, the infrastructure development plays a very important role in the advancement of every transport mode. Hence, the development of other transport modes and the associated future mix of model share will shape the developments in the shipping sector[28, 29].

2.2.4 Technology Development

Technology development plays an important role not only in the emission reduction of the ship but also affects the growth of alternative fuels. Certain policies are designed to promote the transition to better alternative fuels in parallel with efficiency improvement. Technology development affect the total ship emissions as different fuels/technologies have different emission factors and need a different infrastructure. These improvements in technology like efficiency improvements are directly reflected in the capital and operational costs. The costs for reducing emissions will influence the shipping freight rates, and eventually the shipping demand[21]. Not only the technology growth in marine sector matters but it is important to also understand out-sector growth, e.g. common fuels used in various sectors. If different sectors are connected via common technology or common fuel, this might help in reducing the commercial costs.

New innovations might be disruptive. It is difficult to internalize disruptive innovations in energy systems modelling studies[30].

2.2.5 Raw Materials

The commodities, not found/produced locally, involve certain transport mode while transporting from one place to another. Such raw materials are most likely transported by sea because of cheaper freight rates present in the shipping sector. Population and economic growth are the major crucial factors that influence the need of such material resources. In addition, there are four important aspects while calculating maritime demand which are ideal to consider when it comes to the use of the material resources. These are 1) E-delivery sector 2) Location of Consumption 3) Circular Economy 4) Development in Energy systems[26].

Asia has been a major region where E-delivery sector, the delivery of goods bought over internet, has boomingly increased in recent years. Digitalization has brought many international markets within the reach of people. Having many developing countries specially in Asia region, the E-delivery sector has driven the demand growth in the shipping sector, specially in containerships growth[26]. Similar scenarios can happen in Africa countries where the GDP growth is expected to be high in the future.

Location of consumption, hence, is also an important aspect. Most of the countries in the world are developing now or going to be developing country in the recent future, it is expected that the capability to buy more products will increase. The demand is expected to be partly satisfied by the shipping industry since significant amount is shipped to other parts of the world[26].

The ideas and implementation of the circular economy, which envisions material symbiosis and maximize the resource utility of any resource[31], are increasing at present. Successful implementation is likely to result in reduced shipping demand directly. Currently there is very little information about the cost required to implement circular economy ideas in various regions.

Also, energy system is transforming towards non-CO_2 emitting technologies. The use of CO_2 emitting resources, such as oil, coal etc, is expected to decrease, in terms of percentage, in the future. Trade growth in transporting such resources is very unlikely to take place. Use of fossil fuels is expected to decrease and locally produced electricity or fuels may be important substitutes, in the transport sector. On the other hand, an increased need of rare earth materials, used in e.g. electric vehicles and wind power industry, may be new commodities to be traded, leading to an increase of the shipping demand. New resources may or may not need the transportation by the shipping sector.

2.2.6 Overcapacity

The development of larger ships has been seen in the recent years. Theoretically, there is no limit on the size of the ship. But replacement of smaller ships (because of the lifetime) with much larger ships of many fold capacity has taken place[32]. In parallel to increased overall capacity, there has been a tiny growth in the marine shipping demand[26] which has led to a situation of overcapacity. Overcapacity is destructive towards the shipping market as the market may either have lower profits (by lowering freight rates as an effect of that freight rates need to be lowered to get customers to choose the large ships) than before or the shipping market may experience financial loss as the shipping demand is lower than available capacity. Overcapacity and lower freight rates were part of the major reasons for the bankruptcy announced by Hanjin[33], the seventh largest shipping company in the world.

The profits in the shipping market will be defined by the growth in demand. The current situation with relatively low growth in demand but vast growth in capacity can affect the growth of the alternative fuels as the companies will focus more on the cheapest fuel rather than alternative fuel to stay in the market. Considering that the fuel consumption of the ships is proportional to the third power of speed[34], in order to maximize operational profits, the shipping industry have adopted the slow steaming speeds and taking advantage through better speed management[35].

A low profit situation, that may arise from overcapacity in the shipping sector, as well as possible more stringent legislation around emissions are two important challenges for the shipping industry. Such situations lead to slow transformation into a low-emitting shipping sector[32]. So, depending upon the time overcapacity situation exists in the shipping industry, proportional effects may reflect in delay in actions towards reducing GHG emissions for the shipping sector.

2.2.7 New Demands

At present, the shipping sector transports mainly crude oil, petroleum products, gas, iron ore, coal, grain, bauxite, alumina, phosphate rock and containerized sector commodities. With ongoing transformation towards emitting non-CO_2 energy system and transport sector, there will be a reduction in the use of oil and coal. Also, climate change is expected to put more pressure on water availability in many regions. This might affect production of different commodities in regions. New markets are expected to satisfy an increase in demand in such commodities. A part of such demand can transported through ships, for e.g. expected increase of grains in Egypt[22]. In future, these changes are important to consider in the model while developing the future demand for shipping. Some insights on the future mix commodities transported in the marine shipping sector has been discussed in chapter 4 and section (4.1).

Considering the range of impacts from climate change locally as well as globally, a vast range of variables have started to shape the shipping demand and its cost of operations. To summarise, it is forecasted that future shipping demand will be shaped by shifts in global production units, reduced dependence on oil, demographics with changing consumption patterns, arrival of bigger container ships, emergence of new sea routes, technology development, economic growth trends, effect of upcoming circular economy, modal shifts in other transport sectors, effect of present and future emission control areas (ECAs), prolonged fleet overcapacity and policies interventions[3, 36, 30].

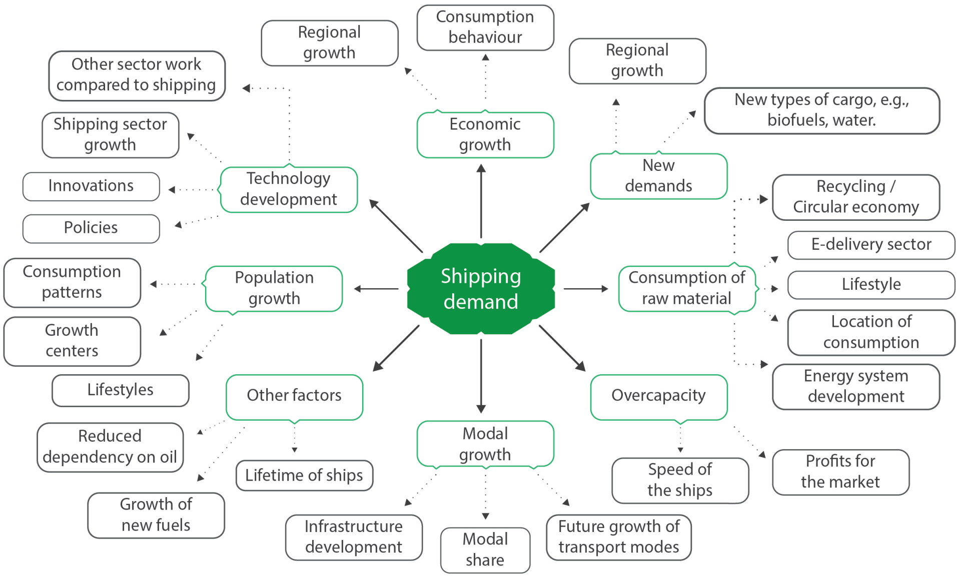


Figure 2.2: Different variables affecting the shipping demand

2.3 Pathways for Emission Reduction in the Shipping Sector

There are three approaches available for emission reduction in the shipping sector. Those are 1) reduce the energy use per km travelled, 2) reduce the amount of distance travelled 3) reduce the emission per energy unit used. The first measure deals with efforts focused towards efficiency improvements. The first and second measures both first and foremost focus on consumer behavior. The third measure is concerned towards the choice of fuel input to the engines/technology[37].

Along the lines of these measures, Vergara et al. proposed the following seven range of strategies, sets of policy and technologies, needed to mitigate the GHG emissions in the shipping sector[18]:

- Mission Refinement (transport system integration, route planning, weather avoidance, port faster transfer etc.)
- Resistance reduction (new lift methods, new hull reforms, painting, viscosity alteration, air cavity, aerodynamic profile, bulbs etc.)
- Propulsor selection (counter-rotating propellers (CRP), water jets, free wheels, ducts, nozzles, etc.).
- Propulsor-hull-prime mover optimization (azimuthal drives, pre- and post-swirl devices, electric drives, etc.).
- Prime mover selection (advanced Rankine cycles, advanced Brayton cycles, hybrid cycles, etc.).
- Propulsion augments (wind energy, kite sails, flaps, solar energy, etc.).
- New fuels (H2, synfuels, biofuels/Th-fission, etc.).

These measures provide a basic idea about what kind of improvements exist that are possible to apply with present state of knowledge[18]. As this thesis is more focuses on the choice of the fuel, prospective fuels are considered more specifically.

2.3.1 Current Shipping Fuels and Available Alternatives

The current and proposed alternative fuels for the shipping sector is presented in this section. Current fuels used in the marine sector are Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). The alternative fuels towards the shipping sector include liquified natural gas (LNG), synthetic fuels, hydrogen, biofuels, e-fuels (fuels produced from electricity, carbon dioxide and water, so called electrofuels) and nuclear fuels. The shipping demand in the military sector is not included in this study. This thesis does not discuss further on the nuclear propulsion ships as most of the use of such ships is done in the military sector[38].

2.3.1.1 Heavy Fuel Oil and Marine Gas Oil

Currently, the shipping fuels are of two types: 1) heavy fuel oils (HFO) and 2) marine gas oils (MGO). HFO is still the most common fuel used in the shipping sector. HFO oil is viscous, dirty, and inexpensive. It is similar to the fuel-oil used in the road transport but has a high viscosity. Viscosity suggests the complexity of fuel heating and handling system as there is a need for heating to correct injection pressure for optimized performance[39]. Approximately, 80% of the fuel used in the shipping industry is HFO and remaining 20% is MGO. A tiny amount of LNG is used in the current shipping sector[40].

HFO consists of approx. 2.7% sulphur on an average. This limit is 2700 times greater than the fuel used in road transportation sector[39].

MGO costs in the same range as HFO but has lower sulphur content. The recent policy standards of 0.1% and 0.5% global sulphur concentration limits[41] in certain areas have started this shift towards increased use of MGO. These emission control zones are known as Sulphur Emission Control Areas (SECA). These SECAs imposed the limit of 1% sulphur limit from 1st July 2010 and 0.1% sulphur limit from 2015. In other areas, the sulphur limit has been lowered to 3.5% in 2012. The global limit is expected to go to 0.5% effective from 2020 or 2025[41].

2.3.1.2 Liquified Natural Gas

LNG has been a proven and feasible solution for the shipping sector as a fuel. LNG is one of the potential solutions for upcoming regulations limiting CO_2, SO_x & NO_x. It is one of the solutions for SO_x reduction but parts of the industry seems to use the scrubber technology with high sulphur content fuel as an alternative way to reduce the sulphur emissions. The price of LNG is relatively low as compared to present fuel. But the handling costs are still high. The use of LNG presents some important risks towards infrastructure such as explosion hazard in case of leakage, high energy content when stored under very low temperature. LNG fuel requires more space unless stored at very low temperature.

2.3.1.3 Synthetic Fuels

Synthetic fuels are Coal-to-Liquid (CTL), Biomass-to-Liquid (BTL) and Gas-to-Liquid (GTL). These fuels can have the same end-product with different raw material in the beginning. Synthetic fuels are produced from syngas, a mixture of carbon monoxide and hydrogen, using for example a process called Fischer-Tropsch process. Such type of fuels has not been used in ships until now. But these fuels can be used in for example heavy diesel engines without any modification. These fuels have lower CO_2 and PM emissions as compared with HFO and MGO with no sulphur emissions. These fuels have lower CO_2 emissions but not zero. These fuels can be a solution for the marine shipping sector when moderate or higher emissions limits are imposed. If the stringent CO_2 limits are put forth, most likely these fuels will be a transitional solution until non-CO_2 emitting resource and corresponding technology become commercial. At present, the future looks bleak for the CCS technology to be implemented in the marine shipping sector.

2.3.1.4 Hydrogen

Hydrogen is also another option using a fuel cell or combustion technology. This technology is not a cost competitive fuel option right now but with improvements in technology and cost reductions in fuel cell technology, the operations are possible. Hydrogen solves many challenges which are perceived towards other intermittent sources. Hydrogen is common in nature, but almost always hardly bound in molecule structures meaning that it demands energy to generate pure H2 and the cost is currently very high. Its lower energy density compared to HFO requires six to seven times more space[42]. Further, the storage requires well-insulated tanks as it can be flammable under certain conditions. Because of non-CO_2 emission when combusted or used in a fuel cell, hydrogen seems as a most promising fuel which can replace fuels in road transportation area. However, the emissions depend on how the hydrogen is produced.

2.3.1.5 Biofuels

A wide range of biofuels are possible to use in present engine technologies with none or small modifications. These fuels are often dividied into three types i.e. 1st generation, 2nd generation and 3rd generation biofuels. These types vary based on their input source. 1st generation biofuels are the fuels that are based on organic material and naturally degraded whilst the product is taken care of, e.g. ethanol from sugarcane, biogas from digestion etc. Furthermore 2nd generation biofuels have origin from biomass but this biomass is treated thermally or chemically in order to make products, e.g. ethanol from biomass through gasification or fermentation. 3rd generation biofuels are viewed as fully synthetic fuels which do not depend upon biomass (by-products from biomass process can be used), e.g. electrofuels[43]. From a lifecycle perspective, most biofuels are carbon positive since the production lead to GHG emissions. Biofuels do generally have a lower energy content per liter of fuels, compared to HFO, which results in a need for larger storages tanks, onboard the ship, in order to keep the same fuelling frequency.

2.4 Socio-Economic Shared Pathways

At present, there is a great interest to understand and analyze the impacts of climate change on socio-economic conditions and vice-versa. Parson et al. (2007) suggested that the socio-economic conditions will shape the impacts of climate change and that the inverse holds true as well[44]. Thus, there will exist a mutual feedback relationship between climate change impacts and socio-economic conditions. One common way to find new insights in this area is to design pathways for the future society based on the proven facts.

Following fig.2.3 shows the relationship link between socio-economic conditions and climate change impacts[44]. This strong link is the biggest motivation to one set of recent but well established scenarios known as Socio-economic shared pathways (SSP)[19]. These scenarios present integrated approach towards climate change impacts and socio-economic conditions with regards to adaptation and mitigation capabilities.

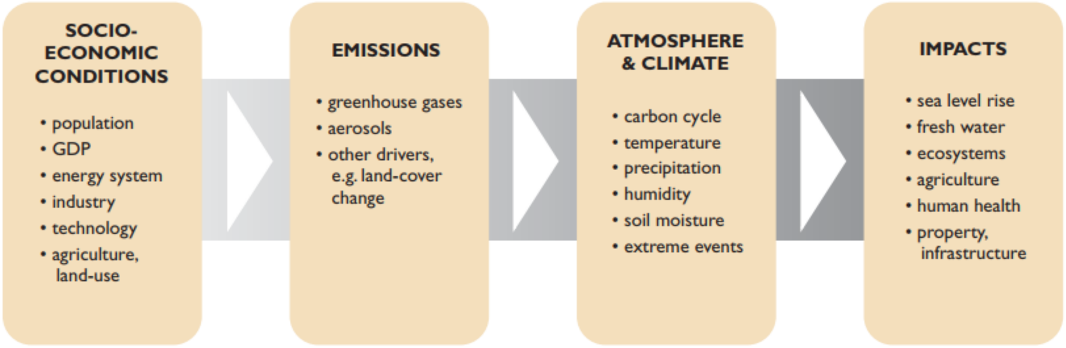


Figure 2.3: Representative relationship chain of socio-economic conditions and climate change[40]

Note: The relationship between socio-economic conditions and climate change is complex. Here this figure is a very theoretical and simplified version of actual relationship.

