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Future Marine Fuels

A Danish Case Study on Climate Compatible Energy Pathways

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Preface

This thesis was prepared at the department of Energy and Environmental Management at the Europa-Universität Flensburg in fulfillment of the requirements for acquiring a Master degree in Engineering.

Flensburg, September 17, 2018

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Abstract

According to the results of this master thesis research project, it seems possible to make the Danish cargo shipping sector carbon neutral by 2050 with existing technologies. Reducing the sector's greenhouse gas emissions by a fair share in line with the Paris agreement demands a thorough system transformation with major investments into new ships and fuel infrastructure, on average around the year 2027. Either an emission cap and ambitious reduction targets or a carbon price of 350 to 450 € per ton CO2e would be necessary. This is equal to a transport cost increase by on average 6 % per cargo value. Hydrogen, methanol and ammonia appear to be most cost compatible, yet among them is no clear winner. It strongly depends on the development of new-build ship costs. A future reduction of transport demand could further improve the system's cost efficiency. A sustainable utilization of liquefied natural gas and bio-methane is threatened by the well-to-propeller methane leakage problem. Only a significant reduction allows for bio-methane as an alternative option. Fossil based natural gas, however, is not an optimal solution. Even under privileged cost and emission conditions, it has a limited window of opportunity of approximately 23 years.

As ships are getting replaced already today, they will in the long run influence the systems fuel composition and capability for a timely switch. Thus, it needs early measures to frame climate compatible energy pathways that lead to a carbon neutral Danish and global shipping sector. Else, this goal will either become even more expensive or unreachable. So, time is rapidly approaching to take action.

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Nomenclature

General Abbreviations

A	Annuity
a	Year
AIS	Automatic identification system
BDO	Bio-diesel oil
bn.	Billion, 10^9
c.p.	Ceteris paribus
CH3OH	Methanol
CH4	Methane
CO2	Carbon dioxide
CST	Set of all cost scenarios
DEA	Danish Energy Agency
DOI	Digital object identifier
DST	Statistics Denmark
ECA	Emission control area
EGC	Exhaust gas cleaner/scrubber
ELEC	Electricity
EM	Electric motor

EST	Eurostat
EU	European Union
EUR	Euro
FC	Fuel cell engine
Gt	Gigaton
H2	Hydrogen
HFO	Heavy fuel oil
i	Interest rate
IC	Internal combustion engine
IDE	Integrated development environment for coding
IMO	International Maritime Organization
J	Joule
kt	Kiloton
LBG	Liquefied bio-methane
LNG	Liquefied natural gas
MDO	Marine diesel oil
MJ	Megajoule
mp	Methane leakage phaseout
Mt	Megaton
NECA	Nitrogen emission control area
NH3	Ammonia
NOx	Nitrogen-x-oxide
PJ	Petajoule

R_0^+ All non-negative real numbers, including zero

REF Reference scenario

REG Set of all regulative scenarios

s.a. Same as

s.t. Subject to

SECA Sulphur emission control area

SNOX Scenario with focus on NOx and SOx emissions

SOx Sulphur-x-oxide

t2p Tank-to-propeller

TDV Transport demand variation

Tier Different levels of NOx emission limits

Ttkm Thousand ton-kilometers

w2p Well-to-propeller

w2t Well-to-tank

Indices and Sets

S Set of all ship types

s Index of ship type

T Set of all time steps, [a]

t Index of time steps

Subsets

NS Set of new-build ship types

NT Set of ship types not in compliance with NECAs regulations

OS Set of old ship types

RO 2-dimensional set of all ship types and each refit option

RS Set of refit ship types ships

SB Set of refit ship types running on BDO

SNE Set of ships not in compliance with SECAs regulations

SNG Set of ships not in compliance with global SOx regulations

SR Set of ships available for refit

Parameters

ba_t Bio-fuel availability, [PJ]

$bachange$ Bio-fuel availability change from T_0 to T_{last}, [J/J]

$bainit$ Bio-fuel availability in T_0, [J/J]

eb Emission Budget, [Mt]

$EC_{t,s}$ Absolute CO2 emissions, [g/MJ fuel]

$ec_{t,s}$ Specific CO2 emissions, [g/MJ fuel]

$EM_{t,s}$ Absolute CH4 emissions, [g/MJ fuel]

$em_{t,s}$ Specific CH4 emissions, [g/MJ fuel]

$epyr$ Year of emission peak

et Emission Target, [%]

li Technical infrastructure lifetime, [a]

ls Technical ship lifetime, [a]

$slnonecayr$ Inception year of SOx regulations, [a]

$tdnoneca$ Transport demand outside ECAs, [Ttkm]

$tdshort$ Transport demand on short range, [Ttkm]

$tdtotal$ Total transport demand, [Ttkm]

$tlecayr$ Inception year of Tier regulations in EU-NECAs, [a]

$ts_{t,s}$ Specific transport supply, [Ttkm/MJ fuel]

Cost Variables

$CF_{t,s}$ Absolute fuel costs, [EUR2016/MJ fuel], R_0^+

$cf_{t,s}$ Specific fuel costs, [EUR2016/MJ fuel], R_0^+

$CI_{t,s}$ Absolute infrastructure costs, [EUR2016/MJ fuel], R_0^+

$ci_{t,s}$ Specific infrastructure costs, [EUR2016/MJ fuel], R_0^+

$CS_{t,s}$ Absolute ship costs, [EUR2016/MJ fuel], R_0^+

$cs_{t,s}$ Specific ship costs, [EUR2016/MJ fuel], R_0^+

Fuel Variables

$fa_{t,s}$ Fuel amount, [PJ], R_0^+

$faicap_{t,s}$ Infrastructure capacity, [PJ], R_0^+

$fainit_{t,s}$ Fuel amount in T_0, [PJ], R_0^+

$faiup_{t,s}$ Additional infrastructure capacity, [PJ], R_0^+

$fascap_{t,s}$ Ship capacity, [PJ], R_0^+

$fasup_{t,s}$ Additional ship capacity, [PJ], R_0^+

CHAPTER 1

Problem

The global shipping industry, including Denmark, is still highly dependent on fossil based fuels, which are a main driver for global warming. Even though more sustainable alternatives exist, they are not yet in place. Therefore, this master thesis' central purpose is to address the following questions:

1. Which fuel technologies could drive the future Danish maritime shipping industry in a climate compatible manner?
2. How could a carbon neutral system be reached by 2050?
3. What would be the additional costs compared to continuing with business-as-usual?
4. When would the switch have to take effect?

In order to provide adequate analysis to the above, a stock model is developed. Its main objective is to minimize the total system costs for supplying all Danish cargo shipping transport demand while complying with greenhouse gas (GHG) emission reduction target and budget. It investigates possible future energy pathways until 2050 towards a CO2 free Danish cargo shipping sector in 2050 in line with the Paris agreement. Considered technical and fuel alternatives to the most commonly used internal combustion engines (IC) that burn heavy fuel (HFO) or marine diesel oil (MDO) are the following: Bio-diesel (BDO), liquefied bio-methane

(LBG), liquefied natural gas (LNG), methane (CH4), methanol (CH3OH), hydrogen (H2), ammonia (NH3) and batteries/wind (BATW). The accumulated system costs represent modifications of the vessel fleet, additional infrastructure and fuel consumption. Because of its holistic nature, the spatial scope is defined as the sum of all commercial shipping activities among Danish ports and half of the shipping activities among Danish and international ports. Thus, when applied to all countries, all considered emissions from shipping would be covered.

CHAPTER 2

State of Discussion

Recently, many papers and reports have been published, which address the issue of air emissions to the environment by maritime transport activities. Generally, they all state the Paris agreement as the emission target's benchmark and reason to strive for zero emission shipping technologies and higher energy efficiency. The main objective in most studies is the economical feasibility. Some investigate a single fuel technology like LNG [KRB17; IMO16b], CH3OH [IMO16a] or H2 [Rau17]. Others, as [BFA12] look at sets of alternative fuels for possible bio-fuel pathways or consider bio-fuel and hydrogen to comply with emission targets whilst maximizing the shipowners revenue on global scale [LRS16]. Further, [SSI18] develops pathways with multiply fuel technologies towards zero emission vessels and [Mel+18] addresses different gas options for future GHG emission free shipping. Recently, [Mån17] conducted a multi-criteria decision analysis of alternative fuels. It evaluates factors based on their influence on the choice of new technologies.

Above, some studies deploy mathematical models to calculate future emission and/or energy pathways. E.g. GloTraM and TIAM-UCL are utilized by [Rau17]. GloTram is a techno-economic optimization model for global freight transport, while TIAM-UCL is an environmental model to investigate inter-linkage between energy use and GHG emissions (see `https://www.ucl.ac.uk/energy-models/models`).

So far, the methane leakage problem has been addressed by only a small number of publications. Though, the awareness of its threat to certain fuels being classified as zero emitting is rising. As a supplementary contribution and in-line with the above research, this thesis develops and discusses several different energy pathways for the Danish maritime transport sector. This is a unique approach, as country-vice models are rare for the maritime freight transport sector. In addition to current fuel technologies it considers a broad range of carbon reducing or neutral alternatives that have already been subject to preceding scientific analysis. With a low level of detail simple, yet comprehensive enough scenarios are modelled. This research includes methane leakage phenomena from well-to-propeller and calculates CO2e prices and transport costs per freight mass in the aftermath.

CHAPTER 3

Methodology

The subject of investigation is the Danish maritime cargo sector. The thesis develops different possible energy pathways towards a state in which this sector has eliminated its contribution to global warming. The pathway analysis focuses on the total system costs, fuel mix development and GHG emissions, both in total and for each year. The pathways are derivatives of comparative analysis of different scenario results. Chapter 8 on page 37 provides detailed information on each scenario's setup. The model is designed as a stock model with existing shipping technologies, current cargo data and fuel consumption. Throughout the model run it has several technology options to invest in, while its scope is delimited by several boundaries. The setting is facing a trade-off between a meaningful level of detail and complexity, striving for an accurate representation of the reality, and justifiable simplifications in order to achieve appropriate solving times. The implemented model dimensions and their limits are set out in Section 3.1.