The SSPs describe the future societal development in the context of climate change impact scenarios[45]. The pathways are numbered SSP1 to SSP5. Each SSP scenario is described briefly in the following paragraphs.

The SSP1 pathway is narrated as the environmentally aware world with more rapid technology development and strong economic growth. This pathway is called as “Sustainability pathway” where the world is making a substantial progress to achieve sustainable development goals. This will also achieve reduced resource intensity i.e. means more implementation of the perspective of circular economy and fossil-fuel independency.

The SSP3 pathway is known as “Fragmentation” where the world is separated into different regions. These regions are characterized by moderate wealth and poverty with the largely growing population.

The SSP4 pathway corresponds to a world of inequality where developed rich countries are responsible for GHG emissions and undeveloped countries are more prone towards climate change impacts.

The SSP5 pathway is based on conventional development where world development is making more progress in terms of economic growth but with the use of energy system with high usage of fossil fuels. Economic growth is considered the solution towards both economic and social problems faced by individuals. In short, the world will make progress towards the future following the development seen in developed countries with high use of fossil energy.

Combining all the scenarios together, the SSP2 pathway is designed with the economic and technical development a seen in the scenario in SSP5 and the world is also making progress towards achieving sustainability development goals like in SSP3. There will still be some inequality in the world where rich countries are still held somewhat responsible for the GHG emissions and where poor countries are prone to climate change impacts like in SSP4 but to a lower extent. Some countries will still be poor and will find hard to maintain living standards of the growing population. The design of SSP2 scenario can be said as the pathway based on the past trends and slowly lead towards sustainability and efforts will continue to increase as the time passes by. A more detailed version of the SSP scenarios can be found in O'Neill et al. (2014)[10]. The reasons behind choosing SSP2 scenarios for the development of the shipping demand in this study are discussed in chapter 3 and section 3.1.

3

Methods

This thesis is an example of global energy system modelling exercise where the shipping transport sector is modelled in detail. The strong relationship of the shipping demand with the economic growth and population is the base for calculating future shipping demand. The developed shipping demand scenarios is then implemented in the developed version of the GET model.

3.1 GET Model

The Global energy transition model is a cost minimization decision-making tool focused on satisfying the global energy demand with the available energy supply assuming stringent CO2 reduction targets. This model was originally developed in the late 1990s[46] with the aim of analyzing minimum cost solutions given carbon constraint. Since then the model has been updated and at present mainly GET-RC 6.5 version is in use[47]. An overview of the GET-RC 6.5 model is shown in fig.3.1.

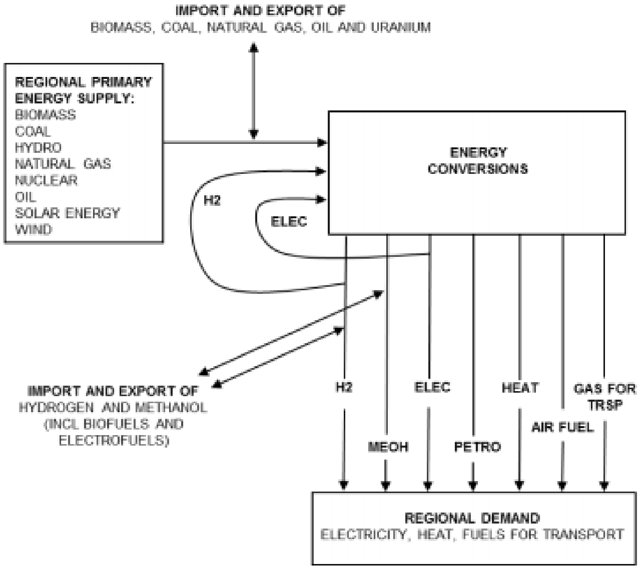


Figure 3.1: The basic flow chart of primary energy supply and fuel choices in the GET Model[40]

The model has 10 different regions with a major focus on the transportation sector. This linear optimization model chooses primary energy resources, conversion technologies, energy carriers and transportation technologies which meet the global energy demand at least cost for every region when subjected to carbon constraints. The solutions for each region are aggregated to present the final global solution with possible movement of energy resource between regions.

The model time-period is 1990-2140 with a time step of 10 years. The results in this study are discussed for the time-period 2010-2100.

The energy demand in this model is divided into three parts i.e. 1) electricity, 2) heat, and 3) transportation. The electricity sector stands for the electricity demand for every region. The heat sector includes all the energy demand that is neither electricity nor transport fuels. The transportation sector has been modelled with most details compared to electricity and heat sector. The transportation sector is divided into two sub-sectors: 1) Passenger demand and 2) Freight demand.

In this thesis the GET-RC model has been developed into model version GET-RC 6.5. Passenger demand in the GET-RC 6.5 model is divided into cars and buses. Also freight sector is divided into trucks, rail, aviation and ships. These demands are function of global population and economic growth data.

Shipping demand under passenger sector is not considered in this sector since most of passenger ships have certain cargo capacity and most likely such ships are taken into consideration when shipping demand is expressed in billion ton-miles. In this updated model version, GET-RC6.5, the shipping demand under the freight demand is divided into six different sectors based on commodity types. The commodity types in the shipping sector include:

1. Main bulk materials;
2. Gas;
3. Oil;
4. Chemicals;
5. Other bulk materials;
6. Containerships.

These categories are modelled using data extracted from the reports mentioned in Review of Maritime Transport documents published annually by United Nations Conference on Trade and Development[30, 48, 26, 36]. Each category under the shipping transport sector represents the demand for the respective commodity transported through the ships. The European Maritime Safety Agency offers the “Equasis” database that comprises information on the merchant fleet based on the lifetime, average sizes (in deadweight tonnes) and number of different types of ships in the shipping sector[49, 50, 51]. This information in addition to the information about annual cargo capacity and annual transport days by different commodity ships[12] is used to total fleet capacity in the marine shipping transport sector.

The information about the technologies used in these six different shipping sectors like capital cost, lifetime, size of the ships and engine costs is approximated using the available information in previous GET-RC 6.4 model[47].

The types of ship in the shipping sector in the earlier GET-RC model versions were based on vessel and engine size. These types were divided into three categories i.e. coast, ocean and container ships[5] based on the categorization present in Buhaug et. al (2009)[12].

In this thesis the GET-RC model has, further, been developed with an updated general energy demand for the heat and electricity sectors following IIASA SSP2-scenario, where previous model version has been built on the much older IIASA C1 scenario[52]. All the demand values are pre-fed into the GET model and these values do not change over the specific run.

Mature cost data is used for all technologies including the shipping sector. The costs of different technologies are average numbers found through different research articles, reports, and company publications. The propulsion technologies in the shipping sector considered in this model are combustion and fuel cell technology. For more information about technology costs and efficiencies of different propulsion technologies, please see appendix 3. The shipping transport sector includes the marine fuels mentioned in the chapter 2 and section 2.3.1. This includes HFO/MGO, LNG, Biofuels, Synfuels, hydrogen and electrofuels(fuels produced from CO2 and water using electricity as main source of energy).

The CO_2 concentration cap limits for each step are extracted from the atmospheric stabilization CO_2 concentrations presented by Wigley et al.(1996)[53]. It is possible to introduce different CO_2 concentration levels/caps. Four different CO_2 concentration levels i.e. 400, 450, 500 and 550ppm has been used in the GET-RC 6.5 model version. The 400 ppm level presents the cap where the CO_2 concentration is leveled off at 400ppm or below at the end of the century and will be used in the base case scenario of this study.

Changes in economic growth data and population has also effect on the final demand of road-based transport sector such as bus, rail, cars and trucks etc. These sub-sectors under road-based transport sector are consistent in GET-RC 6.5 model.

3.1.1 Overview of Assumptions and Constraints

The assumptions and constraints are linked to the cost of all different types of technologies, efficiency of engines and other conversion efficiencies, total supply potential of primary sources based on reserves and resources, CCS diffusion and the growth of technologies included in the GET Model.

The primary supply potentials for the fossil fuels i.e. oil and natural gas are constrained to 12000 EJ and 10000 EJ respectively, twice of the proven reserves in 1990. The global coal supply is constrained to 260000 EJ[46].

In the transportation sector, in the base case it is assumed that maximum 20% of the trucks demand fulfilled with PHEVs and another 20% of HEVs. Further in total, maximum of 60% of the bus demand is fulfilled using HEVs and PHEVs.

Carbon capture and storage (CCS) can be a CO2 reducing technology that can either be assumed becoming large scale available or assumed be a technology that will not take off due to e.g. lack of public acceptance. In this study it is assumed that CCS will become a large scale available technology. In the case when CCS technology is possible to use in the model, further assumptions include zero leakage of the stored CO_2. That means leakage of CO_2 stored using the CCS technology does not take place. The aggregated storage capacity of CO_2 over the entire period 2010-2100 is assumed to be 600 GtC. The expansion rate is constrained by maximum 100MtC per decade.

The amount of electricity produced by the nuclear energy is assumed to be constant over the century. It is assumed that nuclear energy cannot excced the level of today. There is no limitation on the total expansion of the wind and the solar energy but their expansion rate is constrained.

Grahn et al. (2009) assert that the cost-effective use of biomass resources will be in electricity and heat sector rather than in transportation sector. The limited amount of biomass resources available to fulfill the demand and the higher conversion efficiency in the other sectors is the main reason behind this conclusion[54]. Hedenus et al. (2010) found that maximum 50% of the energy demand in the heat sector will come from biomass resource[55].

3.1.2 Limitations

It is important to understand that the GET-RC 6.5 model is not developed to predict future development of the global energy system. It is meant to understand the role of different technologies available in different sectors, inter- and intra-sector interactions, and overall system behavior. In addition, it is hard to predict upcoming disruptive technologies in the long-term future. Hence, the results are more limited by the virtue of present knowledge in the marine shipping sector.

It is possible that the roll-out of different technologies might differ between areas and maybe different time-period as the time to diffuse in the niche markets vary for different technologies to become commercial. Such differential effects are not seen in the model results.

The cost and price elasticity is not present in the GET-RC 6.5 model. Instead, mature and present observed costs are used in the model. Also, the demand scenarios are exogenously given for all the ten regions present in the model and the given energy demand do not change when the model is running.

The electricity sectors of each region are not connected to each other. Thus there is no possibility to transfer electricity between regions. This model does not consider any other GHG emissions than CO_2 emissions, except methane leakage due to combustion of LNG using combustion engines.

The results obtained show a certain possible pathway to achieve the most cost-effective solution. This does not mean that the same path will be followed by the fuels at any point in time. The results give insight when the technology should be in place in order to reduce the emissions in order to get cost-effective solution for society, the reality might be different. Total energy demand calculations for the electricity, the heat as well as the transportation sector are never exact but the calculations are based on the lifetime of technology, energy efficiency, costs, and resource availability.

While calculating the number of ships, the average size of the engines, average speed and average number of days are taken into consideration. So, uncertainties exist over final emissions over the shipping transport sector as well as other sectors.

3.2 Scenarios for the Future Shipping Demand

As mentioned before in section 2.2, the shipping demand scenarios are dependent on several factors. This thesis focuses mostly on the impact of economic growth and population as these factors are a representation of global socio-economic conditions which are assumed to be drivers of climate change.

The statistics over economic growth and population is collected from Knoema statistics (see www.knoema.com) and World bank (see www.worldbank.org) respectively.

This thesis uses the technique of multivariable regression method to forecast future shipping demand. Multivariable regression is a technique to forecast the dependent variable based on two or more independent variables. This technique is used to learn more about the relationship between dependent and independent variables. Such relationships predict future values of dependent variables. In general, suppose, demand d is function of the variables x_1 and x_2, then the relationship between demand and the variable is shown as,

$$d = \beta_0 + \beta_1 * x_1 + \beta_2 * x_2 \tag{3.1}$$

Where, x_1 is in US\$2005 and x_2 is the population number. Beta represents the regression coefficient connected to the dependent variable.
Here, β_1 is the regression coefficient for the economic growth and β_2 is regression coefficient for the population. For every increase of 1 unit in either of the variables, the positive regression coefficient represent increase in the demand and vice-versa. R-squared denotes the measure of how close the data is fitted to the regression line. Using the R-squared values, the correlation coefficient varies between 0 and 1. The relationship is more strong as the coefficient gets closer to 1.

Here, the independent variables are economic growth and population[1] and the dependent variable is the trade expressed in billions of ton-miles. The regression analysis is

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[1] It can be said economic growth and population are not exactly independent factors. The main motivation behind considering this assumption is that population has equally important as economic growth when the pressure of limited supply sources is considered

performed to generate relationship of each demand category under the shipping sector (expressed in terms of billion ton-miles) with economic growth and population. This performed regression analysis presents relationship for every individual commodity type under shipping sector (for commodity types,see section 3.1 on page 18).

This thesis has formulated the mathematical relationship to calculate marine shipping demand as a function of economic growth and population. To model the assumptions for the economic growth and population in the context of climate change until 2100, this thesis incorporates the SSP 2 scenario as a base case to proceed with[45].

This thesis uses the above built relationships between global shipping trade, economic growth and population using multivariable regression analysis. This relationship is based on past data over 25 years. To use this relationship, the demand scenario should consider population and economic growth trends which will follow a similar path as in the past. That means the future trends will follow the recent observed past trends for all the categories. As mentioned in the description of the SSP2 scenario, in section 2.4, the world will follow a path in which social, economic, and technological trends follow recent historical patterns. Therefore, the SSP2 scenario is chosen to be used for the base case scenario in this thesis and is incorporated in the GET model. Also, other transportation demand calculations for passenger transport and freight transport except marine shipping sector are strongly based on the economic growth and population values. This is one another motivation to use SSP2 scenario as a base case scenario.

Thus the population and economic growth numbers are updated based on the SSP2 scenario. The SSP2 scenario is considered a scenario which offers insights about the socio-economic conditions of future global society[].

3.2.1 Sensitivity Analysis

Besides the base case scenario two additional scenarios are developed and used for sensitivity analyses. The reason is that population and economic growth have mutual feedback relationship which could be explored more and which makes the population and economic growth used in the base case scenario uncertain. In the longer term, population growth may affect the living standards of the society[56]. There is fixed quantity of resources present in nature and more growth will put pressure at least on those resources whose production cannot be multiplied using present or upcoming technological advances. Also, the uncertain nature of population can have an impact on economic growth and vice-versa. This bi-directional relationship between population and economic growth is not possible to explore due to limited time in this thesis. It is decided to focus more on economic growth and keep the population data constant.

Research carried out under different socio-economic conditions show a range of possible economic growth situations under different conditions - the expected range of economic growth varies from 0.8% annual growth in GDP to 2.8% annual[57, 58, 59]. The economic growth assumed under base case scenario used in this study is approx. 1.6%/year, which represents the economic growth in the SSP2 scenario. The first variant of the base case used for sensitivity analyses is assumed to have almost double rate of economic growth in terms of GDP_{ppp} i.e. 3.2%/year. The other situation corresponds to approximately half of the growth rate assumed in the base case i.e. 0.8%/year.

There are some concern regarding the feasibility of hydrogen being a marine fuel. The sensitivity of this nature is addressed in next sensitivity analysis(see section 4.6.2 in chapter 4).

In addition, another sensitivity analysis is performed to explore the impact of CO_2 tax levels on the pre-requisites for alternative marine fuels.

4

Results and Analysis

4.1 Trends in Shipping Demand Sector

Fig. 4.1 presents the trends seen in the global seaborne trade of different commodities for the time-period 2000-2014, compared in terms of percentage of total billions of ton-miles[1] transported. The figure shows the trade for all six commodity groups: 1) Chemicals, 2) Gas, 3) Oil, 4) Containers, 5) Main bulk products, and 6) Other bulk products.

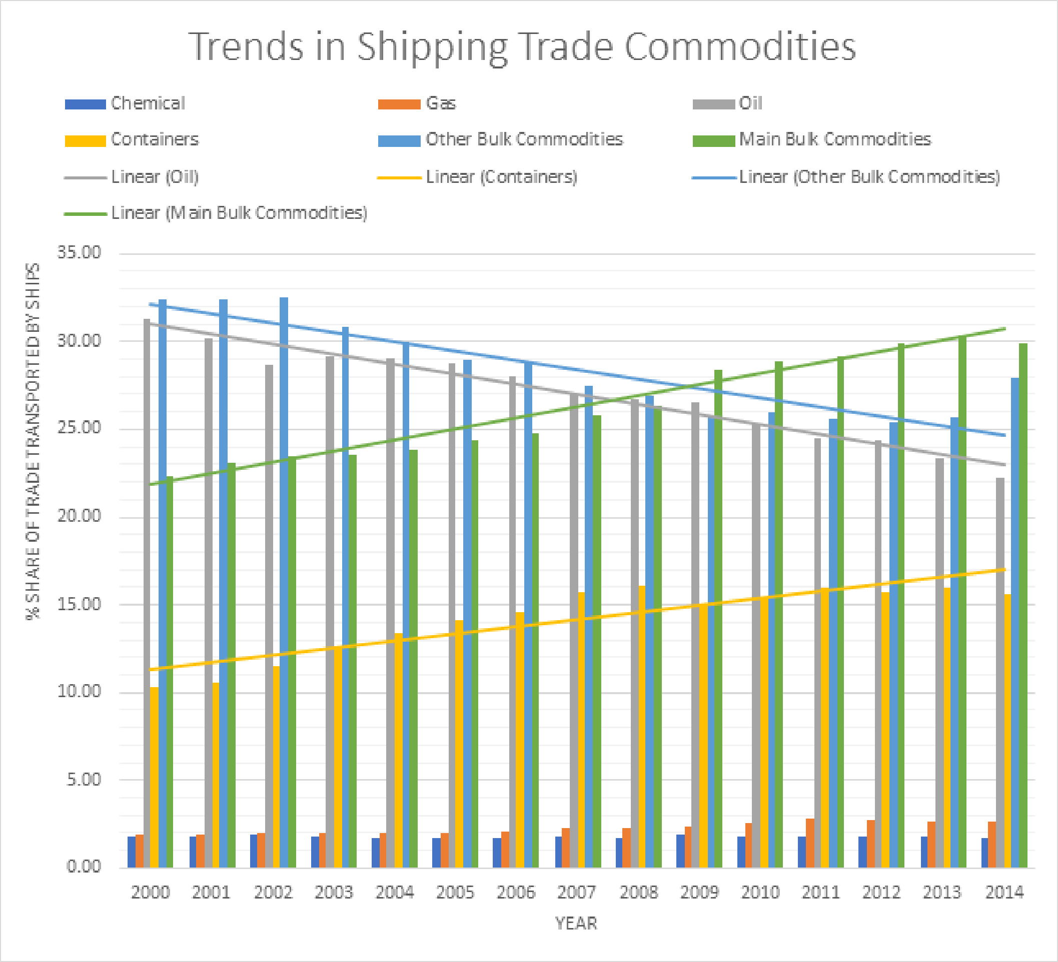

Figure 4.1: Trends in the shipping sector in terms of percentage share of total shipping demand expressed in billion ton-miles, linear lines represent the trendlines[26]

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[1] 1 mile = 1.852 km

The other bulk products commodity category includes all the other commodity types which are transported by the ships but does not include in the first five categories. Overall, the seaborne trade has gradually increased over the time period, in terms of billion ton-miles. Out of the six categories, percentage seaborne trade in the containers and main bulk commodity types is likely to increase and percentage seaborne trade is likely to decrease in oil and other bulk commodity types when present trends in every category is taken into consideration.

Fig. 4.2 presents the trends seen in the global seaborne trade of chemicals and gas commodity for the time-period 2000-2014, compared in terms of percentage of total billions of ton-miles transported. The percentage of seaborne trade for chemicals is seen to be constant. The graph presents the trade for chemicals (mostly transported through tankers) which has increased gradually. The percentage of seaborne trade for chemicals is seen to be constant (footnote1), [2] whereas the trend for gas is increasing, although slightly decreased after 2011, as illustrated in picture.

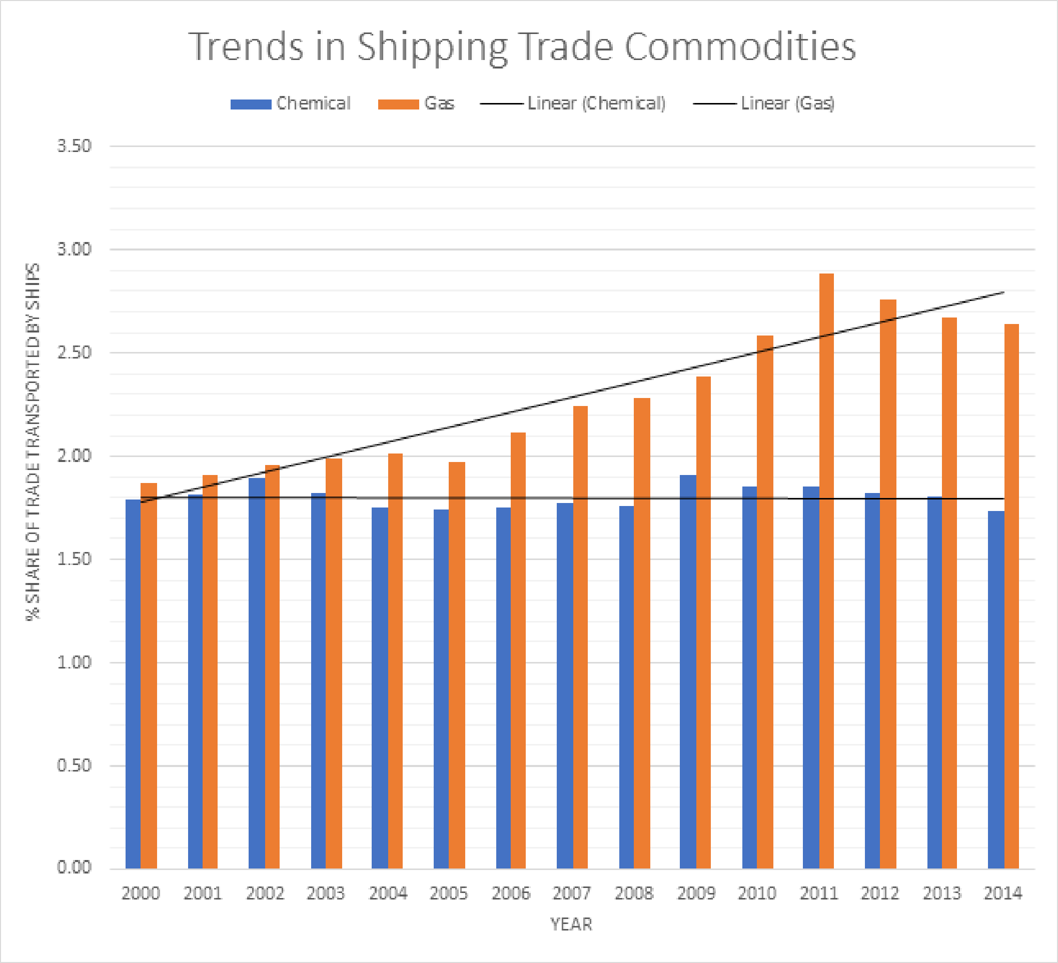

Figure 4.2: Trends in the shipping sector in terms of percentage share of total shipping demand in billion ton-miles for chemicals and gas commodities, linear lines represent the trendlines[26]

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[2] Even though the percentage share is constant for chemicals, the total demand for the shipping sector is increasing.

However, the opposite trends are seen for oil and other-bulk products commodity groups. As mentioned already, since there is ongoing transformation towards non-CO_2 emitting resources and technology, the dependency on the use of oil will certainly decrease, implying a potential reduction in trade of this commodity. There is an upward trend for the main bulk products. This implies that there is likely increase in the use of main bulk products globally i.e. iron ore, grains, coal, bauxite, alumina, and phosphate rock. It is expected that future trade will be affected by climate change, for example from that the crop yield may be changed in the different world regions.[60].

With these trends seen in the recent years, more investments may be seen in the ships which can transport containerized products, main bulk products and gas volumes than in ships transporting oil products and chemicals. Depending on the possibility to use different fuels for ships for different commodities this might impact the prerequisites for different alternative marine fuels. As the economic growth is expected to continue in south-east Asia and upcoming growth in Africa[57, 58, 59], the overall demand in seaborne trade is likely to increase where as the demand in other regions will saturate as the growth saturates in future.

4.2 Estimated Future Shipping Demand

This section presents the future shipping demand estimated in this study based on recent trends observed and their correlation with economic growth and population. Table 4.1 presents the regression parameters and correlation coefficient(R-squared) for every shipping demand category included in this study. After analyzing the regression analysis R-Squared coefficient for "other bulk materials" shipping turned out to be less than 90 percent(Approx.70%). Hence the estimation of future demand for other bulk materials category is done in another way. Fortunately the regression coefficient for overall shipping demand is turned out to be approx. 99%. Hence the demand for the “other bulk materials” shipping category is calculated by subtracting the total demand for the remaining five categories from the total trade demand estimated in this study. The Higher the R-squared values,the stronger is the relationship between total demand of different shipping categories with the past development path of economic growth and population when shipping demand is expressed in terms of billion ton-miles data during the period 1990-2014. Respective R-squared values are shown in table 4.1.

Table 4.1: Regression coefficient for the relation between economic growth, population and shipping demand for different ship categories

Sector	β_1	β_2	β_0	**R-Squared**
Chemical	1.94E-12	2.88E-07	-1330	99.84
Gas	2.02E-11	1.69E-07	-1490	98.58
Containers	8.9E-11	1.85E-06	-12400	98
Main bulk	6.87E-11	6.05E-06	-34100	98.75
Oil	2.69E-11	1.44E-06	-670	84.67
Total	3.99E-10	7.41E-06	-35300	99.12

These relationships are used to calculate future demand values for every category in the shipping sector. Using this relationship and data on estimated economic growth and population as per SSP2 scenario presented in Appendix 1 and 2, the trends are calculated and graphically presented in fig.4.3.

As illustrated in fig.4.3 the transport for Main bulk materials, Containers and other cargo demand categories will increase in higher speed compared to the demand categories Chemical, Gas, and Oil. The remaining categories, Chemical, Gas, and Oil, seem to have saturated demand over the time-period 2020-2100.

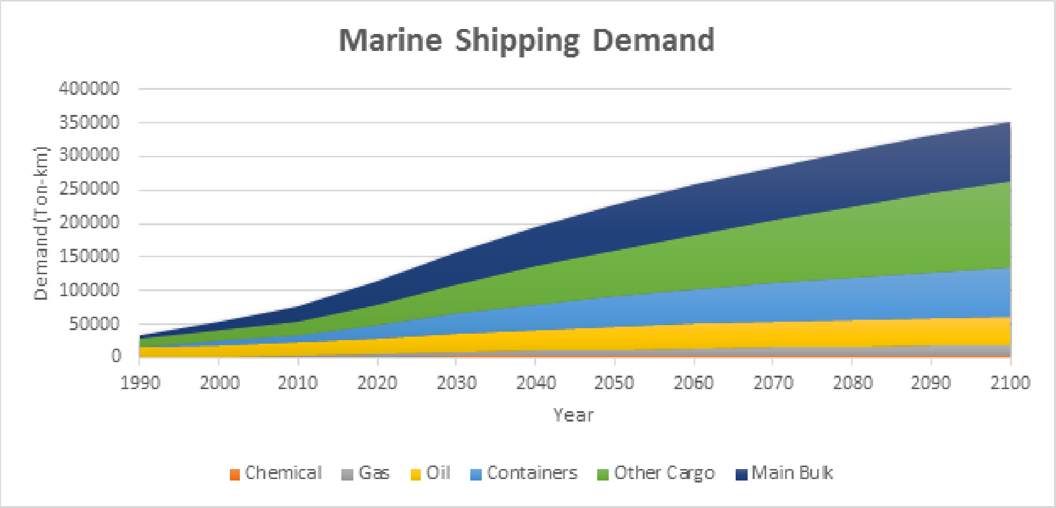

Figure 4.3: Estimated future shipping demand expressed in ton-km for each category of commodity

4.3 The Choice of Marine Fuels in Business-as-Usual Scenario

In the GAMS-based GET-RC6.5 model, the least cost fuel choices for overall representative global energy system, specifically the shipping sector, are explored under given different CO_2 constraints. The Business-as-usual (BAU) scenario used in this study does not put any limit on CO2 emissions and results are first and foremost driven on limited supply potential on e.g. oil and gas. Fig.4.4 presents the cost-effective use of the marine fuels and its corresponding propulsion technology options in the time-period 2010-2100. In the BAU scenario(including the demand in seaborne trade estimated in this study), the global electricity and heat sector is heavily relying on the use of coal since there is no limit on CO_2 emissions, as per the results obtained in this simulation(refer appendix 4).

In accordance with the results for electricity and heat, the use of synfuels, i.e. methanol produced from coal, seems to be the most cost-effective solution for the shipping sector. The use of oil-based fuels, HFO/MGO, start to reduce from 2010 as the supply of oil is limited and it is cost-effective to use the oil based fuels in road based transportation and aviation sector. Hence, the phase-out of HFO/MGO starts in the GET model after

2020. The CO_2 concentration in this scenario run stabilizes around 800ppm. The increasing demand is satisfied with the use of coal based synfuels. Given no constraint on fuel emissions, the combustion technology becomes the most favored technology as it is most cost-effective and already proven technology. There are no cost-related incentives for the shipping sector to adopt more advance technologies, such as fuel cells, in the BAU scenario.

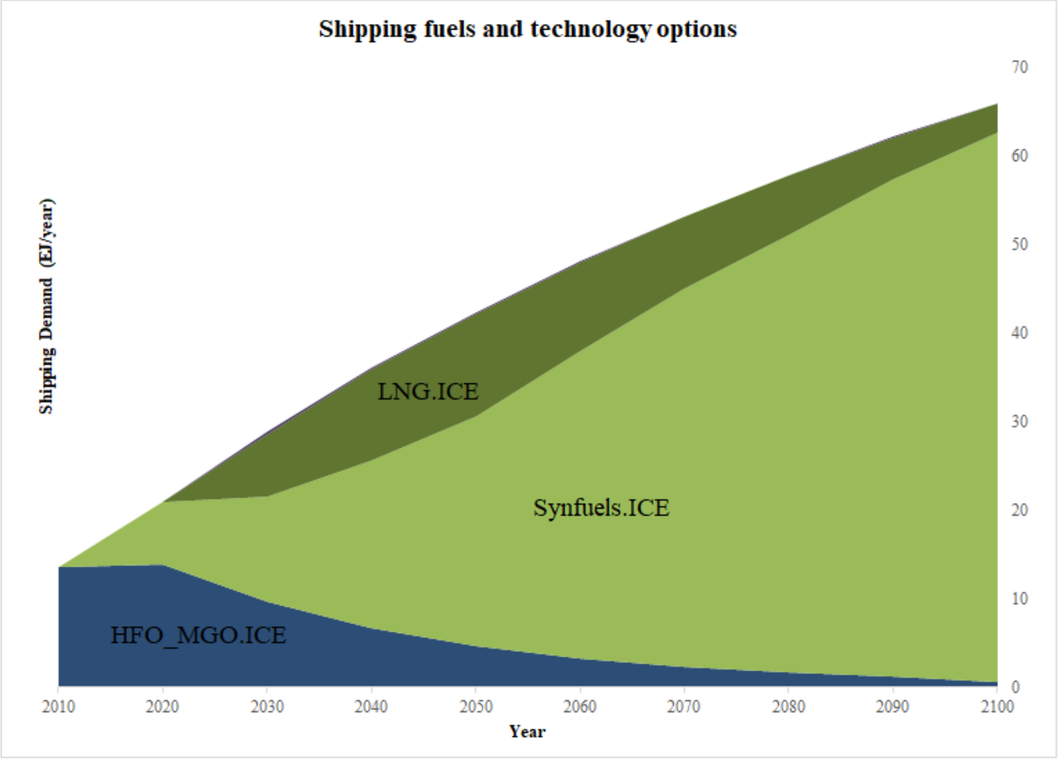

Figure 4.4: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under BAU scenario

Acronyms used are LNG=liquified natural gas, Synfuels= fossil based synthetic fuels: coal-to-liquid and gas-to-liquid, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), and ICE= internal combustion engine.