3.1 Model Scope

The model consists of different scopes and dimensions which mutually influence their own degrees of freedom. The temporal scope of the model ranges from the initial year 2016 until 2050 with an annual resolution. As the focus lies on major long-term investment decisions, a higher resolution is unlikely to provide better understanding of the sectors basic behaviours. In the spatial dimension all annually aggregated shipping routes to and from Danish ports are considered. In order to allocate the responsibility for the negative external effects that, as for now, inevitably accompany the international maritime trade in a fair manner to both trading entities countries, cross-border connections account only with have of their total estimated sailing distances. Fig. 3.1 illustrates this approach. A further dimension taken into account is the system's economy in terms of expenditures into infrastructure and fuels. As the model identifies a certain stock of technologies that will be depreciated over their lifetimes and is in need of new technologies to comply with emission constraints, it has to make investment decisions. Fixed investments are either for the fuel infrastructure or in ships. Variable investments are for the different annual fuel amounts to supply the vessel fleet. The technical dimension is set by the considered ships types. They are distinguished by their power systems as a combination of main engine and fuel type. All other ship specific design characteristics like hull-shapes or operational patterns (e.g. sailing speeds) are neglected. The complete set of ships available to the model can be found in Table 6.3. The emission dimension is composed of global and regional legislation on the one and GHG effective emissions on the other hand. SOx and NOx emissions are legally restricted by the Marpol Annex VI regulations 13 and 14 on global and regional scale [IMO08a; IMO08b]. As for GHG emissions, CO2 and CH4 are regarded and subject to different limitations, depending on the scenario. In general, emissions are restricted by an overall CO2 equivalent budget and emission target in 2050. Their sizes are derived from the IPCC's RCP2.6 pathway aiming at a maximum surface temperature increase of 1.5 degrees Celsius compared to the pre-industrial level [Sto+13, p. 27]. Section 5.5 on page 23 describes the underlying assumptions and conducted calculations.

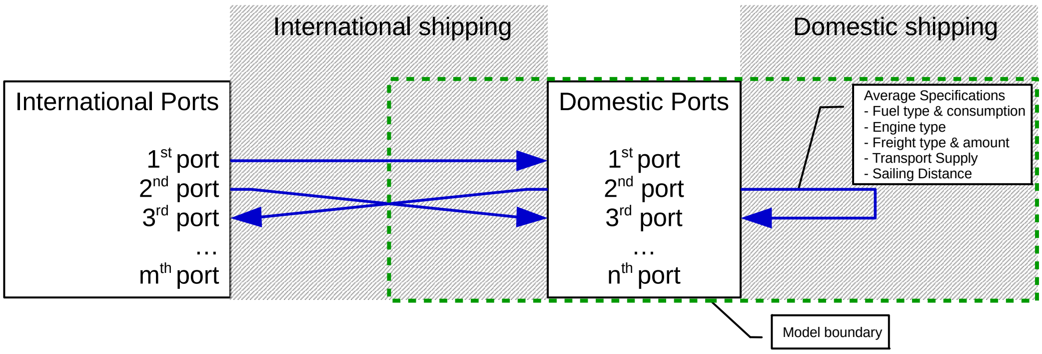


Figure 3.1: Model boundary

3.2 Model Structure

Technically, the model consists of two different components. First there are the model instances, second there is the processes of changing these instances. In the present case instances are spread sheets with numerical and literal data. Processes in turn are the formal operational instructions translated into a software language, here Python is used. The two components alternate throughout the model flow like a cascade. In the model box-flow in Fig. 3.2 white boxes represent data instances, whereas the blue arrows represent processes. An entire model run for a selected scenario starts by loading the technology data, combining them with the scenario specifications and creating the model input files. In the course of generating the model, these input files are translated into parameters and sets. The solver then calculates the model variables based on their degrees of freedom, which are determined by the the input data and the sense of the model objective. The results are stored again as data instances in the output directory. Finally, to allow for interpretations of the results, the post-processing provides edited graphical and tabular data.

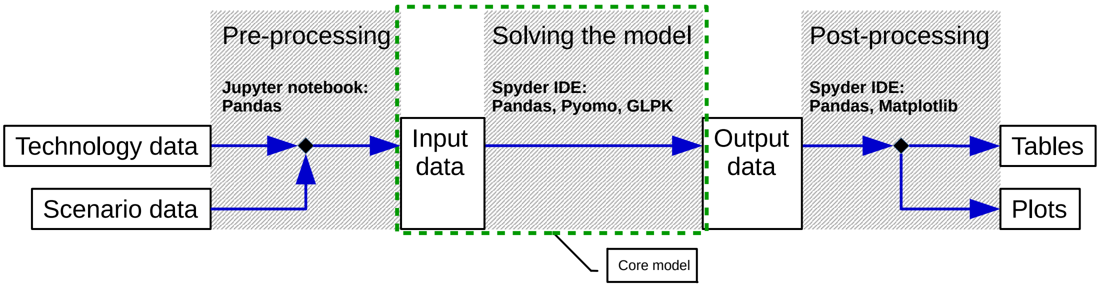


Figure 3.2: Model box-flow

3.3 Open Source Concept

The following section gives an overview of the measures undertaken to comply with general open source standards. Making code and data-sets freely available to the public can contribute significantly to reproducibility and transparency of a project [Pfe+18, p. 64]. Thus, it allows for a better understanding of the results and conclusions drawn by third parties, which is fundamental to a science based discourse. Granting an appropriate open licence sets a secure legal framework to further usage of the source. The entire code used to produce the model results is published on the website `https://github.com/` under a GNU General Public Licence. The deployed state of the code is linked to the applied dataset and a DOI is then issued by Zenodo (`https://zenodo.org/`, see [Bra18]). The coupling of the specific code version and data used to conduct this thesis together with the software listed in Table 3.1 assures for the mentioned reproducibility.

Name	Application	Version
Python	Programming language	3.5
Pandas	Python package for data-handling	0.22.0
Pyomo	Python Optimization Modeling Objects software	5.2
GLPK	Solver	4.65
Jupyter notebook	Console for data-processing	1.0.0
Spyder	IDE for the core model and plotting	3.2.8

Table 3.1: Open source software applications and versions create and run the model.

CHAPTER 4

Mathematical Formulation

Note, that...

> »Models are idealised representations of real systems built to perform a specific analysis or answer a specific question [...] .«
> Pfenninger et. al. / Energy Strategic Reviews 10 (2018), p. 65

and...

> »Essentially, all models are wrong, but some are useful.«
> George E. P.; Norman R. Draper (1987). Empirical Model-Building and Response Surfaces, p. 424, Wiley.

The future marine fuels problem is formulated mathematically as a linear and divisible model with the following equations. It is a stock model, initialized with data for the first time step that allows for investments in new technologies in the further course. The investment options are on the one hand forced and on the other limited by the model constraints. They are in general used to give credit to regularities and behaviour patterns that shape the system under investigation. Since the objective's sense is the minimization of the overall system's costs (4.1a), investments are interpreted as adverse but inevitable actions to cope with the constraint's demands, such as: Lowering CO2e emissions to air, (over-)supplying the transport demand in each time-step or scrapping ships, when their lifetime is expired.

The domains of all model variables are within non-negative real numbers, including zero $\left(R_0^+\right)$. Unit and abbreviation details can be found in the nomenclature on page x.

4.1 Objective Function

The model's objective is the minimization of the total system costs. It comprises the sum of all accumulated annual costs for fuel, infrastructure and ships. Asset costs account only with the annual added amounts and are multiplied with their respective lifetimes, since they are given to the model as annuities (see (6.1a)).

Objective Function:

$$min. \sum_{\forall t \in T} \sum_{\forall s \in S} (CF_{t,s} + CI_{t,s} + CS_{t,s}) \tag{4.1a}$$

s.t.

$$CF_{t,s} \geq fa_{t,s} \cdot cf_{t,s} \tag{4.1b}$$

$$CI_{t,s} \geq (faiup_{t,s} - fainit_{t,s}) \cdot li_s \cdot ci_{t,s}, \forall t \in T_0 \tag{4.1c}$$

$$CI_{t,s} \geq faiup_{t,s} \cdot li_s \cdot ci_{t,s}, \forall t \in T_{>0} \tag{4.1d}$$

$$CS_{t,s} \geq (fasup_{t,s} - fainit_{t,s}) \cdot li_s \cdot ci_{t,s}, \forall t \in T_0 \tag{4.1e}$$

$$CS_{t,s} \geq fasup_{t,s} \cdot li_s \cdot ci_{t,s}, \forall t \in T_{>0} \tag{4.1f}$$

4.2 Constraints

This section is subdivided into fuel, demand and emission constraints.

4.2.1 Fuel Constraints

The following fuel constraints refer to the amounts of fuel per ship type in each time step. Investments in infrastructure, new-build and refit ships consider exclusively the sum of the added capcities per ship or infrastructure over the respective lifetime. Ships and infrastructure are separated, due to different costs and lifetimes, even if they belong to the same technology.
Infrastructure Capacity: Sum of all added infrastructure capacity within the respective proceeded technical lifetime.

$$faicap_{t,s} \leq \sum_{\mathbf{x}}^{t-1} \left(faiup_{x,s} \right), \forall t \in T_{>0}, \forall s \in S \tag{4.2a}$$

s.t.

$$x = T_0, \forall t \leq (li_s + T_0 - 1) \tag{4.2b}$$

$$x = t - li_s + 1, \forall t > (li_s + T_0 - 1) \tag{4.2c}$$

Additional Infrastructure: Annual additional infrastructure capacity needed to supply the corresponding ship-types.

$$faiup_{t,s} \geq fa_{t,s} - faicap_{t,s}, \forall t \in T_{>0}, \forall s \in S \tag{4.3}$$

Ship Capacity: Sum of all added ships within the respective proceeded technical lifetime.

$$fascap_{t,s} \leq \sum_{\mathbf{x}}^{t-1} (fasup_{x,s}), \forall t \in T_{>0}, \forall s \in S \tag{4.4a}$$

s.t.

$$x = T_0, \forall t \leq (ls_s + T_0 - 1) \tag{4.4b}$$

$$x = t - ls_s + 1, \forall t > (ls_s + T_0 - 1) \tag{4.4c}$$

Added Ships: Annual additional ship capacity needed to satisfy the transport demand.

$$fasup_{t,s} \geq fa_{t,s} - fascap_{t,s}, \forall t \in T_{>0}, \forall s \in S \tag{4.5}$$

Refit: Defines in each time-step the fuel amount available for refit by old ships.

$$fa_{t,s} + fa_{t,r} - fa_{T_0,s} \leq 0, \forall t \in T_{<(T_0+ls_s)}, \forall s, r \in RO \tag{4.6a}$$

$$fa_{t,s} + fa_{t,r} = 0, \forall t \in T_{\geq(T_0+ls_s)}, \forall s, r \in RO \tag{4.6b}$$

Bio-fuel: Limits the bio-fuel availability in each time step.

$$\sum_{\forall s \in SB} (fa_{t,s}) - ba_t \leq 0, \forall t \in T \tag{4.7}$$

4.2.2 Demand Constraints

Transport Demand: The transport supply of all ships must either be greater or equal to the transport demand in each time-step.

$$tdtotal_t \leq \sum_{\forall s \in S} (fa_{t,s} \cdot ts_{t,s}), \forall t \in T \tag{4.8}$$

Short Transport Demand: The amount of fuel available for short range ships is limited by the transport demand of that range.

$$tdshort_t \geq \sum_{\forall s \in SR} (fa_{t,s} \cdot ts_{t,s}), \forall t \in T \tag{4.9}$$

Non-SECAs Transport Demand: The amount of fuel available for the ships that are not in compliance with the sulphur regulations, which is limited by the transport demand outside of the SECAs.

$$tdnoneca_t \geq \sum_{\forall s \in SNE} (fa_{t,s} \cdot ts_{t,s}), \forall t \in T \tag{4.10}$$

4.2.3 Emission Constraints

Emission Budget: The CO2e emission budget must be greater or equal to the total systems up- and downstream emissions.

$$eb \geq \sum_{\forall t \in T} \sum_{\forall s \in S} (EC_{t,s} + EM_{t,s}) \tag{4.11a}$$

s.t.

$$EC_{t,s} = fa_{t,s} \cdot ec_{t,s}, \forall t \in T, \forall s \in S \tag{4.11b}$$

$$EM_{t,s} = fa_{t,s} \cdot em_{t,s}, \forall t \in T, \forall s \in S \tag{4.11c}$$

Emission Target: Limits the CO2e emissions from the selected year (2050) onwards.

$$\frac{\sum_{\forall s \in S} (EC_{T_0,s} + EM_{T_0,s})}{\sum_{\forall s \in S} (EC_{t,s} + EM_{t,s})} \cdot et \geq 1, \forall t \in T_{\geq (etyr - T_0)} \tag{4.12}$$

Global SOx Limit: From the year 2020 onwards the fuel amount of those ship types is set to zero, whose sulphur content exceeds the global sulphur limit and have no scrubber installed.

$$fa_{t,s} = 0, \forall t \in T_{\geq slnonecayr - T_0}, \forall s \in SNG \tag{4.13}$$

Tier: Sets the fuel amount to zero for ships not in compliance with the NOx regulations inside the EU-NECAs from 2021 onward.

$$fa_{t,s} = 0, \forall t \in T_{\geq tlecayr - T_0}, \forall s \in NT \tag{4.14}$$

CHAPTER 5

Danish Shipping Data

This chapter describes the average Danish cargo shipping sector of the years 2015 and 2016. The characteristics of the fleet are compiled in aggregated form by cargo amount and type, sailing distance, transport work, fuel consumption and related air emissions. The two main sources consulted are statistical records from Eurostat and Statistics Denmark [Eur18; DST18]. Each single aggregation step can be retraced in the jupyter notebook ”data_shipping_dk.ipyn” at [Bra18].

5.1 Cargo

In general, data about cargo transport work refers to a mass or volume of any commercial commodity that is moved from one place to another over a certain distance within a certain time period. Depending on the kind of transport, different unit combinations to describe the transport work are favorable. Shipping large amounts of cargo over long distances and aggregating these data annually, typically for maritime transport systems, a suitable unit combination is thousand tonne kilometers. Research focus is not restricted to the cargo itself, but also on the energy used to supply the total annual transport demand. The mass transported is aggregated per year and port combination, disregarding the cargo type. Further, the distance between the port combinations is multiplied with the mass, while its summation give the final result.

The data about the amount and type of cargo shipped to and from domestic ports is retrieved from two sources. [Eur18] provides detailed data about the cargo amount, given in thousand tonnes per year, but it lacks information about the cargo type that was shipped. This gap is filled by [DST18] that provides a high level of detail regarding the shipped commodities. Even though, the transport demand disregards the cargo type, the information of which is needed to gain a better understanding about the structure of the current cargo fleet. An intuitive example is the commodity Mineral Oil, which is usually transported by a tanker.

Finally, the cargo is grouped into four different types: Liquid and solid bulk, container and rolling unites. The bulk commodities represent almost 90 percent of the total amount in mass, of which approx. 50 % are fossil based fuels (see Fig. 5.1).

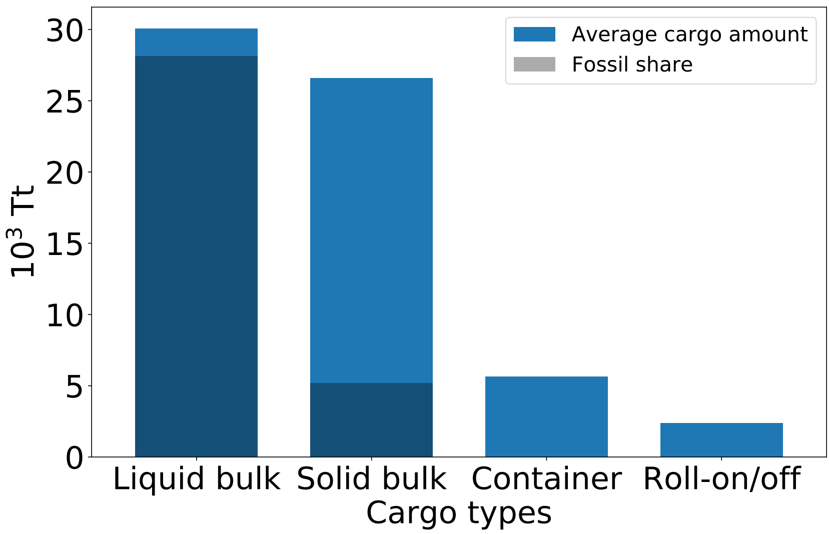


Figure 5.1: Cargo by type, average of 2015/2016, based on [DST18].

The total annual maritime freight volumes of the past 18 years have varied within a range of -10 to +15.5 % towards the mean value. With shipping being a derived service from economic activities, it is coupled with the global economy [RAK17, p. 16]. Thus, the differences in the yearly amounts can be associated with international market developments like the recession due to the economic crisis of 2009 [KC16, p. 2]. This inter-sector relation can be investigated in Fig. 5.2. Recently the cargo development as stabilized at a mean level of about 86 million tonnes. Since future market fluctuations are hard to predict, this average value is used as the initial cargo transported and will further be subject to continuous modifications, depending on the scenario setup.

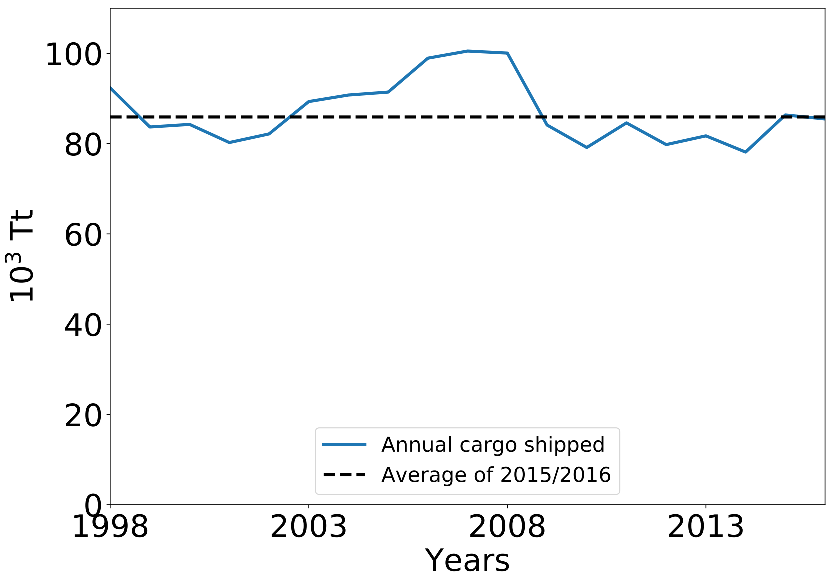


Figure 5.2: Cargo development in Denmark, based on [Eur18].

An additional reason to use the average values of 2015 and 2016 is the difference in cargo turnover per port and year (see Fig. 5.3 on page 18). While some ports report the same amounts for both years, others show significant differences, especially when a data point is missing. In this case the existing value is used for both years. Having robust data about the usual cargo turnover of each single port and commodity is important for applying the distances. The product of a long sailing distance with an over- or under-estimated large cargo amount would lead to distorted transport work shares. The application of average values is an approach to minimize this unwanted effect.

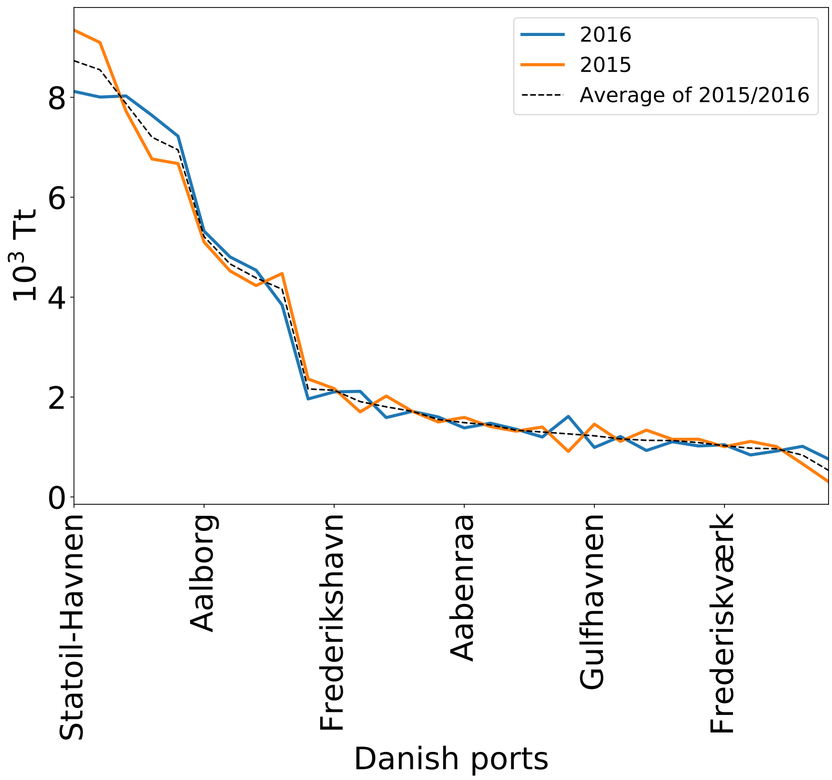


Figure 5.3: Cargo per Danish port, based on [Eur18]

5.2 Distances

The applied sailing distances between the considered ports are based on a preceding master thesis by Alfi Wisdom submitted at DTU [Wis17]. According to Mr. Wisdom, an online tool like `https://sea-distances.org` was used to compile the data. The original unit nautical miles was converted to kilometers with the factor 1.852.

Due to scaling effects, the accuracy of long sailing distances between two ports needs to be higher than for short distances, e.g. between two domestic ports. Therefore it is acceptable that the data from [Wis17] holds the same distance for each domestic port combination, but provides more detail on the international routes. The average distances per aggregated region are listed in Table 5.1. Russia is split up and either assigned to Asia east or west, whereas the Pacific region is ignored due to very small cargo amounts shipped. Fig. 5.4 illustrates the regions involved in maritime trade with Denmark, their estimated distances and accumulated cargo amounts.