4.4 Cost-effective Fuel Choices under CO_2 Stabilized Concentration at 400 ppm

The primary aim of this study is to analyze the cost-effective marine fuel choices under CO_2 constraints. However, in order to understand the fuel choices in the marine shipping sector, the development of other sectors is also important. This section presents the results for primary energy usage, global heat and electricity use, alternative fuels in the land based transportation sector and cost-effective choices in the marine shipping sector assuming a long-term stabilization of the atmospheric CO_2 at 400 ppm concentration.

4.4.1 Global Primary Energy Use

Fig.4.5 presents the primary energy use in the global energy system in 400 ppm emission scenario. The mix of future primary energy resources looks different than what it looks today. Looking at the result, there is need for relatively rapid decrease in CO_2 emissions. The use of present primary energy sources should be reduced and transformation must lead to the more use of less CO_2 emitting sources. Hence, the model introduces hydrogen, electricity, solar, wind and biofuels as alternative fuels for the global system. The electricity is generated from solar and wind while hydrogen is made from electrolysis process. To maintain 400 ppm concentration by the end of century, the GET-RC6.5 model needs to reduce the use of coal as early as possible. Also, the limited supply of natural gas and oil must be used carefully until 2100.

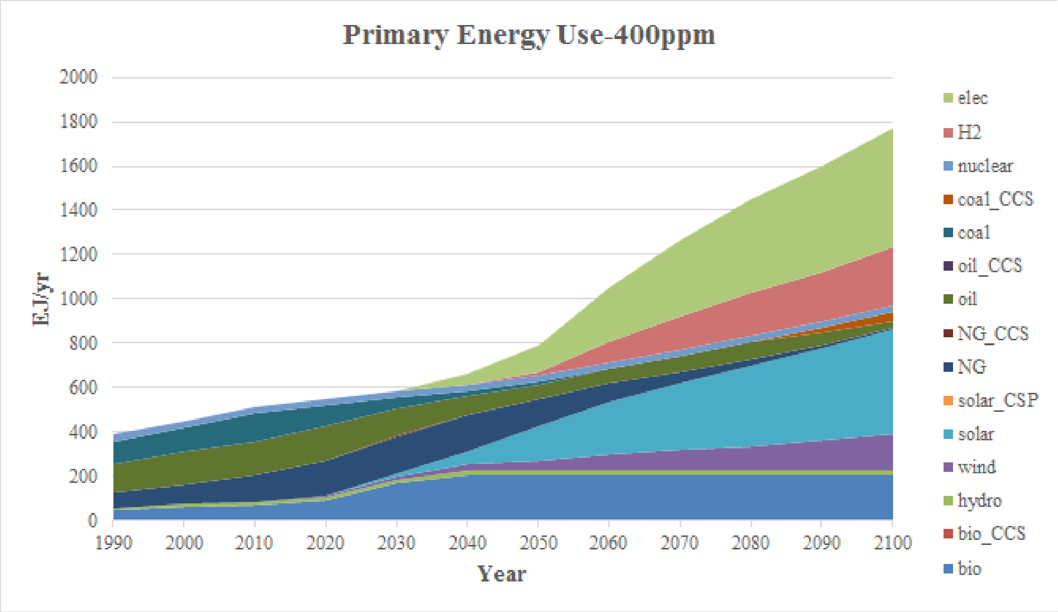

Figure 4.5: Cost-effective primary energy use in global energy system

Acronyms used are CCS= Carbon, capture and storage, H2=hydrogen, NG=natural gas, hydro= hydro power and CSP= concentrated solar plants.

In this scenario, the electricity use becomes very high in the 2nd half of 21st century. The high electricity use corresponds to the hydrogen production using electricity. This hydrogen is then utilized in all the main demand sectors. The use of wind and solar energy take place in the electricity sector in order to reduce dependence on the coal. The use of biomass has reached to its maximum supply potential given in this GET-RC 6.5 model. The limited biomass supply potential is mainly utilized in the heat sector as a cost-effective use according to the results found in the simulations.

4.4.2 Electricity Sector

Acronyms used are CCS= Carbon, capture and storage, H2=hydrogen, NG=natural gas, hydro= hydro power and CSP= concentrated solar plants.

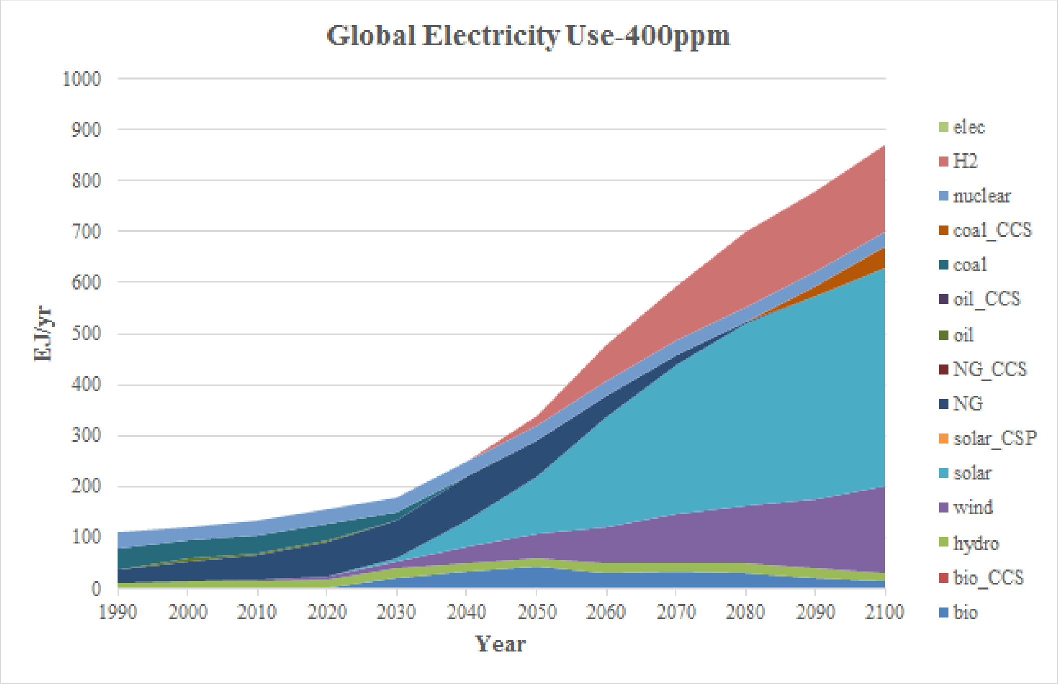

Figure 4.6: Global electricity use under 400 ppm concentration and SSP2 scenario

The use of different fuels utilized in the electricity sector under 400 ppm constraint is shown in fig.4.6. Looking at the results, the share of renewable technologies, wind and solar, in the 2nd half of the 21st century grow to high levels. As the coal sources are abundant in nature, the usage of coal will vary in the electricity sector depending on the successful commercialization of CCS technology and its cost compared to other technologies. In addition, CO_2 leakage from storage is another concern. So, these uncertainties make renewable grow extensively in the electricity sector when there is a stringent GHG emission constraint. In this study it is assumed that CCS will become a large scale available technology. Even though hydro energy is nearly renewable and cheap source to generate electricity, the available sites for such production is limited and return on investment is very high due to high capital investment.

4.4.3 Global heat Use

As illustrated in fig.4.7, model results show that global heat use is dominated by the use of biomass as the most cost-effective choice throughout the time-period 2010 to 2100. Since there is limited amount of biomass supply, hydrogen satisfies the remaining heat use. The use of hydrogen is motivated as the investment cost for generating heat using combustion technology for hydrogen is comparably low (150 GUSD/TW) as compared to other options which are coupled with CCS technology (ranges from 450 to 750 GUSD/TW).

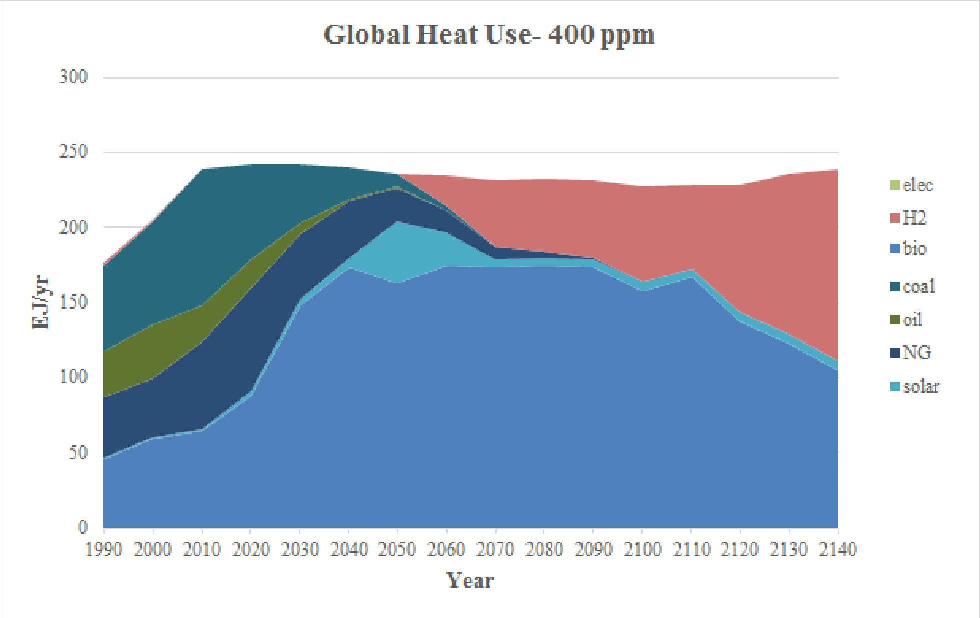

Figure 4.7: Global heat use under 400 ppm concentration and SSP2 scenario

Acronyms used are H2=hydrogen and NG=natural gas.

4.4.4 Land-based Transportation Use

For the land based transportation sector, the use of hydrogen is expected to skyrocket in the time-period 2050 to 2100, as illustrated in fig.4.8. Railways will continue to use the electricity in the entire studied period. The rapid decrease in the conventional sources of energy in the transportation sector (e.g. petrol) indicate that there is need to have fuel transformation very soon. Also in this sector, the land based transport sector seems to be the first sector to undergo transformation when stringent emission constraint start to become a reality.

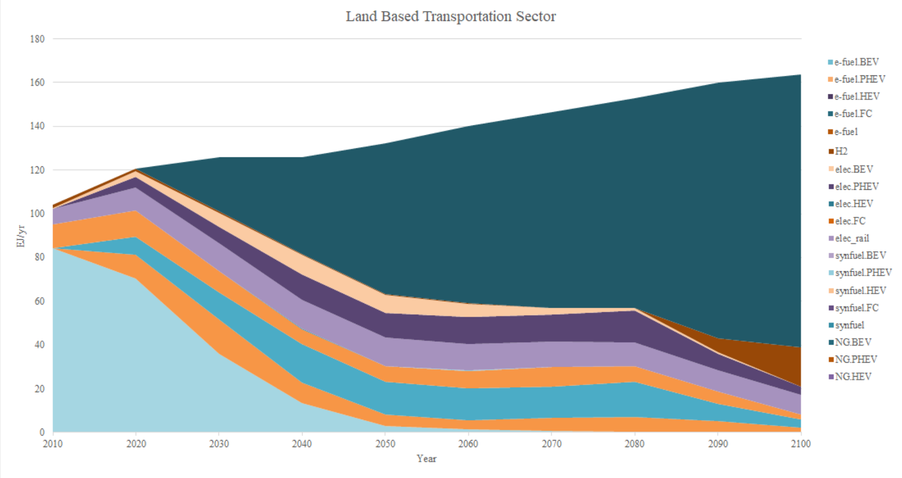

Figure 4.8: Cost-effective choices of Global land based transportation sector under 400 ppm concentration and SSP2 scenario

Acronyms used are BEV= battery electric vehicles, PHEV= plug-in hybrid electric vehicle, HEV=hybrid electric vehicle, FC=fuel cell, e-fuel=electrofuels, H2= hydrogen, elec=electricity, and Synfuels= fossil based synthetic fuels: coal-to-liquid and gas-to-liquid.

4.4.5 Shipping Fuels under 400 ppm Constraint and SSP2 Scenario

Fig. 4.9 shows the alternative and renewable fuels as well as corresponding propulsion technology options for the marine shipping sector under 400 ppm constraint. The results for the different ship categories has been added together and presented as an aggregated result. From the same figure, it is clear that LNG act as a transitional fuel whereas hydrogen is the most cost-effective fuel option that dominates in the long run. The use of natural gas as LNG in the shipping sector is observed as a transitional solution until the use of hydrogen and its corresponding propulsion technology options become commercial.

As seen from the result, the use of natural gas is coupled with both fuel cell technology and combustion technology. The reason behind this is methane leakage which take place due to combustion of natural gas. Since fuel cell technology is more efficient than combustion technology, the marginal demand during time-period 2020 to 2040 is satisfied by fuel cell technology. But as allowed emission concentration reduces over time, the transition is seen from LNG with fuel cell to hydrogen. Overall LNG use peaks around 2040. More stringent (deep decarbonization) CO_2 limits correspond towards higher use of hydrogen in the shipping sector as a cost-competitive solution.