Region	Average distance $[km]$	Total cargo $[Tt]$
Australia	21800	5
Asia, east	18500	1367
Africa, south	11800	329
America, south	11300	1580
America, center	8500	78
America, north	7800	3103
Asia, west	7100	2252
Africa, north	5500	1126
Unspecified	2600	2861
Europe	1500	58332
Denmark	150	15721

Table 5.1: Average shipping distances and cargo amounts per region in 2015/2016.

5.3 Transport Work

The average annual transport work in 2015 and 2016 for Denmark comprises the sum of all unique values for each port combination. They are calculated as the product of the total cargo amount on that route and and its distance. As mentioned in Chapter 3 on page 5, the international voyages account with half of their distance and domestic voyages entirely.

In order to be able to take account of regulative and technical constraints, the transport work is subdivided. On the regulative side the emission control areas at the coastline of the United States, in the Baltic Sea and parts of the North Sea set

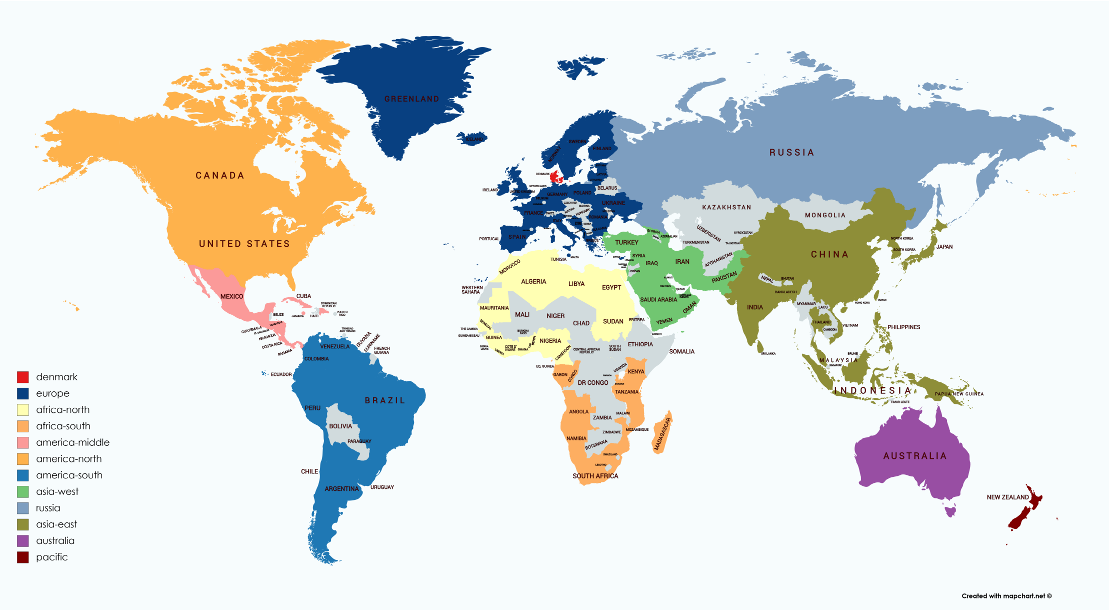


Figure 5.4: Map of international trading regions, created with `https://mapchart.net`

limitations to the application of certain ship types, as specified by the MARPOL Annex VI. Additionally, the potential operational range sets a technical limitation to conduct the transport work. In the case of Danish shipping, all considered voyages are at least partly within the EU-ECAs, since Denmark is fully surrounded by them. Domestic routes and routes to countries bordering the Baltic Seas and North Sea account with their full distance. The applied distances within ECAs for the different possible routes are listed in Table 5.2.

Route	EU-ECA	USA-ECA	Distance inside ECA
Domestic	100 %	0 %	Full distance
To Baltic & North Sea border states	100 %	0 %	Full distance
To United States	500 nm*	250 nm*	750 nm (1389 km)
Other	500 nm*	0 %	500 nm (926 km)

(*Own assumption)

Table 5.2: ECAs distance estimations per route.

Currently two fuel types are dominating the maritime transport: Heavy fuel oil (HFO) and marine diesel oil (MDO) [MPA18]. The standard HFO does not comply with the sulphur regulation in the designated ECAs, unlike MDO, which can be used globally. Since HFO is cheaper, it is assumed that MDO is only used when the vessel has to comply with the sulphur regulations inside the ECAs. This simplification allows for allocation the transport work between the two fuels (see Table 5.3).

	Unit	HFO	MDO	Sum
Transport work	[$10^9 tkm$]	96	56	**152**
Share	[%]	37	63	100

Table 5.3: Average ECAs transport work in 2015/2016.

Assuming, that a full electric vessel has the shortest operational distance, it sets the threshold of what is in this study considered as short range. The design specification of a concept for a battery powered container ship points to 35 hours of autonomous operation. With an estimated speed of 15 knots it allows voyages of up to 500 nautical miles [Ste18]. Fig. 5.5 shows the transport work shares, when setting the distance threshold between long and short range operation to 500 nautical miles (approx. 926 kilometers). Further, it illustrates, that all ship types, except for the full electric vessels, are suitable for short and long range operation. The technical specifications are discussed in detail in Chapter 6 on page page 27. In total the Danish transport work amounts to 152 giga-tonne kilometers, 20 inside and the remaining 132 to destinations outside the EU-ECAs. In a global perspective, IMO reported for 2012 a transport work of around 300 Terra-tonne kilometers [Smi+14, p. 256]. That corresponds to a difference by a factor of 2000, so that the Danish shipping share amounts to approx. 0.05 %.

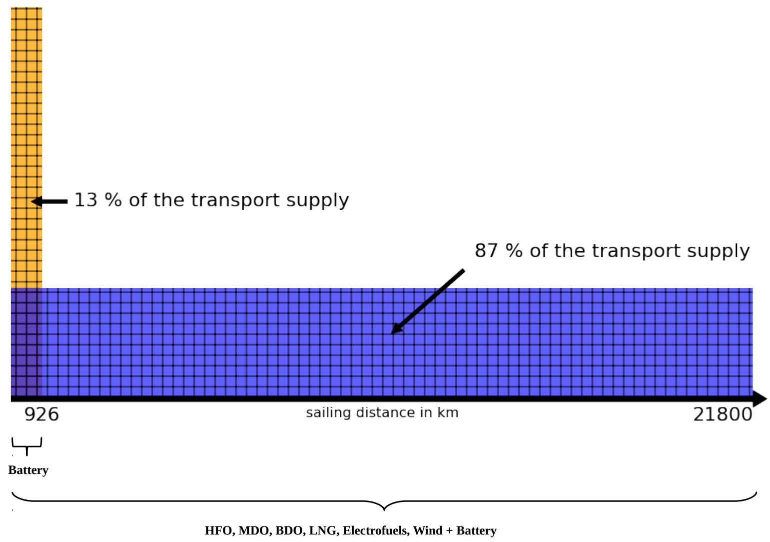


Figure 5.5: Cargo shares per range.

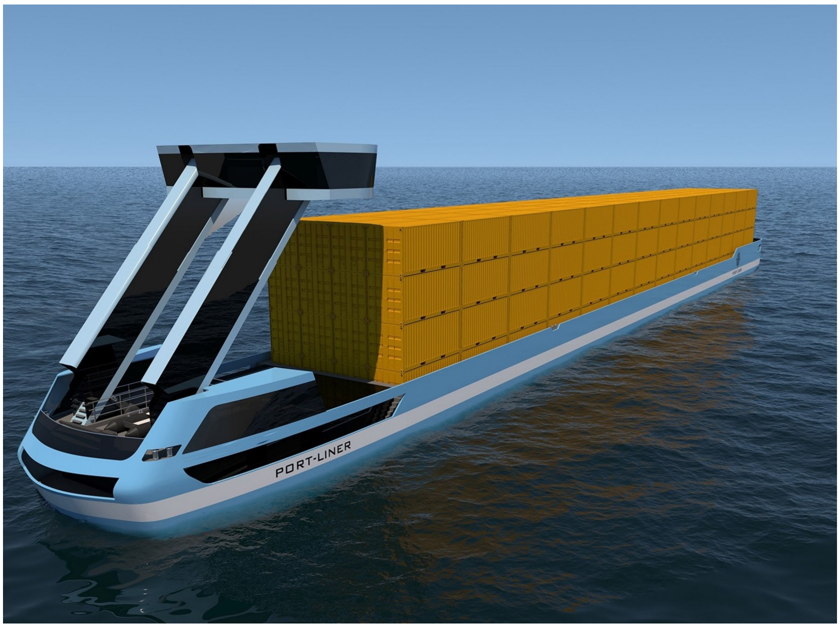


Figure 5.6: Port Liner concept (`http://scm.dk/port-liner`).

5.4 Fuel Consumption

The study focuses on fuel consumption during operation. Hence, any consumption at berth is not considered. The total fuel consumption is calculated as the product of transport work and energy demand of the specific ship type, while running on design speed. The energy demand per transport work is taken from [Kri12] and shows high volatility with respect to the maximum dead-weight. Average fuel consumption of 2015 and 2016 adds up to 16 PJ (see Table 5.4). Note, that [DEA16] reports with 28 PJ a higher amount of bunker fuels dedicated to Danish international maritime transport in 2016. Since that includes by definition fishery, military and also cruise ships, the calculated Danish fuel consumption for freight shipping seem to lie in a reasonable range.

	Unit	HFO	MDO	Sum
Transport work	$[10^9 tkm]$	96	56	
Energy demand	$\left[\frac{MJ_{fuel}}{tkm}\right]$	0.103	0.106	
Fuel consumption	$[PJ_{fuel}]$	9.93	5.99	**15.92**

Table 5.4: Average fuel consumption in 2015/2016.

5.5 Emissions

Emissions in this study's context are emissions to air, which are either major drivers for global warming (CO2, CH4) or subject to legislative restrictions due to other hazardous potentials, e.g. to the human health (NOx, SOx). Decisive for the climate competitiveness assessment are only the levels of GHG emissions. They are calculated in CO2 equivalent units (CO2e). This study regards solely CO2 and CH4 as green house gases. The totally emitted mass of CO2e emissions is calculated as the sum of each GHG with its respective global warming potential (GWP). For a time horizon of 100 years the GWP of CO2 is 1 and of CH4 is 25 [IPC07, Tab. 2.14].

A positive climate compatible assessment for the Danish maritime cargo sector is granted, when both, the total CO2e emissions until 2050 stay below the in Section 5.5.1 estimated emission budget of 19.12 Mt and the annual emissions in 2050 do not exceed the in Section 5.5.2 envied target of zero Mt. In 2016 the absolute CO2e emission level was roughly at 1.2 Mt (Table 5.5). The amount represents emissions at sea and is a function of total consumed fuel and operational fuel emission factor. The operational factors are compiled from [Kri12] for the CO2 part on the one and [BFA14; BFA12] for CH4 on the other hand.

	Unit	HFO	MDO	Sum
Fuel consumption	$[PJ_{fuel}]$	9.93	5.99	
Operational fuel emission factor	$\left[\frac{g_{CO2e}}{MJ_{fuel}}\right]$	74.2	76.0	
CO2e emissions	$[Mt]$	0.76	0.44	**1.2**

Table 5.5: Average CO2e emissions in 2015/2016.

Further, NOx and SOx emissions to air are currently under legislative regulation on global and regional level. On regional level sulphur emission control areas (SECAs) have been implemented at the coast of the USA, in the Baltic Sea and North Sea. As shown in Table 5.6 however, the Tier 3 demands of the nitrogen emission control areas (NECAs) are only established in the USA, yet. According to [MEP16, p. 38], an introduction of NECAs in the EU is planned for 2021. Additionally, from 2020 on-wards the global sulphur emissions will be lowered to a seventh of what is currently permitted (see Table 5.6). An alternative to switching the fuel technology in order to comply with future SOx limits is the installation of an exhaust gas cleaner (EGC or scrubber) [IMO08b]. Such option is provided in the model.

ECAs	SOx Implementation	SOx Max. sulphur content [$\%_{mass}$]	NOx Implementation	Tier level for ships build from 2000	2011	2016
Outside ECAs	established 2020	3.5 0.5	established	-	-	2
Baltic & North Sea	established	0.1	2021	1	2	3
US Coast	established	0.1	established	1	2	3

Table 5.6: ECAs regulations, based on [IMO08a; IMO08b].

5.5.1 Emission Budget

The CO2e emission budget sets a limit to the total allowed GHG emissions to air over full temporal scope. For Denmark it is derived from the global emission budget estimate by the IPCC [Sto+13, Tab. SPM.3, RCP2.6] and its corresponding global maritime transport share, provided by the ICCT [Olm+17]. The lower limit of 510 Gt of the RCP2.6 pathway is selected. Comparison of recent global maritime CO2e emissions from the 3rd IMO GHG Study with the Danish ones is displayed in Table 5.5. Its relative share to the ICCT's global budget leads to the Danish CO2e budget. With this budget the current emission level could be held constant for another 15 years and is more ambitious than just a linear decrease of emissions from 2016 to 2050 as illustrated in Fig. 5.7. Comparing maritime emissions from 2012 and 2016 can be considered a conservative estimation, as the global maritime trade volume has increased over this time gap [TD17, Tab. 1.3, p. 5]. Thus, the Danish budget would be lower by the same proportion.

	Unit	**CO2e emissions**	Reference
Global budget	[Gt]	**510**	[Sto+13]
Global maritime budget share	[%]	**3**	[Olm+17]
Global maritime budget	[GT]	**15.3**	
Global maritime emissions in 2012	[Mt]	**961**	[Smi+14]
Danish maritime emissions in 2016	[Mt]	**1.2**	Table 5.5
Danish maritime emission share	[%]	**0.125**	
Danish budget	[Mt]	**19.12**	

Table 5.7: Derivation of CO2e emission budget from global to Danish level.

5.5.2 Emission Target

The emission target is defined as the maximum amount of carbon emissions allowed within a selected year. For the reference scenario described in Section 8.1 the target is set to zero Mt CO2e emissions in 2050, which is even more ambitious than of what the IPCC states in its RCP2.6 pathway [Ede+14]. In contrast to that, the IMO proclaims in its ambition and guiding principles the ability to lower the emissions in 2050 by 50 % compared to the level of 2008 [MEP18, Annex I, p.5]. In terms of Danish cargo shipping the emissions would have to decrease from 1.2 to 0.72 Mt, or by 40 %. When assuming a linear decrease of CO2e emissions from 2016, a zero emission system would be achieved in the year 2100 (Fig. 5.7). Compared to a linear phase-out until 2050, IMO's cumulative emissions would amount to roughly the threefold.

	Unit	2008	2012	2016	2050
IMO emission projection	$[Mt_{CO2e}]$	1157*	961		578.5
Difference	[%]		-10		-40
Danish shipping share	$[Mt_{CO2e}]$			1.2	**0.72**

*Based on [Smi+14, p. 1,tab. 1(b)]

Table 5.8: Danish shipping shares in 2016 and 2050 based on IMO's emission reduction levels of ambition.

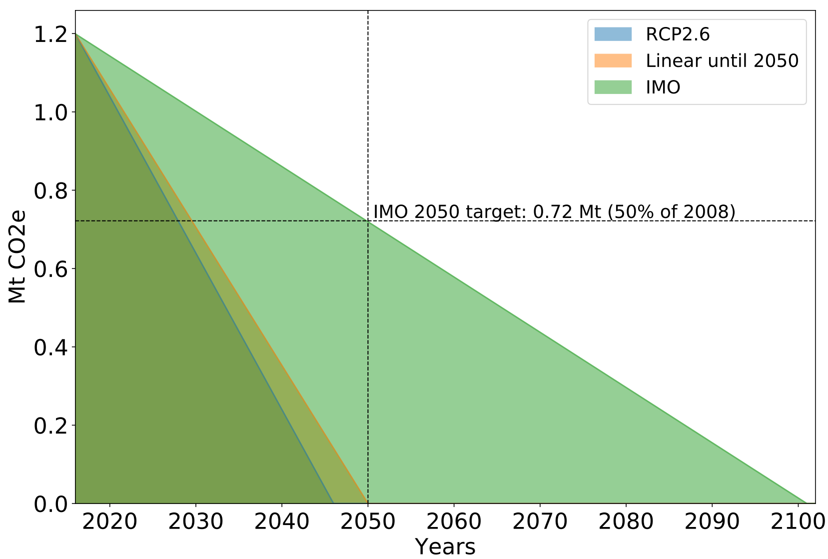


Figure 5.7: Different CO2e emission budgets and targets.

CHAPTER 6

Technology Data

The technology data consists of two static datasets, one for fuel and one for ship types. From here on they are referred to as fuels and ships. They are considered static as they are left unchanged throughout all different scenarios. Solely their development over time is subject to variation. Both comprise the information to all their unique characteristics. In general, the model utilizes specific financial and emission data. Hence, most data is based on the fuel amount as a quantity of energy (MJ). The number and type of required categories differs between fuels and ship. For fuels see Table 6.1, for ships Table 6.3. The performed calculations and unit transformations are described in the following chapters.

All specific cost and emission parameters are based on the amount of energy used to run the ships main engine. That includes the production of propulsion power as well as some auxiliary devices on the ship during operation. Any amount of fuel consumed is treated as it was used at design speed.

The system costs are split into its fixed and variable components. Thereby considering infrastructure and ship costs as fixed investment costs. Solely the fuel costs represent the variable component. Unlike the fixed part, they occur annually and are therefore not subject to the annual interest rate. Fixed costs depend on the investment's financial lifetime. With lifetime and annual interest rate the annuity rate is calculated based on equation (6.1a). The annuity rate multiplied by the total fixed costs returns the total fix financial burden. It is assumed that first financial and technical lifetime are equal and second that the annual interest rate is with 3 % constant over all model time steps [JAE17, p. 8]. Second, any costs are converted from their original units to EUR2016 by utilizing the currency conversion table of [Ber16].

$$A = \frac{x \cdot i}{x - 1} \tag{6.1a}$$

s.t.

$$x = (1 + i)^n \tag{6.1b}$$

$$n := \text{financial lifetime} \tag{6.1c}$$

During the pre-processing for the model input parameters, Tables 6.1 and 6.3 are joined based on the specific fuel type. Thus, each ship type holds the information of its fuel.

6.1 Fuels

The set of fuel parameters ranges from fuel and infrastructure costs, over well-to-tank CO2e emission operation factors and sulphur content to the fuel infrastructure's technical lifetime. Regarding fuel costs, it is assumed that the bunker index prices of the currently available fuels (HFO, MDO, BDO) comprise all upstream cost components from well-to-tank. Thus, the fixed costs of the supply chain are already incorporated (e.g. sufficient fuel supply infrastructure). In contrast to new fuel technologies, their costs are divided into fixed and variable shares. If upgrading facilities are required, they are assumed to be placed directly at the port. In that way, no additional fuel transport infrastructure needs to be build. Further, upon consultation with the Danish transmission grid operator EnergiNet, the gas transmission grid is capable to meet any conceivable additional fuel transport demand.

The jupyter notebook ”fuel_data_preparation.ipyn” holds additional detailed information on prior preparation steps to each single table entry [Bra18].

Fuel-type	cf	ci	ec(w2t)	em(w2t)	sulphur content	li
	$\left[\frac{EUR_{2016}}{GJ_{fuel}}\right]$	$\left[\frac{EUR_{2016}}{GJ_{fuel}}\right]$	$\left[\frac{g_{co2}}{MJ_{fuel}}\right]$	$\left[\frac{g_{ch4}}{MJ_{fuel}}\right]$	$[\%_{mass}]$	$[a]$
HFO	6.547		8.148	0.090	2.9525	40
MDO	12.775		7.728	0.090	0.7500	40
BDO	24.240		0	0.030	0.1498	40
LNG	4.888	0.139	6.600	0.033	0.0500	36
LBG	27.847	1.599	0	0.130	0.0750	25
H2	20.885	1.199	0	0	0.	25
CH3OH	29.240	1.679	0	0.042	0.0912	25
NH3	26.803	1.802	0	0	0	20
ELEC	13.889	2.929	0	0	0	20

Table 6.1: Fuel type data for each specific parameter.

The original sources of the fuel’s data sheet can be viewed in Table 6.2.

Fuel-type	cf, ci, li	ec(w2t)	em(w2t)	sulphur content
HFO	[BIX18, Index 380]	[Gil+18, p. 860]	[BFA12, tab. 4]	[BFA14, Tab. 3]
MDO	[BIX18, MGO]	[Gil+18, p. 860]	[BFA12, tab. 4]	[AM15, Tab. 2]
BDO	[SSI18, p. 5]		[BFA12, tab. 4]	[BFA12, Tab. 4]
LNG	[Ene18]	[Gil+18, p. 860]	[BFA14, tab. 3]	[AM15, Tab. 2]
LBG	[Bry+18, p. 4]		[BFA12, tab. 4]	[BFA12, Tab. 4]
H2	[Bry+18, p. 4]			
CH3OH	[Bry+18, p. 4]		[BFA14, tab. 3]	[BFA14, Tab. 3]
NH3	[MMM17, p. 9]			
ELEC	[D V08, pp. 18-19]			

Table 6.2: Fuel type data references.