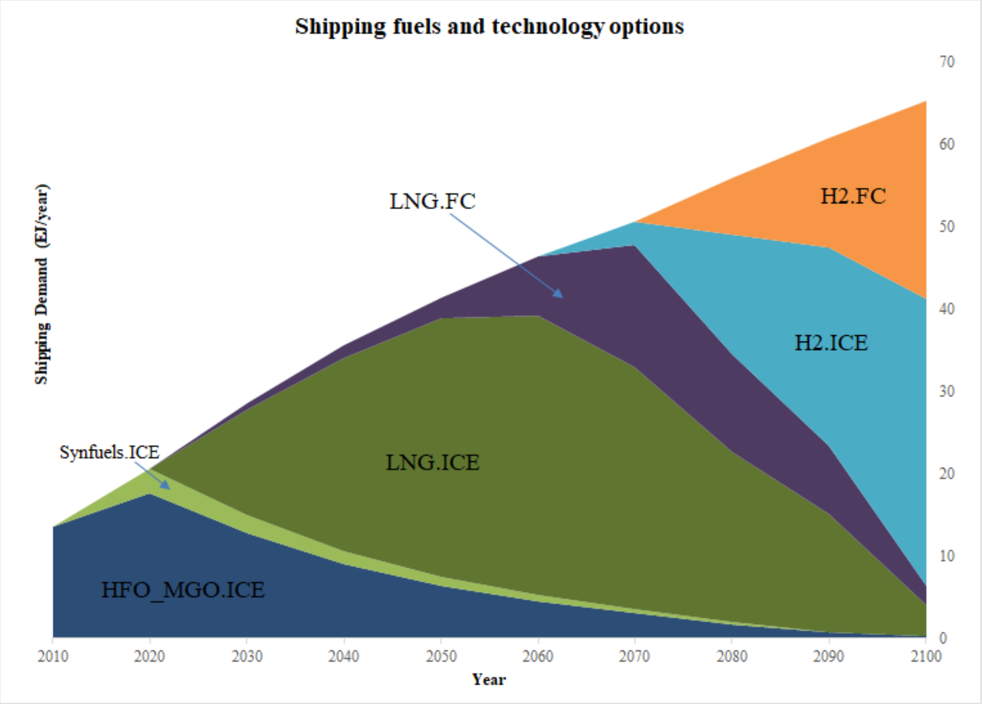

Figure 4.9: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under 400ppm constraint and SSP2 scenario

Acronyms used are LNG=liquified natural gas, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), H2=hydrogen, ICE= internal combustion engine and FC=fuel cell.

Comparing the transition towards renewable fuels in different sub-sectors, the phase out of fossil fuels is expected to start first in land transportation sector from 2010 and later in the electricity sector from 2020. This is a bit unusual result where in reality it is seen that the global electricity sector has been undergone the transition before land based transportation sector. One can argue that such transition is a result of different policies, for e.g. subsidies towards and wind and solar technologies etc. Although the result does not encompass the reality, it does show the importance of sooner phase out of fossil-fuels in the land-based transport sector.

4.5 Shipping Fuels under 550 ppm Constraint and SSP2 Scenario

Fig.4.10 shows the alternate renewable fuels as well as corresponding propulsion technology options for the marine shipping sector under 550 ppm constraint. Under less stringent emission constraint, the use of natural gas is seen to increase as compared to the cost-effective use in the 400ppm constraint(see fig.4.9).

In this scenario, hydrogen is still seen as the dominant technology by the end of 21st century. When compared to the cost-effective fuel choices observed in 400 ppm scenario, less stringent emission limit seems to delay the transition from LNG to hydrogen and increase the use of combustion propulsion technology in the shipping sector.

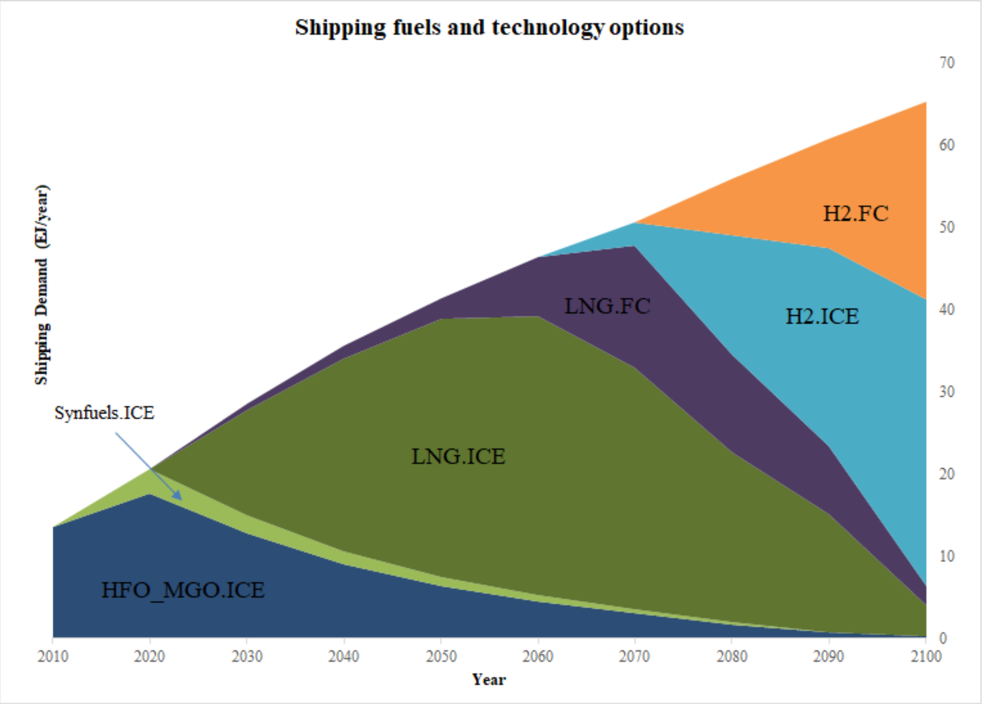

Figure 4.10: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under 550ppm constraint and SSP2 scenario

Acronyms used are LNG=liquified natural gas, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), Synfuels= fossil based synthetic fuels: coal-to-liquid and gas-to-liquid, H2=hydrogen, ICE= internal combustion engine and FC=FC=fuel cell.

4.6 Sensitivity Analysis

There are many assumptions taken into consideration before developing the model for the shipping sector. Some factors directly affect the demand and technology growth of the marine shipping sector such economic growth, population, innovation and efficiency improvements in technology and new commodity types which now are transported using ships. Some factors indirectly affect the growth of the shipping sector such as modal growth in other transport sector and reduced costs are the biggest motivation for using other modes of transport if possible. In addition, the year when the technology becomes commercial and its mature costs are uncertain to some extent. In order to better understand the robustness of the GET-RC6.5 model for the fuel choices in the shipping sector following sensitivity analysis is performed.

Here, three major sensitivity analyses are performed: 1) demand variation 2) uncertainty in using hydrogen as an alternative marine fuel 3) different carbon tax levels. The initial two sensitivity analyses are performed under 400 ppm scenario while the third analysis is performed assuming the carbon tax will trigger the cost-effective transformation in overall global energy system.

4.6.1 Demand Variations

In this study, the shipping demand is calculated as the function of the economic growth and population using regression analysis. In the SSP2 scenario, the resulted economic growth is approximately found to be 1.6%/year[59]. In this sensitivity analysis, following rate of economic growth in term of GDP are considered.

1. Base case: Economic growth rate (1.6%/year)
2. SSP2-X2 scenario: Economic growth rate (3.2%/year)
3. SSP2-X3 Scenario: Economic growth rate (0.8%/year)

Numbers on future population is also another uncertainty which has an impact on the shipping demand. However, in the GET-model the assumption on population is first and foremost affecting demand for passenger transport and since the shipping sector is dominated by freight transport it has been decided to not explore the effect of different population assumptions.

The change in overall shipping demand due to varying economic growth rates is represented in equation 3.1 in chapter 3 and section 3.2. The fig.4.11 demonstrates the most cost-effective fuel choices required in the shipping sector under SSP2-X2 scenario where twice the rate of economic growth is assumed when compared to IIASA-SSP2 scenario.

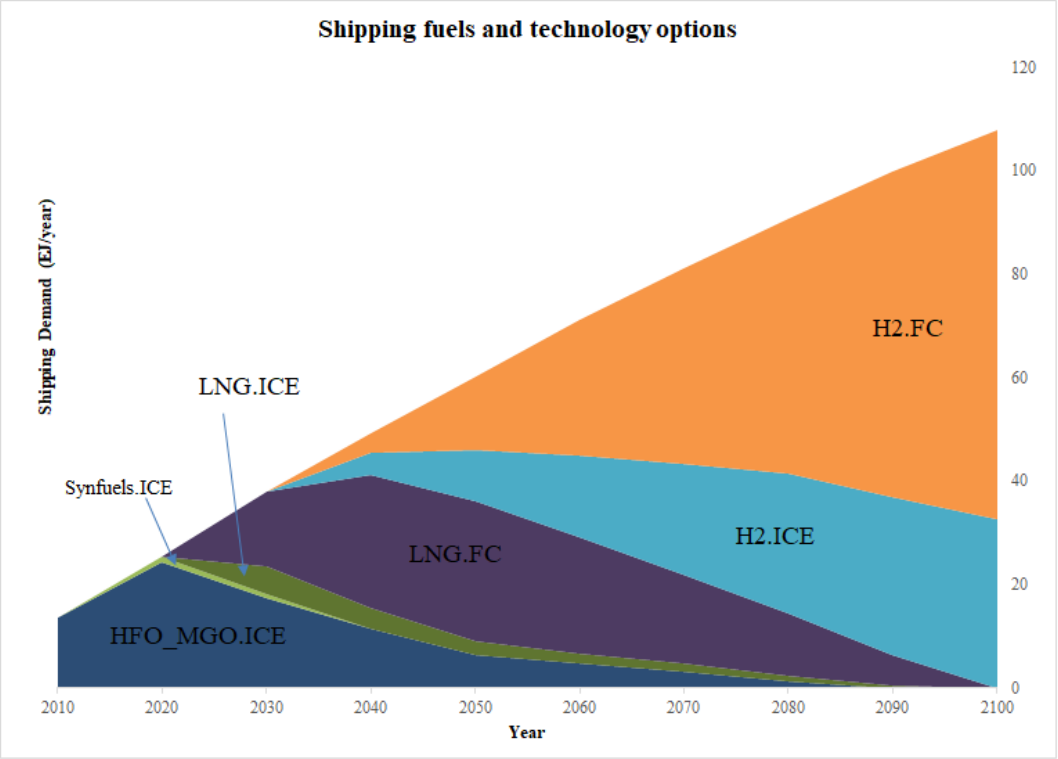

Figure 4.11: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under 400ppm constraint and SSP2-X2 scenario

Acronyms used are LNG=liquified natural gas, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), Synfuels= fossil based synthetic fuels: coal-to-liquid and gas-to-liquid, H2=hydrogen, ICE= internal combustion engine and FC=fuel cell.

The overall demand in this scenario is increased to 110EJ from approx. 65EJ. With increase in the demand, the hydrogen is still the most cost-effective choice for the shipping sector. From the fig4.11 and fig.4.9, it becomes clear that the higher the demand for the shipping sector, the transition from LNG to hydrogen, due to even more stringent emission limits in upcoming years, is observed very early in the simulation results. This puts requirement of early commercialization of hydrogen use in the shipping sector. Higher economic growth in global society also means the demands for other transportation sector increase and hence the transition from HFO/MGO should take place even at faster rate than before.

SSP2-X3 corresponds to half of the overall economic growth rate of the IIASA-SSP2 scenario which leads to lower aggregated shipping demand of approx. 45EJ (65 EJ in base case). As seen in the fig.4.13, opposite happens in this context compared to SSP2-X2 scenario. Lower demand due to lower economic growth corresponds to a significantly higher use of LNG as a shipping fuel in both combustion engines and fuel cells before the use of hydrogen is expected from 2040. After that the use of hydrogen dominates in the time-period 2070-2100. Lower economic growth reduces the demand in other sectors and allows the shipping sector to emit more GHG emissions.

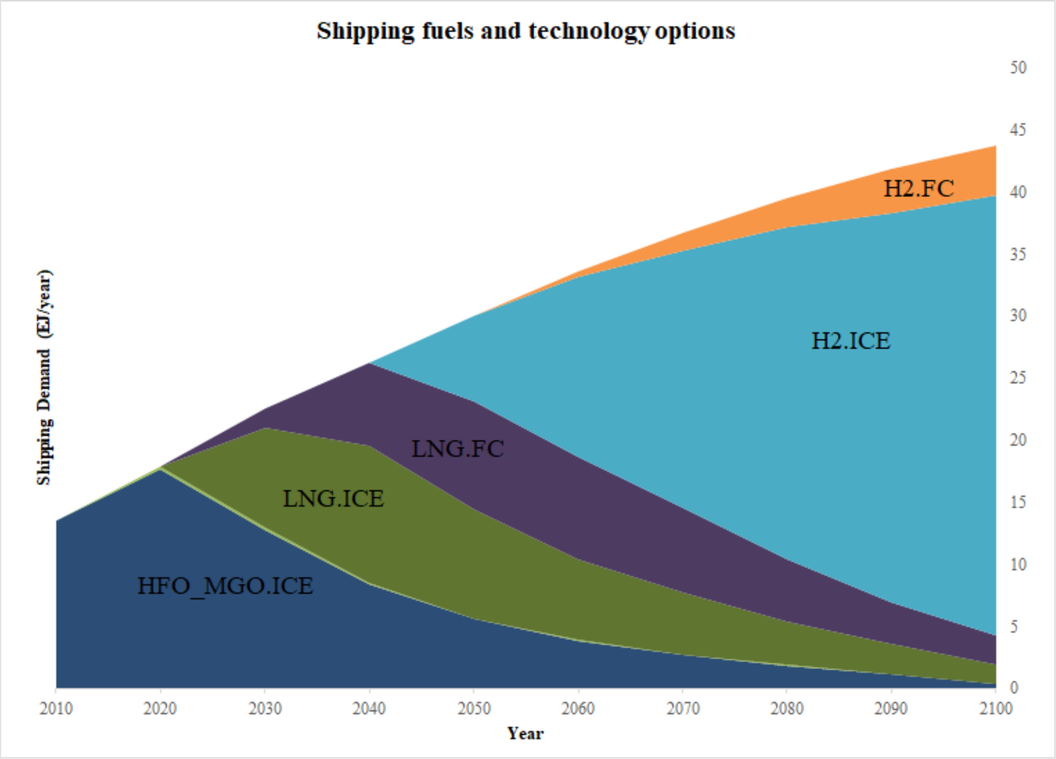

Figure 4.12: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under 400ppm constraint and SSP2-X3 scenario

Acronyms used are LNG=liquified natural gas, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), H2=hydrogen, ICE= internal combustion engine and FC=fuel cell.

Comparing all the three demands in the three scenarios, it is indicated that the hydrogen is the expected cost-effective fuel choice in the shipping sector in longer term scenario provided with stringent CO_2 constraints in the scenario about supply potentials of primary energy resources. Depending upon the level of demand in the marine shipping sector, the transition of alternative fuels is decided. As the demand increases, the transition from HFO/MGO to LNG and then to hydrogen is expected at an early year and in a faster way. Methane leakage is very important factor when it comes to using the natural gas in the shipping sector. More stringent emission limits results in more usage of fuel cell technology coupled to natural gas used to power the ships. Also, the use of energy conversion technology coupled with the use of hydrogen is dependent on the amount of shipping demand. Observing the composition of future fuels to be used in the shipping sector by the end of this century against the level of demand, it is seen that the percentage of hydrogen coupled with fuel cell technology increases with increase in demand. This happens due to limited supply potentials of different primary resources such as oil and bio-energy etc. Overall, all the different results suggest how the level of demand is an important variable which will affect the cost-effective choice of alternative shipping fuel.

4.6.2 Concerns Towards Hydrogen as A Marine Fuel

There are still concerns about hydrogen as an alternative fuel in the marine shipping sector about safety issues, energy density and lack of infrastructure. As seen from the results until now in this study, hydrogen is expected to become an energy carrier which will increase the deep decarbonization efforts in the marine transportation sector at a minimum cost to the whole energy system. But Hydrogen requires larger space to store onboard the ships. Even if it is kept under 700 bars pressure, there is a still requirement of six times bigger storage space[42]. Lower energy density means more fuel consumption for the same energy content provided by HFO. This results in even more space requirement.

Hydrogen propulsion is yet to be tested successfully in the marine shipping sector for large scale energy production. The advent of this unproven technology might be a slow process. Also, supply infrastructure is another concern which needs to be addressed. It is commonly referred to as a “chicken-and-egg” problem. Some of these concerns reflect in uncertain mature commercial costs of using hydrogen as a shipping fuel. That’s why the sensitivity analysis is performed to understand which alternative and marine fuels help the shipping sector to reduce its emission when hydrogen is not a feasible option.