6.2 Ships

Compared to the fuel's category set, the ship's set is more divers. This is because of technical information needed to distinguish the different ship types and applying relevant regulative and technical constraints. However, just like the fuels, it consists of fuel specific parameters. They range from transport supply, over investment costs to the tank-to-propeller CO2e emission operation factors. Furthermore the initial fuel amount per ship of Table 5.4 is provided. The transport demand in the first year is equal to the sum-product of fuel amount and transport supply. Future fuel amounts are calculated by the model.

Technical categories complement the ones related to the fuel. First, there is the range (discussed in Section 5.2), which is unlimited for all but full electric ships (see Fig. 5.5). It is followed by the ship's technical lifetime. For old ships, the average remaining lifetime is 11 years. If the same technical lifetime as for new ships would apply, the average age of the current fleet is 14 years. This is the sum of the average age in 2016 of the three main Danish cargo ship types bulker, containers and tankers listed in [TD17, Tab. 2.2, p. 27] and combined with their market shares shown in Fig. 5.1. Information, whether a refit is possible and towards which technology, Tier level and scrubber status complete the set.

Refits are build upon existing ships, which is why the corresponding ship costs are very low. Ships with internal combustion engines that run on HFO can be refitted with scrubber. When operating with a scrubber SOx emissions are reduced. However, the downside is a loss in transport supply capability, since the scrubber impairs the ship's energy efficiency. Refit of old ship with an internal combustion engine that use MDO towards the use of BDO is simply a fuel switch and has no associated major investment costs. Note, that the refit measures have no effect on the ships lifetime. The model simply transfers the residual lifetime of the old ship to the one refitted. Consequently, the lifetime provided for refit ships in Table 6.3 is the maximum value.

Based on the NOx regulations in Table 5.6, Tier levels are decisive for ship operations in the NECAs. All new-build ships have the Tier 3 rating as they are being constructed later than 2016. In contrary, old ships have no or a Tier rating of 1, as the average construction year was in 2002. Here, no rating is selected. Hence, old ships will either be scrapped after 2021 or need a refit to gain a higher rating. The original data sources of the ship's data sheet can be viewed in Table 6.4.

Ship-type	Range	ls $[a]$	fa_{2016} $[PJ_{fuel}]$	ts $\left[\frac{Ttkm}{GJ_{fuel}}\right]$	cs $\left[\frac{EUR_{2016}}{GJ_{fuel}}\right]$	ec(t2p) $\left[\frac{g_{CO2}}{MJ_{fuel}}\right]$	em(t2p) $\left[\frac{g_{CH4}}{MJ_{fuel}}\right]$	Refit	Refit opt.	Tier	Scrubber
IC HFO (old)	long	11	9.93	9.69	8.72	76.06	0.00045	yes	IC HFO (refit)	0	no
IC MDO (old)	long	11	5.99	9.40	8.45	74.36	0.00045	yes	IC BDO (refit)	0	yes
IC HFO	long	25	0	9.40	8.45	75.90	0.00045	no		3	yes
IC MDO	long	25	0	9.40	8.45	74.32	0.00045	no		3	yes
IC HFO (refit)	long	11	0	9.40	0.02	75.90	0.00045	no		3	yes
IC BDO (refit)	long	11	0	9.40	0	0	0.00045	no		3	yes
IC BDO	long	25	0	9.40	8.45	0	0.00045	no		3	yes
IC LNG	long	25	0	10.13	96.98	54.36	0.71000	no		3	no
IC LBG	long	25	0	10.13	96.98	0	0.79000	no		3	no
IC H2	long	25	0	10.13	109.29	0	0	no		3	no
IC CH3OH	long	25	0	10.13	109.29	0	0.79000	no		3	no
IC NH3	long	25	0	10.13	109.29	0	0	no		3	no
FC LNG	long	25	0	22.47	134.80	54.36	0.22763	no		3	no
FC LBG	long	25	0	22.47	134.80	0	0.22763	no		3	no
FC H2	long	25	0	22.47	134.80	0	0	no		3	no
FC CH3OH	long	25	0	22.47	134.80	0	0.22763	no		3	no
FC NH3	long	25	0	22.47	134.80	0	0	no		3	no
EM ELEC	short	30	0	11.86	1,047.05	0	0	no		3	no
WIND ELEC	long	30	0	35.58	2,094.11	0	0	no		3	no

Table 6.3: Ship type data for each specific parameter.

Ship-type	Range	ls	fa_{2016}	ts	cs	ec(t2p)	em(t2p)	Tier	Scrubber
IC HFO (old)		[TD17, p. 27]	[Eur18; Wis17]	[Kri12]	[RAK17]	[Kri12]	[BFA14, tab. 3]	[IMO08a]	
IC MDO (old)		[TD17, p. 27]	[Eur18; Wis17]	[Kri12]	[RAK17]	[Kri12]	[BFA12, tab. 4]	[IMO08a]	[Kri12]
IC HFO		[TD17, p. 27]		[Kri12]	[RAK17]	[Kri12]	[BFA14, tab. 3]	[IMO08a]	[Kri12]
IC MDO		[TD17, p. 27]		[Kri12]	[RAK17]	[Kri12]	[BFA12, tab. 4]	[IMO08a]	[Kri12]
IC HFO (refit)		[TD17, p. 27]		s.a. IC HFO	[MRW13, p. 31]	s.a. IC HFO	s.a. IC HFO	[IMO08a]	s.a. IC HFO
IC BDO (refit)		[TD17, p. 27]		s.a. IC MDO	[Wis17, p. 31]	s.a. IC BDO	s.a. IC BDO	[IMO08a]	s.a. IC MDO
IC BDO		[TD17, p. 27]		s.a. IC MDO	s.a. IC MDO	[BFA12, tab. 4]	[BFA12, tab. 4]	[IMO08a]	s.a. IC MDO
IC LNG		[TD17, p. 27]		[Kri12]	[RAK17]	[Kri12]	[BFA14, tab. 3]	[IMO08a]	
IC LBG		[TD17, p. 27]		s.a. IC LNG	s.a. IC LNG	[BFA12, tab. 4]	[BFA14, tab. 3]	[IMO08a]	
IC H2		[TD17, p. 27]		s.a. IC LNG	s.a. IC CH3OH	[GM13, p. 9]		[IMO08a]	
IC CH3OH		[TD17, p. 27]		s.a. IC LNG	[AM15]	[BFA14, tab. 3]	s.a. IC BDO	[IMO08a]	
IC NH3		[TD17, p. 27]		s.a. IC LNG	s.a. IC CH3OH			[IMO08a]	
FC LNG		[TD17, p. 27]		s.a. FC H2	[Bie+16, p. 358]	s.a. IC LNG	s.a. FC CH3OH	[IMO08a]	
FC LBG		[TD17, p. 27]		s.a. FC H2	[Bie+16, p. 358]	s.a. IC LNG	s.a. FC CH3OH	[IMO08a]	
FC H2		[TD17, p. 27]		[USD15, p. 1]	s.a. FC CH3OH			[IMO08a]	
FC CH3OH		[TD17, p. 27]		s.a. FC H2	[Bie+16, p. 358]	s.a. IC LNG	[Bri+05, p. 2005]	[IMO08a]	
FC NH3		[TD17, p. 27]		s.a. FC H2	s.a. FC CH3OH			[IMO08a]	
EM ELEC	[DNV15, p. 24]	[DNV15, p. 24]		[DNV15, p. 24]	[DNV15, p. 25]			[IMO08a]	
WIND ELEC		s.a. EM ELEC		three times EM ELEC	double of EM ELEC			[IMO08a]	

(s.a.: same as)

Table 6.4: Ship type data references.

CHAPTER 7

Scenario Data

The scenario data set consists of fuel rates, ship rates and regulative limits. Assuming that model parameters are not necessarily constant over all model time steps some parameters are made subject to variation. The variations are given as the total percentage change between 2016 and 2050. This difference is translated into a fixed annual changing rate. Therefore, the change is not linear but exponential. In the pre-processing, time variable data frames are created for each affected parameter. The reference scenario provides the baseline rates and limits. When a different scenario is calculated, the final value in 2050 of a selected parameter can be alternated by any percentage. Though, the minimum threshold is -100 %, that would correspond to a reduction towards zero costs or no limitations.

Where appropriate, changing rates are clustered, due to market coupling effects. E.g. in the reference scenario the fuel costs of all electro-fuels change with the same rate.

7.1 Fuel Rates

Table 7.1 gives an overview of the percentage change from 2016 to 2050 and their sources for fuel and infrastructure costs. Changing rates for currently available fuels are based on analysis assumptions as they are used by the Danish transmission system operator EnergiNet [JAE17, p. 13].

Parameter	Unit	Fuel type	Reference Scenario **Change to 2050**	Reference
Infrastructure cost rate	[%]	HFO	**0**	Included in fuel costs
		MDO	**0**	
		BDO	**0**	
		LNG	**-20**	[Bry+18, fig. 6, p. 13]
		LBG	**-20**	
		H2	**-20**	
		CH3OH	**-20**	
		NH3	**-20**	
		ELEC	**-20**	
Fuel cost rate	[%]	HFO	**110**	[JAE17, fig. 13, p. 3]
		MDO	**110**	
		BDO	**110**	
		LNG	**110**	
		LBG	**-20**	[Bry+18, fig. 6, p. 13]
		H2	**-20**	
		CH3OH	**-20**	
		NH3	**-20**	
		ELEC	**-20**	

Table 7.1: Fuel technology changing rates per type until 2050 in the REF scenario.

7.2 Ship Rates

Depending on the development stage of the engine technology, prices for new-build ships vary. Since internal combustion engines have been deployed for many years, its associated cost reduction potential is assumed to be low. Fuel cells are still quite new and therefore hold a higher cost reducing potential. The highest cost reduction potential however is assumed to be for wind and full electric cargo ships. In general, future cost estimations are subject to high uncertainties. Especially when it comes to technologies that are new to the market or even still in the design stage. This is why the ship's cost rates are investigated for their sensitivity to variation. Table 7.2 on page 35 displays the applied rates in the reference scenario.