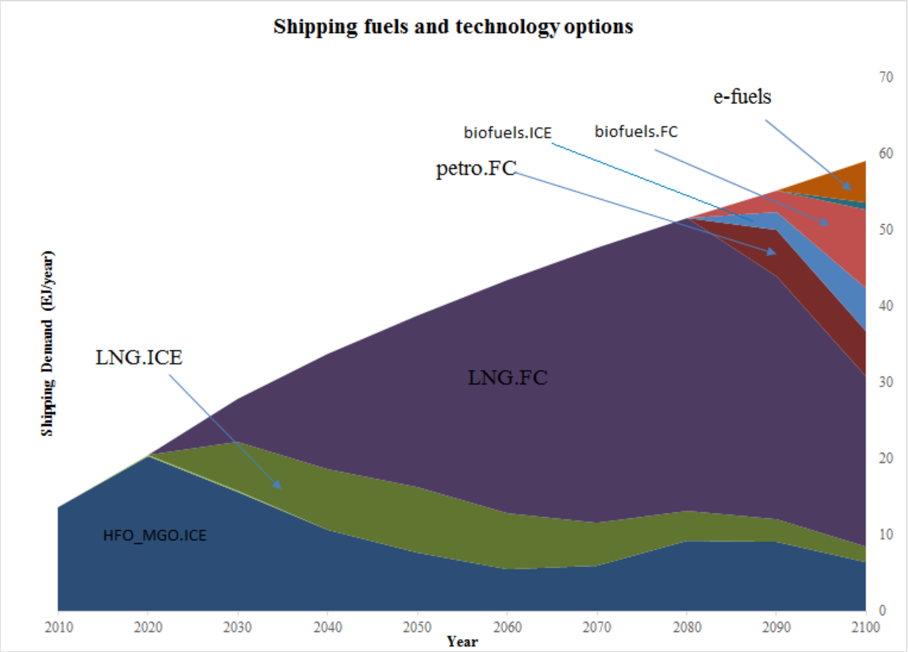

Figure 4.13: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under 400ppm constraint, SSP2 scenario and hydrogen is not available as a marine fuel

Acronyms used are LNG=liquified natural gas, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), ICE= internal combustion engine, e-fuels=electrofuels and FC=fuel cell.

Fig.4.13 shows the alternative fuels and technology options under 400 ppm scenario when hydrogen is not assumed to be a shipping fuel. The results in this particular simulation show that the LNG will be most dominant fuel from 2040 to 2100. The remaining demand during 2080 to 2100 is satisfied by various fuels which are biofuels, e-fuels and HFO/MGO used in fuel cell technology. The use of LNG is more coupled with fuels cells since the fuel cell technology is more efficient than the combustion technology. The use of HFO/MGO remain longer in this scenario than the base case.

Comparing the results in this sensitivity analysis(Fig.4.13), higher use of LNG stresses out the important role of LNG in the shipping sector. The use of LNG increases drastically as compared to base case. Also, methane leakage constraint and better efficiency compared to combustion technology are the main reasons behind having results for the use of more fuel cell technology than combustion technology in this sensitivity analysis. Also, supply potential of natural gas is limited in this model. So, if the supply of the natural gas is reduced, it is better to use natural gas in the shipping sector rather than road transportation sector. This is due to reduced infrastructure cost for LNG used in the ships as compared to road transportation sector. Table 4.2 demonstrates the use of NG in the road transportation sector in this sensitivity analysis and compares it with SSP2 demand scenario results both under 400 ppm constraint.

Table 4.2: Use of natural gas in the road transportation(expressed in EJ) from the two cases where hydrogen is assumed to be or not to be, a feasible shipping fuel

Scenarios/Year	Hydrogen as an infeasible shipping fuel	Hydrogen as a shipping fuel
1990	0	0
2000	2.09	5.5
2010	4.85	10.66
2020	4.41	11.82
2030	3.6	9.66
2040	2.43	7.07
2050	1.72	7.09
2060	0.95	8.14
2070	0.46	8.83
2080	0.2	7.02
2090	0.09	5.29
2100	0.04	2.26

4.6.3 Tax Levels in the Shipping Sector

Recently IMO has indicated that there should be a carbon tax of \$25/tCO_2 for the shipping and aviation sector starting from 2020[61]. Tax is one type of market-based instruments which brings revenues to the government and is expected to be used in the same sector to reduce the externalities. There is no condition on using these collected revenues in the same sector unless it is mentioned in policy regulations. The tax provides direct incentive towards shipping companies to find cost effective solutions in terms of better technologies or different fuels. Different tax levels are analyzed under this sensitivity analysis.

The first sensitivity analysis checks whether tax level of \$25/tCO_2 for all the regions and all sectors is sufficient to reach carbon concentration in the range of 400ppm.

In case, the tax of \$25/tCO_2 is insufficient, then the second sensitivity analysis is carried out assuming the tax level is increased in 2050 to \$125/tCO_2 and second at \$250/tCO_2 level. The global society is getting increasingly conscious about the climate impacts. This increase to either levels is motivated because of this consciousness. As the lifetime of the ships is considered as 30 years and the implementation of higher tax will still take time to undergo the total fleet transformation of the marine shipping sector. If the shipping sector must make fleet transformation, the increased tax levels should be implemented around the time-period 2050-2060. This section hence provides two variations of tax levels(\$125/tCO_2 and \$250/tCO_2 in 2060-2100) under the sensitivity analysis.

Looking at the results seen in fig.4.14 and fig.4.15, tax level under both cases show that most dominant fuel is synfuel for the time-period 2020 to 2100. Comparing these results with results under 400 ppm, the cost-effective fuel choices are different. This suggests that the tax levels under both cases are significantly lower than required to meet 400ppm level. In reality, the tax levels are different in different sectors. Even if the tax levels are likely to be high in other sectors than shipping sector, the use of synfuel is going to increase as the allowance to emit is higher in both tax levels.. The observed CO_2 concentration under both cases is 782 ppm and 724 ppm by year 2100 respectively .

Looking at above-mentioned results and comparing the results obtained with 400ppm scenario, there is a need to find the tax level which corresponds to similar CO_2 level as in 400 ppm level. Further sensitivity analysis is carried out at \$1250/tCO_2 and \$3750/tCO_2 tax levels to see what carbon concentrations are achieved in the global energy system. Here, these tax levels are roughly assumed as the equivalent tax amount for the time-period 2010 to 2100. At \$3750/tCO_2 tax level, the shipping fuels and technology options under this tax level is shown in fig.4.17. There is a huge difference between this needed tax level and ongoing discussions by IMO[61] to put CO_2 tax in the marine shipping sector.

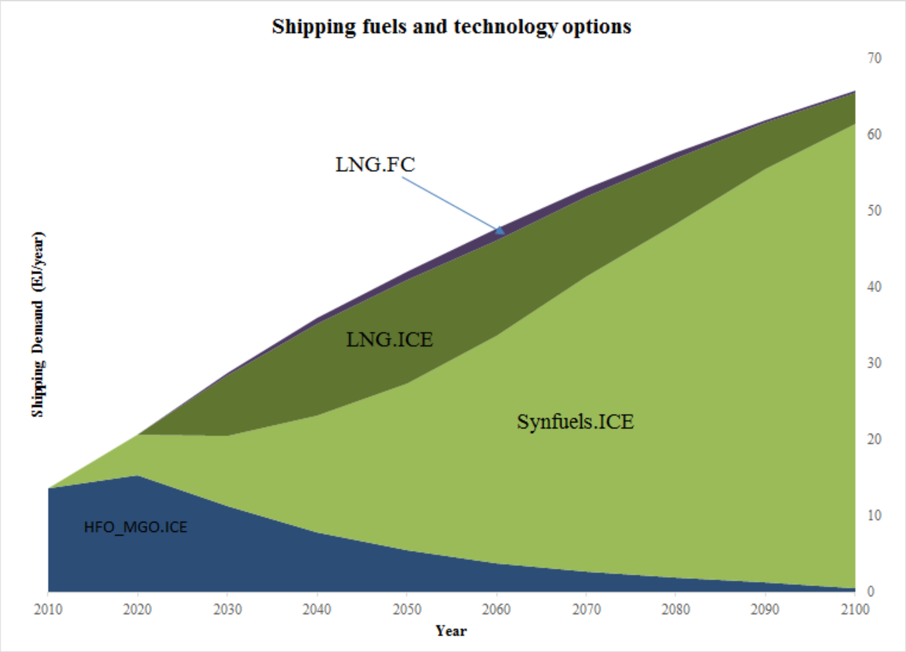

Figure 4.14: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under tax level \$25/tCO_2 in 2020-2050 and \$125/tCO_2 in 2060-2100

Acronyms used are LNG=liquified natural gas, Synfuels= fossil based synthetic fuels: coal-to-liquid and gas-to-liquid, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO) and ICE= internal combustion engine.

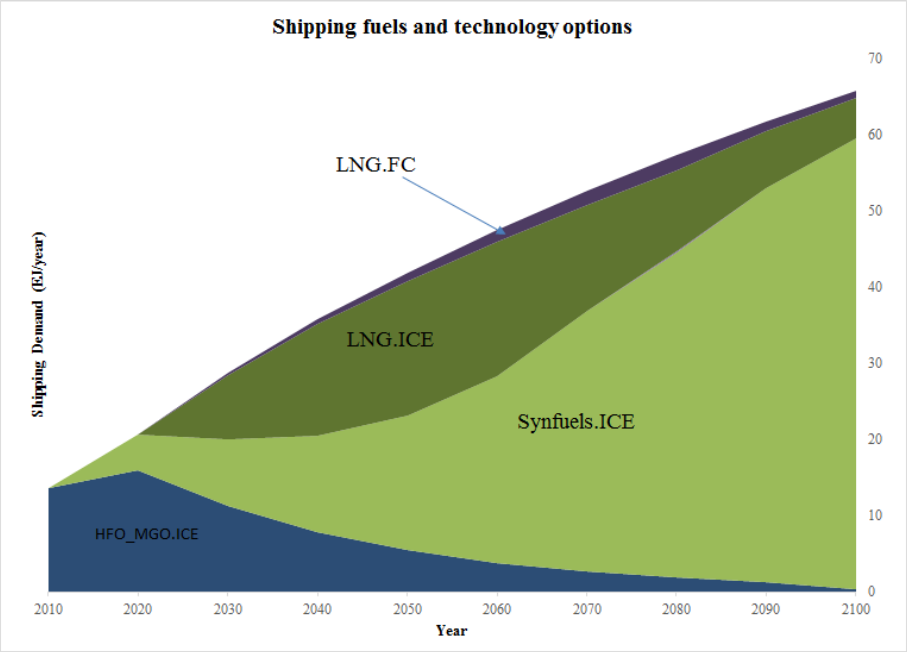

Figure 4.15: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under tax level \$25/tCO_2 in 2020-2050 and \$250/tCO_2 in 2060-2100

Acronyms used are LNG=liquified natural gas, Synfuels= fossil based synthetic fuels: coal-to-liquid and gas-to-liquid, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO) and ICE= internal combustion engine.
Here, the tax levels mentioned above imply the extra cost paid by GHG emitting producers[3]. The different tax levels are targeted to see the transition which will make technologies like LNG or hydrogen competitive with HFO/MGO.

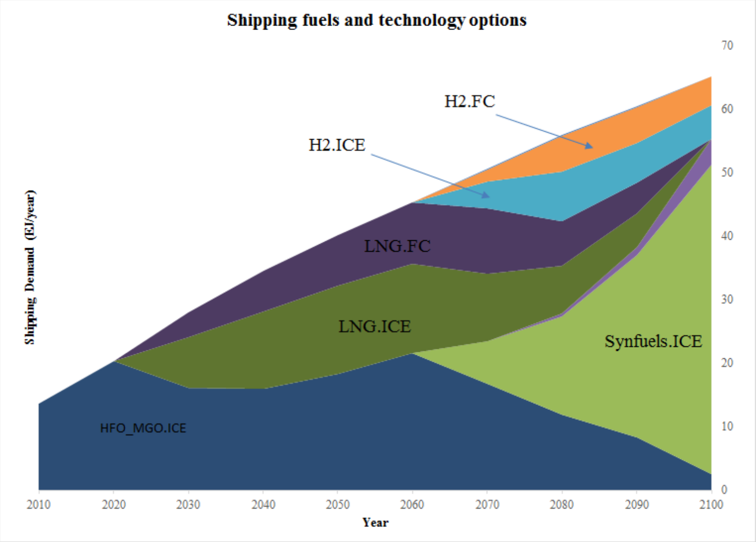

Figure 4.16: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under tax level \$1250/tCO_2 in 2020-2100

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[3] In general, taxes are designed to avoid undesirable impacts on human health and environment. Tax is an instrument to alter the behavior of industry or society to maximize deemed society welfare by policymakers.

Acronyms used are LNG=liquified natural gas, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), Synfuels= fossil based synthetic fuels: coal-to-liquid and gas-to-liquid, H2=hydrogen, ICE= internal combustion engine and FC=fuel cell.

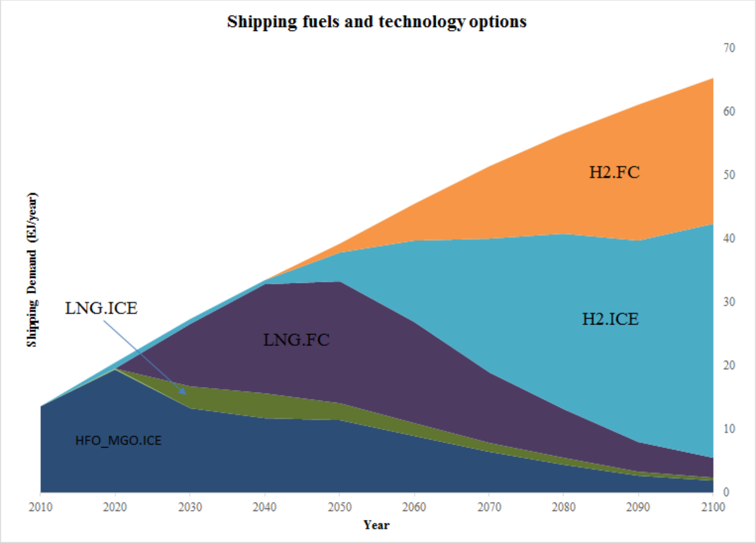

Figure 4.17: Cost-effective choice of shipping fuels and its corresponding propulsion technology options under tax level \$3750/tCO_2 in 2020-2100

Acronyms used are LNG=liquified natural gas, HFO_MGO=petroleum based fuels for ships: heavy fuel oil (HFO) and marine gas oil (MGO), H2=hydrogen, ICE= internal combustion engine and FC=fuel cell.

If the shipping industry must contribute towards equivalent 400 ppm CO_2 concentration assuming all the sectors should have same CO_2 tax level, then the expected level of tax should be set in between \$1250/tCO_2 to \$3750/tCO_2. In case these CO_2 tax levels are set in higher range compared to other sectors, then the required tax level will shift towards \$1250/tCO_2 as more emissions are allowed than the case in \$3750/tCO_2 tax level. The generated revenue via this tax level, most likely IMO or local/regional policy regulator, can be used in the marine shipping sector to address other externalities such as marine acidification[13].

5

Discussion and Conclusion

The results obtained from the GET model suggest that the cost-effective choices in the marine shipping sector require a transition beginning in 2010 from HFO/MGO to methanol/LNG/hydrogen in different scenario analysis. Even in BAU scenario, the cost-effective choices suggest transition beginning in 2010 and 2020 from HFO/MGO to methanol and LNG respectively. This is because of the limited supply potentials of oil reserves. These alternate fuels used in the marine shipping sector in BAU scenario only use already proven and cheap combustion technology. Also this combustion technology is already being used in all the continents of the world and unclear incentives towards the shipping industry might generate technology lock-in situation.