Parameter	Unit	Ship-type	Reference Scenario **Change to 2050**	Reference
		IC HFO (old)	**0**	
		IC MDO (old)	**0**	
		IC HFO	**0**	
		IC MDO	**0**	
		IC HFO (refit)	**0**	
		IC BDO (refit)	**0**	
		IC BDO	**0**	
		IC LNG	**-40**	
		IC LBG	**-40**	
Ship costs	[%]	IC H2	**-40**	
		IC CH3OH	**-40**	
		IC NH3	**-40**	
		FC LNG	**-50**	High fluctuating, [RAK17]
		FC LBG	**-50**	
		FC H2	**-50**	
		FC CH3OH	**-50**	
		FC NH3	**-50**	
		EM ELEC	**-75**	
		WIND ELEC	**-75**	
		IC HFO (old)	**0**	
		IC MDO (old)	**0**	
		IC HFO	**15**	
		IC MDO	**15**	
		IC HFO (refit)	**15**	
		IC BDO (refit)	**15**	
		IC BDO	**15**	
		IC LNG	**15**	
		IC LBG	**15**	
Transport supply	[%]	IC H2	**15**	
		IC CH3OH	**15**	[Smi+14, tab. 51, p. 282]
		IC NH3	**15**	
		FC LNG	**15**	
		FC LBG	**15**	
		FC H2	**15**	
		FC CH3OH	**15**	
		FC NH3	**15**	
		EM ELEC	**15**	
		WIND ELEC	**15**	
		IC HFO (old)	**0**	
		IC MDO (old)	**0**	
		IC HFO	**-10**	
		IC MDO	**-10**	[Smi+14, tab. 51, p. 282]
		IC HFO (refit)	**-10**	
		IC BDO (refit)	**0**	
		IC BDO	**0**	
		IC LNG	**-10**	[Smi+14, tab. 51, p. 282]
		IC LBG	**0**	
CO2 emission operation factor (w2p)	[%]	IC H2	**0**	
		IC CH3OH	**0**	
		IC NH3	**0**	
		FC LNG	**-10**	[Smi+14, tab. 51, p. 282]
		FC LBG	**0**	
		FC H2	**0**	
		FC CH3OH	**0**	
		FC NH3	**0**	
		EM ELEC	**0**	
		WIND ELEC	**0**	
		IC HFO (old)	**0**	
		IC MDO (old)	**0**	
		IC HFO	**-10**	
		IC MDO	**-10**	
		IC HFO (refit)	**-10**	
		IC BDO (refit)	**-10**	[Smi+14, tab. 51, p. 282]
		IC BDO	**-10**	
		IC LNG	**-10**	
		IC LBG	**-10**	
CH4 emission operation factor (w2p)	[%]	IC H2	**0**	
		IC CH3OH	**0**	
		IC NH3	**0**	
		FC LNG	**-10**	[Smi+14, tab. 51, p. 282]
		FC LBG	**-10**	
		FC H2	**0**	
		FC CH3OH	**0**	
		FC NH3	**0**	
		EM ELEC	**0**	
		WIND ELEC	**0**	

Table 7.2: Ship type changing rates per type until 2050 in the REF scenario.

7.3 Regulations

Most regulations are valid from either a certain year onwards, or - as for the emission budget - apply over the full temporal scope (see Table 7.3). These regulations are not time variable, but stay constant. Modifications to the REF scenario introduce new limits. Exclusively, bio-fuel availability and transport demand allow for change over time. It is assumed that in 2050 40 % of today's fuel consumption can be supplied by bio-fuel. Further, transport demand remains unchanged. According to [ITF18, p. 18] 3D printing and circular economies could reduce global shipping demands. [RAK17, pp. 10,18] states that the demand is likely to grow slower, no matter the segment and that renewable energy driven growth reduces maritime trading potential. Above, in [TD17, p. 16] all sources project decreasing growth rates until 2030.

Parameter	Unit	Reference Scenario **Limit/Change to 2050**	Reference
Emission budget	$[kt_{CO2e}]$	**19120**	
Emission target	[%]	**0**	[Sto+13, tab. SPM.3]
Year of emission target	$[a]$	**2050**	
SOx limit in SECA	$[\%_{mass}]$	**0.1**	
SOx limit outside SECA	$[\%_{mass}]$	**0.5**	
Year of SOx limit outside SECA	$[a]$	**2020**	[IMO08b]
NOx limit in NECAs for new ships	$[Tier]$	**3**	
Year of NOx limit in NECAs	$[a]$	**2021**	
Biofuel availability in 2016	$[_{fuel}]$	**0**	[DEA16]
Biofuel availability change to 2050	[%]	**40**	Own assumption
Transport demand change to 2050	[%]	**0**	[ITF18, p. 18]; [RAK17, p. 19]

Table 7.3: Regulative limits and changing rates until 2050 in the REF scenario.

CHAPTER 8

Scenarios

In principle, the scenarios are separated into two groups. On the one hand there are the regulative (REGs) and on the other hand the cost scenarios (CSTs). Both represent modifications of the reference scenario (REF). The regulative scenarios investigate the impact of changes to the legislative framework, which are imposed from the outside to the system. The focus lies here on emission to air regulations and their time of implementation. Additionally, one scenario evaluates the possible impact of a future reduction in transport demand. Cost scenarios however maintain the regulations of the REF scenario and focus exclusively on the implications of different cost curves for each of the system's cost components.

To obtain an overview of the conducted scenarios and a short description, see Table 8.1. The static and time variable input parameters that are changed - in comparison to REF - are described in detail in Section 8.1.1 on page 39. The static parameters are listed in Table 8.2 and regulate the system emissions. Time variable data is described in Section 8.1.1.

Group	**Acronym**	Description	Modified Parameters
Reference scenario	**REF**	Reference scenario, based on literature	-
Regulative scenarios	**REF(mp)**	Reference scenario + methane leakage phaseout	em
	BAU	Business as usual, frozen policy	eb, et
	IMO	International Maritime Organization	eb, et
	TDV	Transport demand variation	tdtotal
	SNOX	Stricter NOx and SOx regulations	eb, et, slnoneca, slnonecayr, tlecayr
Cost scenarios	**BATW**	Cost variation of battery and wind	cf, ci, cs
	BDO	Cost variation of bio-diesel oil	cf
	CH3OH	Cost variation of methanol	cf, ci, cs
	H2	Cost variation of hydrogen	cf, ci, cs
	LBG	Cost variation of liquefied bio-methane	cf, ci, cs
	LBG(mp)	Cost variation of liquefied bio-methane + methane leakage phaseout	cf, ci, cs, em
	LNG	Cost variation of natural gas	cf, ci, cs
	LNG(mp)	Cost variation of natural gas + methane leakage phaseout	cf, ci, cs, em
	NH3	Cost variation of ammonia	cf, ci, cs

Table 8.1: Scenario overview with description and modified parameters.

8.1 Reference Scenario

The following section comprises the input and output data of the reference scenario. On the input side there are static and time variable parameters (see Section 8.1.1), while the output side shows the resulting fuel mix and emission development together with the annual system cost (see Section 8.1.2). Static parameters are single data points, whilst time variable parameters are data series. Thus, static data is visualized in tables and time variable data as line graphs.

8.1.1 Input Data of Reference Scenario

The input data consists of all static and time variable parameters that are sent to the model. The applied changing rates are described in Chapter 7.

Static

Parameter	Unit	**REF**
Emission budget	$[kt_{CO2e}]$	**19120**
Emission target	$[\%]$	**0**
Year of emission target	$[a]$	**2050**
SOx limit in SECA	$[\%_{mass}]$	**0.1**
SOx limit outside SECA	$[\%_{mass}]$	**0.5**
Year of Sox limit outside SECA	$[a]$	**2020**
NOx limit in NECAs for new ships	$[Tier]$	**3**
Year of Nox limit in NECAs	$[a]$	**2021**

Table 8.2: Static parameters in the REF scenario.

Time variable

In the following, all eight time variable parameters are displayed. Each parameter has its own figure and depends either on the fuel or ship type. In order to credit the different lifetimes for ships and infrastructure and to make their costs comparable, the fixed costs of Figs. 8.4 and 8.7 are multiplied with the respective lifetimes. Else, only the annuities would be visible. This operation is not done in the pre-processing stage, but in the objective function of the model (4.1a). In general, it is believed that costs decrease (see Figs. 8.3, 8.4 and 8.7) and energy efficiency increase over time. Hence, fuel specific transport work increases (see Fig. 8.8), whilst CO2 and CH4 emissions go down (see Figs. 8.5 and 8.6). Though fossil fuels are an exception, as they are a scarce resource, which makes them possibly more expensive in the future. The shape of each curve depends on fuel or ship type and the starting values in 2016. E.g. a comparably low CO2 emission level in 2016 leaves less reduction potential until 2050 than higher starting values. Additionally, bio-fuel availability will improve (see Fig. 8.2) and transport demand remains constant (see Fig. 8.1). When several fuel or ship types have identical colors, their values are either identical, too, or have an insignificant difference that is indistinguishable in the graph.