In a 400 ppm scenario, the cost-effective choices suggest LNG as a transitional fuel and hydrogen as the longer term marine renewable fuel for the shipping sector. Also, these choices suggest the use of more efficient fuel cells. As mentioned before the technology dispersion of the combustion technology makes it hard to get implemented everywhere at the same time. Policymakers need to create incentives for the shipping investors to invest in this technology. In addition, these incentives must be created soon in order to transform the shipping fleet. To make this transformation happen, the IMO must start providing information about long term plans and expected policy measures in future. More and clearer information about emissions will help IMO to design policies in a better way. This will also help the investors to set their own environmental goal as well as take into account upcoming policies[62].

The results also conclude that the level of the shipping demand (expressed in EJ) plays very important role in deciding the role of different technologies coupled to the use of renewable fuels, specifically in case of hydrogen. The higher the shipping demand, the more use of fuel cells is expected as per cost-effective solution, specifically as the shipping demand rises above 40EJ. Particularly both the fuel cell technology and hydrogen costs are very uncertain and not proven in the marine shipping sector. In short-term, the focus should be to address this issue of commercialization as early as possible. Not only higher demand suggests the additional use of hydrogen with fuel cells and limit the use of combustion engines with hydrogen but also suggest a quick and early transition to hydrogen beginning in 2040.

The costs for hydrogen storage plays an important role in the marine shipping sector. It is expected that the use of hydrogen will take place first in the road transportation sector and then the technology may become commercial in the shipping sector. The progress needs to be faster by identifying more niche markets for hydrogen such as submarines and military ships and bring down costs for hydrogen storage. More investment in niche markets will bring down costs for hydrogen storage as well as technology expertise eases the use in the shipping sector.

In order to make hydrogen competitive, there is a huge difference between the IMO discussed tax level[61] and the needed tax level. This difference sends rather unwanted signal towards shipping industry in a longer term. During the time-period when SO_x and NO_x policies implementation took place, the industry favored using scrubber technology when sufficient incentives were present to start transition towards LNG as a marine fuel. This showed a situation where a major part of industry refused to undergo fuel transformation when the incentives were present. Taking into consideration such kind of situations, it is better to create incentives for hydrogen as early as possible. This will help to address after implementation issues.

In case the shipping industry starts considering hydrogen to be an infeasible solution due to cost of implementation or security concerns, then LNG (to a greater extent), bio-fuels, e-fuels and oil based fuels coupled with fuel cells are the cost effective choices for the shipping sector. The use of natural gas seems to be a very important and best possible use in the marine shipping sector.

To conclude, cost-effective solutions for the shipping transport sector suggest the use of hydrogen and LNG as the future alternative and renewable marine fuels. Both solutions are a way forward to the shipping sector rather picking one solution. To increase the diffusion of these fuels in the shipping sector, the energy infrastructure is another aspect that needs to be addressed. Policymakers, could start making regulations, for example subsidies, which will set up the infrastructure for hydrogen and LNG refueling stations.

6

Future Work

Following ideas are identified during the thesis work:

- Improved information about technology investment cost for every category would be beneficial for the analyses.
- Concrete information about feasibility of different fuels and corresponding propulsion technology options in different shipping categories would provide more detailed analyses.
- Advanced information about technical configuration of ships and their average sizes will increase the reliability of fleet number for every shipping category.
- In depth information about energy supply potentials in different regions would be beneficial for detailed understanding of global energy system dynamics.
- Technology commercialization and dispersion varies in different regions. If possible, this can improve the results for different sensitivity analysis.
- If possible, technology learning index can be added to efficiency values to improve the overall results for cost-effective fuel choices.

Bibliography

[1] R. K. Pachauri, *Climate Change 2014 Synthesis Report*. IPCC, 2014.

[2] W. N. Adger, *Fairness in adaptation to climate change*. MIT press, 2006.

[3] T. W. P. Smith, J. P. Jalkanen, B. A. Anderson, J. J. Corbett, J. Faber, S. Hanayama, E. O'Keeffe, S. Parker, L. Johansson, L. Aldous, C. Raucci, M. Traut, S. Ettinger, D. Nelissen, D. S. Lee, S. Ng, A. Agrawal, J. J. Winebrake, and A. Hoen, M., "Third IMO Greenhouse Gas Study 2014," *International Maritime Organization (IMO)*, p. 327, 2014.

[4] M. Cames, J. Graichen, A. Siemons, and V. Cook, "Emission Reduction Targets for International Aviation and Shipping," Tech. Rep. 9, 2015.

[5] M. Taljegard, S. Brynolf, M. Grahn, K. Andersson, and H. Johnson, "Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World : Results from a Global Energy Model," *Environmetal Science and Technology*, vol. 46, no. 21, pp. 12 986–12 993, 2014.

[6] S. Arrhenius, "in the Air upon the Temperature of the Ground," *Philosophocal Magazine and Journal of Science*, vol. 41, no. page 270, pp. 237–279, 1896.

[7] J. Leggett, W. J. Pepper, R. J. Swart, J. Edmonds, L. G. Meira Filho, I. Mintzer, M. X. Wang, and J. Wasson, "Emissions scenarios for the IPCC: an update," in *Climate change 1992: the supplementary report to the IPCC scientific assessment*, 1992, pp. 69–95.

[8] "Summary for Policymakers," *IPCC*, pp. 1–37, 2000.

[9] R. H. Moss, J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, S. Emori, M. Kainuma, T. Kram, G. A. Meehl, J. F. B. Mitchell, N. Nakice-novic, K. Riahi, S. J. Smith, R. J. Stouffer, A. M. Thomson, J. P. Weyant, T. J. Wilbanks, and N. Nakicenovic, "The next generation of scenarios for climate change research and assessment," *Nature*, vol. 463, no. 7282, pp. 747–756, 2010. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/20148028

[10] B. C. O'Neill, E. Kriegler, K. L. Ebi, E. Kemp-Benedict, K. Riahi, D. S. Rothman, B. J. van Ruijven, D. P. van Vuuren, J. Birkmann, K. Kok, M. Levy, and W. Solecki, "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century," *Global Environmental Change*, vol. 42, pp. 169–180, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004

[11] V. Eyring, H. W. Köhler, A. Lauer, and B. Lemper, "Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050," *Journal of Geophysical Research D: Atmospheres*, vol. 110, no. 17, pp. 183–200, 2005.

[12] Ø. Buhaug, J. J. Corbett, O. Endresen, V. Eyring, J. Faber, S. Hanayama, D. S. Lee, H. Lindstad, A. Markowska, A. Mjelde, D. Nelissen, J. Nilsen, C. Pålsson, J. J.

Winebrake, W. Wu, and K. Yoshida, “Study 2009,” International Maritime Organization, London, Tech. Rep., 2009.

[13] O. Endresen, M. Eide, S. Dalsoren, I. Isaksen, and E. Sorgard, “The Environmental Impacts of Increased International Maritime Shipping,” *Global Forum on Transport and Environment in a Globalising World*, no. November, pp. 1–43, 2008.

[14] J. J. Corbett, C. Wang, J. J. Winebrake, and E. Green, “Allocation and forecasting of global ship emissions,” Clean Air Task Force, Boston, MA, USA, Tech. Rep. August 2015, 2007.

[15] K. L. Ebi, S. Hallegatte, T. Kram, N. W. Arnell, T. R. Carter, J. Edmonds, E. Kriegler, R. Mathur, B. C. O’Neill, K. Riahi, H. Winkler, D. P. van Vuuren, and T. Zwickel, “A new scenario framework for climate change research: Background, process, and future directions,” *Climatic Change*, vol. 122, no. 3, pp. 363–372, 2014.

[16] Ocean Policy Research Foundation, “The World’s Changing Maritime Industry and a Vision for Japan,” Ocean Policy Research Foundation (OPRF), Tech. Rep., 2008.

[17] C. C. Chang, “Marine energy consumption, national economic activity, and greenhouse gas emissions from international shipping,” *Energy Policy*, vol. 41, pp. 843–848, 2012.

[18] J. Vergara, C. McKesson, and M. Walczak, “Sustainable energy for the marine sector,” *Energy Policy*, vol. 49, pp. 333–345, 2012. [Online]. Available: http://dx.doi.org/10.1016/j.enpol.2012.06.026

[19] K. Riahi, D. P. V. Vuuren, E. Kriegler, J. Edmonds, B. C. O. Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. Crespo, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L. Aleluia, D. Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Stre, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-campen, M. Obersteiner, A. Tabeau, and M. Tavoni, “The Shared Socioeconomic Pathways and their energy , land use , and greenhouse gas emissions implications : An overview,” vol. 42, pp. 153–168, 2017.

[20] “Towards new scenarios for analysis of emissions, climate chage impacts and response strategies,” *IPCC*, 2007.

[21] P. Agnolucci, N. J. Lazarou, S. Mander, and C. Walsh, “Shipping Demand Scenarios Using Estimated Elasticities,” in *Shipping in Changing Climates Conference 2015*, 2015.

[22] M. Traut, S. Hanson, and C. Walsh, “Report from the lookout Understanding climate change impacts on shipping,” no. November, pp. 10–11, 2016.

[23] R. Schuitmaker, “Evolution of Global Maritime Freight Energy demand and co_2 emissions: A BAU and 2DS Scenario,” vol. 2016, no. November, p. 69, 2016.

[24] C. Raucci, C. Walsh, J. Calleya, M. Traut, N. Smith, S. De la Fuente, S. Haji, and T. Smith, “Low carbon pathways,” Lloyd’s Register, Tech. Rep. June, 2015.

[25] A. F. Friedlaender and R. H. Spady, “A derived demand function for freight transportation,” *The Review of Economics and Statistics*, vol. 62, no. 3, pp. 432–441, 1980. [Online]. Available: http://www.jstor.org/stable/1927111

[26] UNCTAD, “Review of Maritime Transport 2016,” in *United Nations Conference on Trade and Development*. Geneva, Switzerland: United Nations Conference on Trade and Development, 2016.

[27] M. Cropper and C. Griffiths, “The interaction of population growth and environmental quality,” *The American Economic Review*, vol. 84, no. 2, pp. 250–254, 1994. [Online]. Available: http://www.jstor.org/stable/2117838

[28] I. T. F. T. Outlook, *ITF Transport Outlook 2015*, 2015. [Online]. Available: http://www.oecd-ilibrary.org/transport/itf-transport-outlook-2015{_}9789282107782-en

[29] Exergia, “Study on Clean Transport Systems Project 2010 n . 419-1-Unit Move B4 Multiple Framework Services Contract with reopened competition for Technical Assistance,” *European Commission, Directorate-General for Mobility and Transport*, no. November, p. 248, 2011.

[30] “Review of Maritime Transport 2015,” in *United Nations Conference on Trade and Development*, no. October, 2015, p. 204.

[31] M. S. Andersen, “An introductory note on the environmental economics of the circular economy,” pp. 133–140, 2007.

[32] Y. Kou and M. Luo, “Strategic capacity competition and overcapacity in shipping,” *Maritime Policy & Management*, vol. 43, no. 4, pp. 389–406, 2016.

[33] S. Schlott, “Large Engine Building Complexity Soars,” *MTZ worldwide*, vol. 78, no. 3, pp. 8–15, 2017. [Online]. Available: http://dx.doi.org/10.1007/s38313-017-0017-x

[34] J. J. Corbett, H. Wang, and J. J. Winebrake, “The effectiveness and costs of speed reductions on emissions from international shipping,” *Transportation Research Part D*, vol. 14, no. 8, pp. 593–598, 2009. [Online]. Available: http://dx.doi.org/10.1016/j.trd.2009.08.005

[35] MAN Primeserv, “Slow Steaming Practices in the Global Shipping Industry,” Tech. Rep., 2012.

[36] “Review of Maritime Transport 2013,” in *United Nations Conference on Trade and Development*, 2013.

[37] J. Wismans, M. Grahn, and I. Denbratt, “Low-carbon transport–health and climate benefits,” in *Background report to UNRCD Intergovernmental Ninth Regional Environmentally Sustainable Transport (EST) Forum in Asia. Chalmers University of Technology*, 2016.

[38] J. Gravina, J. I. R. Blake, P. A. Shenoi, P. S. Turnock, and S. Hirdaris, “Concepts for a Modular Nuclear Powered Containership,” 2007.

[39] K. Juoperi, “Heavy fuel oil- still the dominent fuel quality for diesel engines,” 2005.

[40] OECD, “Environmental Impacts of International Shipping: The Role of Ports,” OECD Publishing, Paris, Tech. Rep., 2011.

[41] N. Molloy, “ The IMO’s global sulfur cap: What a 2020 sulfur constrained world means for shipping lines, refineries and bunker suppliers,” S&P Global, Tech. Rep. October, 2016.

[42] C. Azar, K. Lindgren, and B. Andersson, “Hydrogen or methanol in the transportation sector?” Tech. Rep. i, 2000.

[43] F. Mosheni, “Power to gas – bridging renewable electricity to the transport sector,” *KTH Royal Institute of Technology, Stockholm*, 2012.

[44] E. Parson, V. Burkett, K. Fisher-Vanden, D. Keith, L. Mearns, H. Pitcher, C. Rosenzweig, and M. Webster, “Global-change Scenarios: Their Development and Use,” *US Department of Energy Publications*, vol. 7, no. July, p. 7, 2007.

[Online]. Available: http://www.climatescience.gov/Library/sap/sap2-1/finalreport/sap2-1b-final-authors.pdf

[45] O. Fricko, P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, M. Strubegger, H. Valin, M. Amann, T. Ermolieva, N. Forsell, M. Herrero, C. Heyes, G. Kindermann, V. Krey, D. L. McCollum, M. Obersteiner, S. Pachauri, S. Rao, E. Schmid, W. Schoepp, and K. Riahi, "The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century," *Global Environmental Change*, vol. 42, pp. 251–267, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.gloenvcha.2016.06.004

[46] A. Andersson, C. Azar, and K. Lindgren, "Global energy scenarios meeting stringent CO_2 constraints— Cost-effective fuel choices in the transportation sector," *Energy Policy*, vol. 31, pp. 961–976, 2003.

[47] M. Grahn, S. Brynolf, J. Hansson, and M. Taljegard, "The cost-effectiveness of electrofuels in comparison to other alternative fuels for transport in a low carbon future," in *European Biomass Conference and Exhibition*, 2016, pp. 6–9.

[48] "Review of Maritime transport 2003," in *United Nations Conference on Trade and Development*. United Nations, 2003. [Online]. Available: http://unctad.org/en/Docs/rmt2003{_}en.pdf

[49] "The world merchant fleet in 2015 Statistics from Equasis," European Maritime Safety Assessment, Tech. Rep., 2015.

[50] "The world merchant fleet in 2010 Statistics from Equasis," European Maritime Safety Assessment, Tech. Rep., 2010.

[51] "The world merchant fleet in 2010 Statistics from Equasis," European Maritime Safety Assessment, Tech. Rep., 2005.

[52] "SSP Database 2017. [Online].
Available: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=series. [Accessed: 20- Mar- 2017]."

[53] T. Wigley, R. Richels, and J. Edmonds, "Economic and Environmental choices in the stabilization of atmospheric co_2 concentrations," *Letters to Nature*, vol. 379, 1996. [Online]. Available: https://www.nature.com/nature/journal/v379/n6562/pdf/379240a0.pdf

[54] M. Grahn, *Cost-effective fuel and technology choices in the transportation sector in a future carbon constrained world*, phd thesis ed. Gothenburg: Chalmers University of Technology, 2009.

[55] F. Hedenus, S. Karlsson, C. Azar, and F. Sprei, "Cost-effective energy carriers for transport – The role of the energy supply system in a carbon-constrained world," *International Journal of Hydrogen Energy*, vol. 35, no. 10, pp. 4638–4651, 2010. [Online]. Available: http://dx.doi.org/10.1016/j.ijhydene.2010.02.064

[56] T. Malthus, "An Essay on the Principle of Population," London, Tech. Rep., 1998.

[57] I. F. Crespo and T. D. If, "Income projections for climate change research : A framework based on human capital dynamics §," vol. 42, pp. 226–236, 2017.

[58] R. Dellink, J. Chateau, E. Lanzi, and B. Magne, "Long-term economic growth projections in the Shared Socioeconomic Pathways §," vol. 42, pp. 200–214, 2017.

[59] M. Leimbach, E. Kriegler, N. Roming, and J. Schwanitz, "Future growth patterns of world regions – A GDP scenario approach," *Global Environmental Change*, vol. 42,

pp. 215–225, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.gloenvcha.2015.02.005

[60] I. P. on Climate Change, *Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects*. Cambridge University Press, 2014.

[61] “Market-Based Instruments for International Aviation and Shipping as a Source of Climate Finance,” *International Monetary Fund and World Bank*, no. November, 2011.

[62] M. Mahmudur, T. Islam, and S. Kuruppu, “Regulating global shipping corporations ’ accountability for reducing greenhouse gas emissions in the seas,” vol. 69, pp. 159–170, 2016.

A

Appendix 1

Table A.1: Estimated Population in IIASA-SSP2 Scenario

Final Population Count (Gpeople)												
Year	**1990**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
NAM	2.87E-01	3.20E-01	3.48E-01	3.77E-01	4.06E-01	4.31E-01	4.53E-01	4.74E-01	4.93E-01	5.06E-01	5.13E-01	5.15E-01
EUR	5.57E-01	5.80E-01	6.02E-01	6.26E-01	6.45E-01	6.58E-01	6.66E-01	6.68E-01	6.64E-01	6.55E-01	6.42E-01	6.25E-01
PAO	1.87E-01	1.97E-01	2.01E-01	2.05E-01	2.05E-01	2.02E-01	1.97E-01	1.90E-01	1.83E-01	1.74E-01	1.64E-01	1.54E-01
FSU	2.90E-01	2.90E-01	2.86E-01	2.88E-01	2.87E-01	2.85E-01	2.83E-01	2.79E-01	2.73E-01	2.65E-01	2.56E-01	2.46E-01
LAM	4.38E-01	5.16E-01	5.85E-01	6.44E-01	6.91E-01	7.24E-01	7.42E-01	7.44E-01	7.35E-01	7.18E-01	6.95E-01	6.70E-01
MEA	2.76E-01	3.43E-01	4.24E-01	5.06E-01	5.79E-01	6.43E-01	6.95E-01	7.31E-01	7.51E-01	7.58E-01	7.55E-01	7.44E-01
AFR	4.80E-01	6.22E-01	8.12E-01	1.02E+00	1.25E+00	1.48E+00	1.70E+00	1.88E+00	2.04E+00	2.17E+00	2.25E+00	2.31E+00
CPA	1.28E+00	1.43E+00	1.48E+00	1.54E+00	1.55E+00	1.51E+00	1.43E+00	1.33E+00	1.22E+00	1.10E+00	9.94E-01	9.00E-01
PAS	3.66E-01	4.32E-01	4.94E-01	5.46E-01	5.87E-01	6.14E-01	6.26E-01	6.26E-01	6.15E-01	5.97E-01	5.74E-01	5.48E-01
SAS	1.12E+00	1.36E+00	1.63E+00	1.86E+00	2.07E+00	2.24E+00	2.37E+00	2.45E+00	2.47E+00	2.44E+00	2.38E+00	2.29E+00
Global	5.28E+00	6.09E+00	6.87E+00	7.61E+00	8.26E+00	8.78E+00	9.16E+00	9.37E+00	9.44E+00	9.38E+00	9.22E+00	9.00E+00

Table A.2: Estimated Economic Growth (GDP$_{PPP}$ values)(billion US$2005)

Year	**1990**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
NAM	8711.32	12166.08	13939.47	16724.46	20760.28	25046.00	29472.12	34166.48	39226.29	44418.72	49504.75	54413.73
EUR	10620.70	13140.42	15391.96	19480.79	25595.43	31744.80	37434.02	42812.84	48155.71	53342.00	58499.77	63525.01
PAO	3701.64	4286.23	6274.45	6982.69	7891.85	8879.91	9782.14	10639.47	11456.12	12166.02	12788.59	13326.06
FSU	2733.71	1757.33	3005.10	5104.50	6991.96	8173.94	9017.24	9873.31	10900.16	11989.93	13094.95	14269.99
LAM	3023.69	4165.17	5387.83	7799.55	10470.66	13304.35	16762.15	20328.26	23486.72	26555.23	29643.72	32747.39
MEA	1462.27	2405.63	3083.02	4622.04	6648.69	9290.37	12221.66	15237.95	18298.07	21475.78	24837.93	28243.46
AFR	756.82	962.03	1260.60	2278.26	3738.64	5959.92	9073.15	13102.03	17967.43	23624.19	30091.19	37237.86
CPA	1949.49	4606.70	9672.20	25191.77	39487.06	48293.49	53109.35	55265.82	55733.61	55262.29	54081.04	52758.03
PAS	986.26	1566.21	2349.24	4081.13	6444.23	8867.28	11378.30	14174.00	16503.67	18546.09	20559.52	22478.63
SAS	1365.34	2271.89	4650.84	11197.89	21143.35	30615.33	39009.23	47701.96	56670.93	64892.87	72528.16	79537.55
Global	35311.24	47327.69	65014.72	103463.07	149172.15	190175.40	227259.35	263302.11	298398.71	332273.14	365629.64	398537.69

B

Appendix 2

Table B.1: Average technical configurations assumed for different ship categories(for more information refer 3rd GHG study by IMO)

Category	**DWT**	**Avg Speed**	**Avg Days**	**Ton_Km/Ship**	**Size**	**MJ**	**Annual Cargo-capacity**	**MJ/billion ton-kms**
		Knots	**Annual**	**(billion)**			%	
Chemicals	20000	12	200	2.13	6	1.04E+08	0.64	0.18
Gas	30000	14	200	3.73	12	2.07E+08	0.48	0.27
Oil	40000	12	200	4.27	7	1.21E+08	0.48	0.14
Main Bulk	50000	12	200	5.33	8.9	1.54E+08	0.55	0.12
other	10000	14	200	1.24	5	8.64E+07	0.6	0.27
Containers	22250	20	200	3.96	12.5	2.16E+08	0.7	0.18

Table B.2: Estimated shipping demand in billion ton-km

Year	**Chemical**	**Gas**	**Oil**	**Containers**	**Other Cargo**	**Main Bulk**
2010	1442	1815	20315	11370	19877	22015
2020	1976	3486	24212	20254	30281	35235
2030	2487	5400	28223	30015	43684	48332
2040	2913	7097	31661	38566	55971	59410
2050	3248	8603	34517	45974	67503	68366
2060	3490	10017	36874	52637	79406	75312
2070	3651	11350	38795	58643	91617	80502
2080	3742	12600	40332	64033	103928	84179
2090	3777	13798	41569	68986	116508	86641
2100	3775	14958	42606	73635	129225	88294

C

Appendix 3

Table C.1: Technology Investment costs under different transport demand sectors(US$/type)

Type–>	**p_car**	**f_road**	**f_container**	**f_other**	**f_chemical**	**f_gas**	**f_oil**	**f_mbulk**
BTL.0	100	100	1800	100	1500	1500	1500	1500
CTL_GTL.0	100	100	1800	100	1500	1500	1500	1500
LNG.0	9800	1100	7400	7400	7400	7400		
H2.0	2600	10300	23800	1900	20800	20800	20800	20800
petro.FC	6300	20200	80400	7900	37300	37300	37300	37300
BTL.FC	6300	20200	81700	8000	38500	38500	38500	38500
CTL_GTL.FC	6300	20200	81700	8000	38500	38500	38500	38500
LNG.FC	84700	8200	41400	41400	41400	41400		
H2.FC	6600	22700	99000	9100	55000	55000	55000	55000
BTL.HEV	1700	5800						
CTL_GTL.HEV	1700	5800						
BTL.PHEV	5600	21800						
CTL_GTL.PHEV	5600	21800						
petro.0	0	0	0	0	0	0	0	0
petro.HEV	1600	5700						
petro.PHEV	5500	21700						
elec.BEV	15600	62500						
NG.0	1600	6000						
NG.FC								
e-fuel.0	100	100	1800	100	1500	1500	1500	1500
e-fuel.FC	6000	19400	81700	8000	38500	38500	38500	38500
e-fuel.HEV	1700	5800						
e-fuel.PHEV	5600	21800						

Table C.2: Transport static efficiencies taken into consideration

	p_car	f_road	p_air	f_air	p_bus	(p_rail,f_rail)	f_container	f_other	f_chemical	f_gas	f_oil	f_mbulk
BTL.0	1	1	0	0	1	0	0.94	0.94	0.94	0.94	0.94	0.94
BTL.FC	1.3	1.3	0	0	1.3	0	1.06	1.06	1.06	1.06	1.06	1.06
CTL_GTL.0	1	1	0	0	1	0	0.94	0.94	0.94	0.94	0.94	0.94
CTL_GTL.FC	1.3	1.3	0	0	1.3	0	1.06	1.06	1.06	1.06	1.06	1.06
BTL.HEV	1.3	1.1	0	0	1.1	0	0	0	0	0	0	0
CTL_GTL.HEV	1.3	1.1	0	0	1.1	0	0	0	0	0	0	0
BTL.PHEV	1.7	1.5	0	0	1.5	0	0	0	0	0	0	0
CTL_GTL.PHEV	1.7	1.5	0	0	1.5	0	0	0	0	0	0	0
H2.0	1.13	1	0	0	1	0	0.9	0.9	0.9	0.9	0.9	0.9
H2.FC	2	1.5	0	0	1.5	0	1.01	1.01	1.01	1.01	1.01	1.01
petro.0	1	1	1	1	1	0	1	1	1	1	1	1
petro.FC	1.2	1.2	0	0	1.2	0	1.13	1.13	1.13	1.13	1.13	1.13
petro.HEV	1.3	1.2	0	0	1.2	0	0	0	0	0	0	0
petro.PHEV	1.7	1.5	0	0	1.5	0	0	0	0	0	0	0
NG.0	1.01	0.9	0	0	0.9	0	0	0	0	0	0	0
NG.FC	0	0	0	0	0	0	0	0	0	0	0	0
elec.0	0	0	2	0	0	1	0	0	0	0	0	0
elec.PHEV	3	2.7	0	0	2.7	0	0	0	0	0	0	0
elec.BEV	3.5	3	0	0	0	0	0	0	0	0	0	0
air_fuel.0	0	0	1	1	0	0	0	0	0	0	0	0
LNG.0	0	0	0	0	0	0	0.96	0.96	0.96	0.96	0.96	0.96
LNG.FC	0	0	0	0	0	0	1.08	1.08	1.08	1.08	1.08	1.08
e-fuel.0	1	1	1	1	1	0	0.94	0.94	0.94	0.94	0.94	0.94
e-fuel.FC	1.3	1.3	0	0	1.3	0	1.06	1.06	1.06	1.06	1.06	1.06
e-fuel.HEV	1.3	1.1	0	0	1.1	0	0	0	0	0	0	0
e-fuel.PHEV	1.7	1.5	0	0	1.5	0	0	0	0	0	0	0

D

Appendix 4

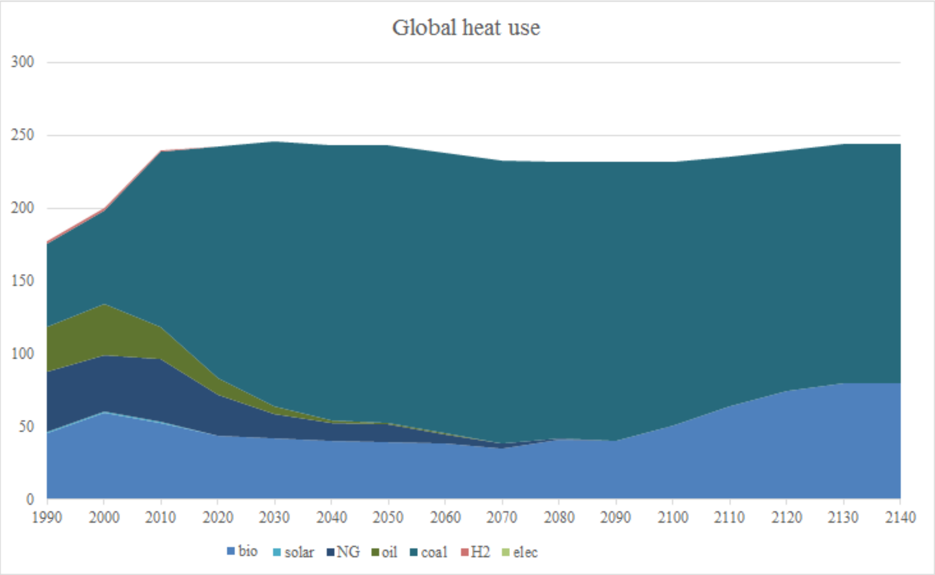

Figure D.1: Global heat use under 400 ppm concentration and BAU-scenario

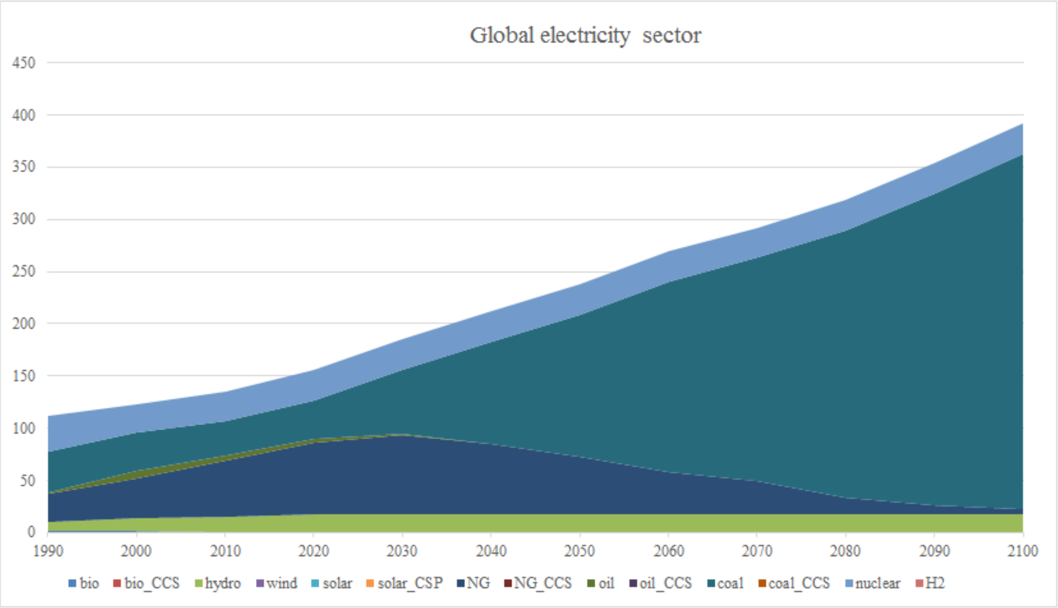

Figure D.2: Global electricity use under 400 ppm concentration and BAU-scenario