Figure 8.1: Transport demand, REF

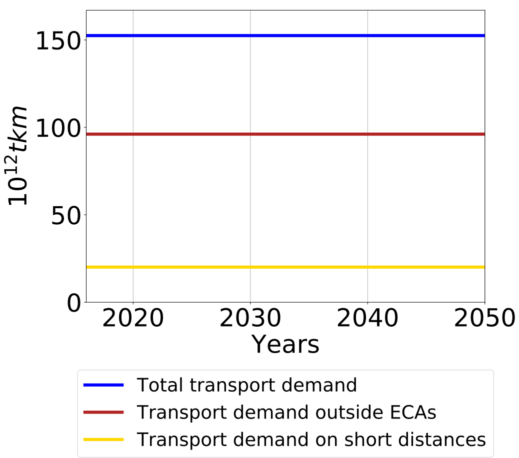


Figure 8.2: Bio-fuel availability, REF

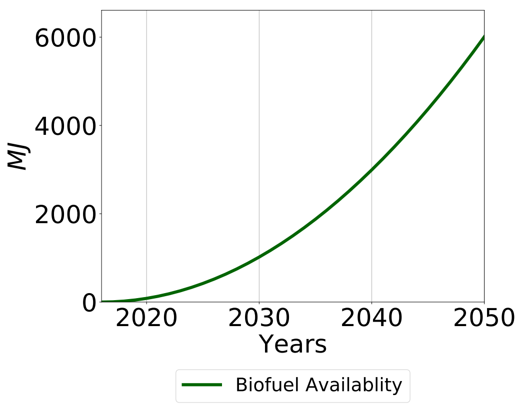


Figure 8.3: Fuel costs, REF

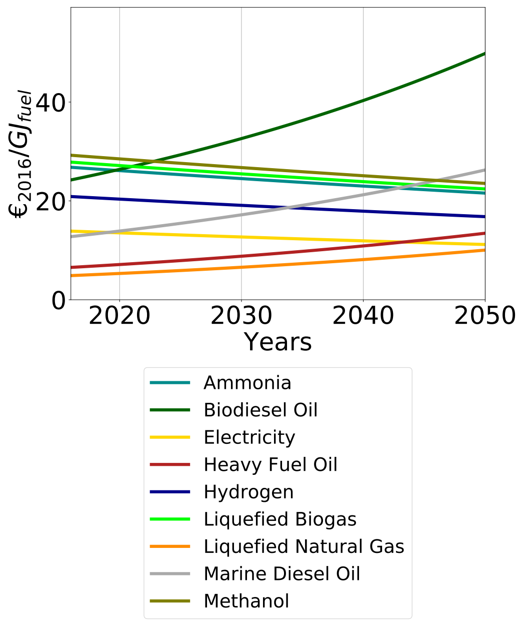


Figure 8.4: Infrastructure costs, REF

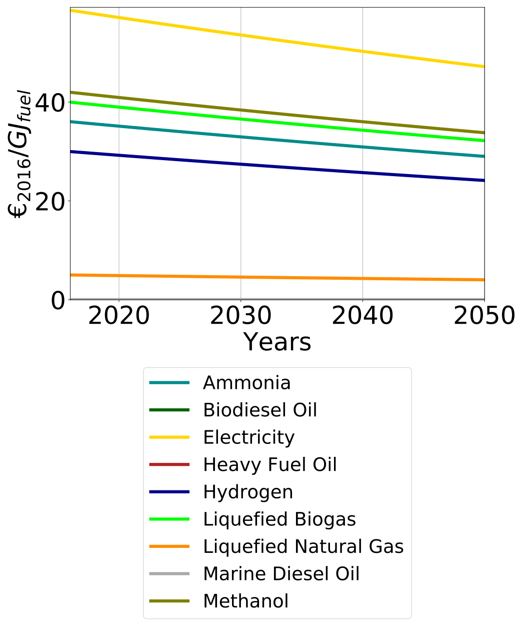


Figure 8.5: CO2(w2p), REF

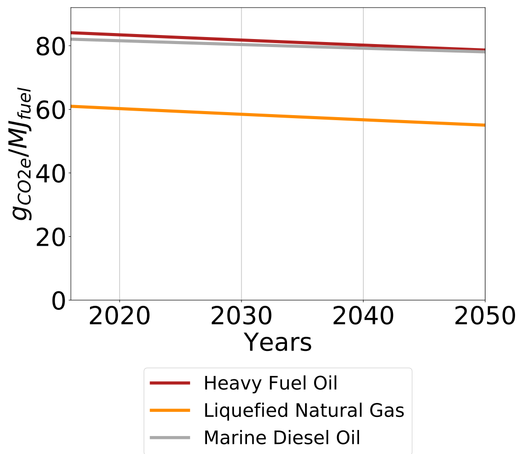


Figure 8.6: CH4(w2p), REF

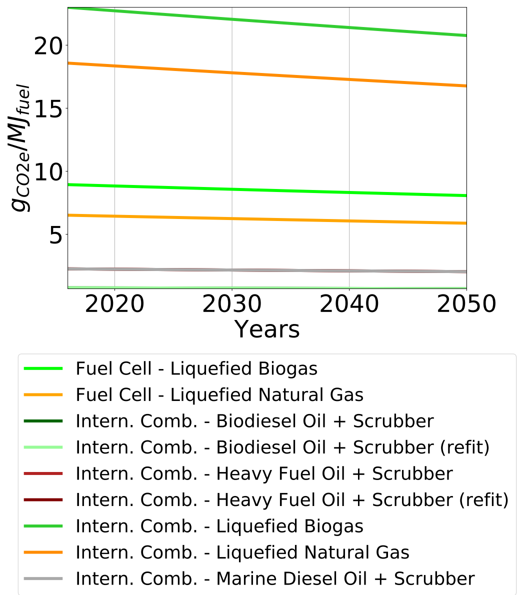


Figure 8.7: Ship costs, REF

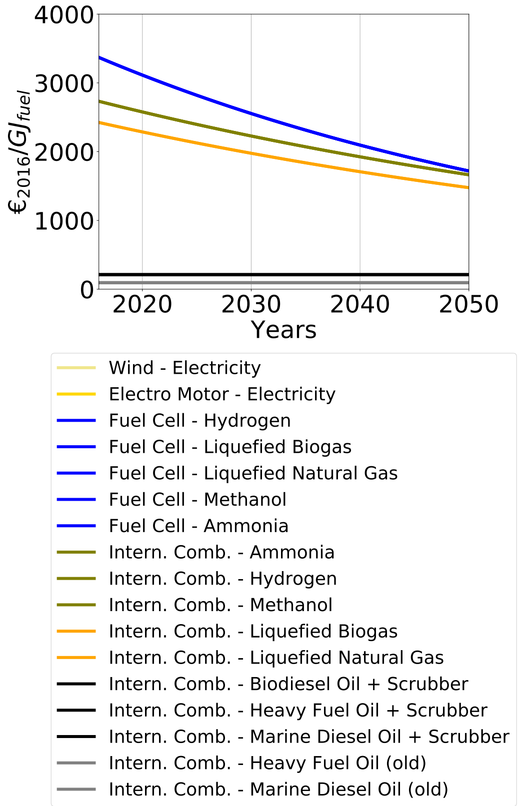
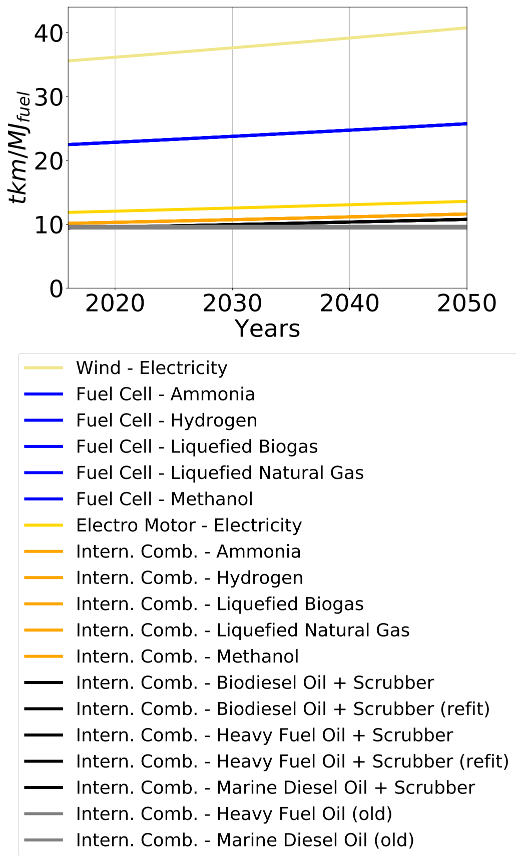


Figure 8.8: Transport work, REF



8.1.2 Output Data of Reference Scenario

As this study investigates possible future setups for the Danish maritime sector, it focuses on associated costs and emissions to air of different fuel technology options. Fig. 8.9 shows the resulting fuel composition for which the model has calculated the minimum system costs. The annual costs are displayed in Fig. 8.10 and amount to more than 20 billion EUR2016 (see Table 8.5). The model exploits the full CO2e emission budget of 19.12 Mt (see Table 8.5) and reaches the 2050 target of zero GHG emissions (see Fig. 8.11). Noticeable, in 2020 all IC HFO ships are being refitted with scrubbers - the inception year of the global SOx limit - and in

2027 a major switch to FC H2 ships is conducted. In this year all old ships are scrapped as their technical lifetime expires. Apparently, this affects not only the system costs that peak in the same year (see Fig. 8.10), but also the emissions drop significantly after this technology change (see Fig. 8.11).

Figure 8.9: Annual fuels, REF

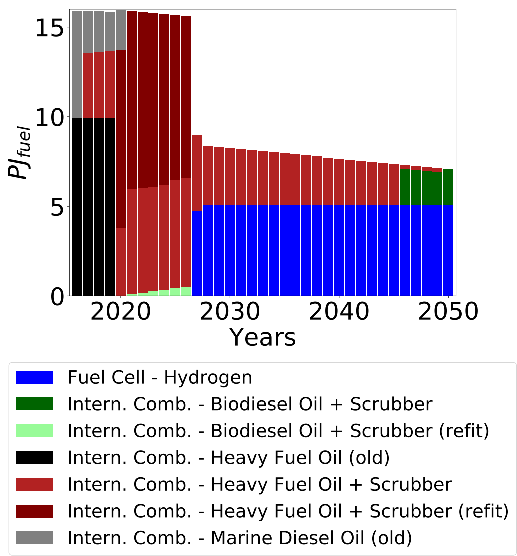


Figure 8.10: Annual costs, REF

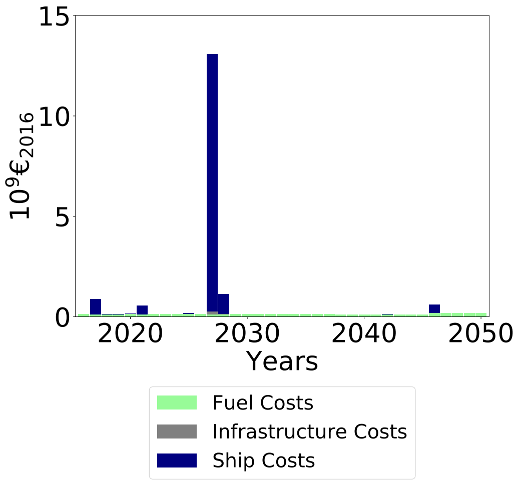


Figure 8.11: System emissions, REF

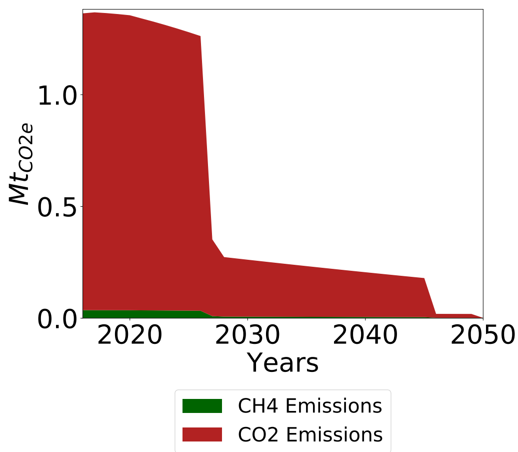


Fig. 8.11 includes annual up- and downstream emissions for CO2 and CH4. Consequently, its level in 2016 is higher than the operational emission estimation of 1.2 Mt stated in Table 5.5.

8.2 Regulative Scenarios

In this study regulative scenarios are referred to as REGs. As stated in Table 8.1 on page 38 they all change one or more parameters simultaneously compared to the REF scenario. The main purpose of the REGs is to analyze impacts and implications of different legislative frameworks regarding all emissions considered in this study (CO2, CH4, NOx, SOx). The BAU scenario, like a frozen policy scenario, has no further emission restrictions than what is already agreed upon. Further, to assess IMO's environmental ambition, a scenario of same name is conducted with its respective targets. The SNOX scenario serves to evaluate effects of stricter NOx and SOx regulations and their early implementation. Last, two scenarios with other focus areas complete the set. In the TDV scenario the transport demand parameter is decreased to a level, where no fossil fuels are being shipped, whilst the REF(mp) introduces a methane leakage phaseout (mp).

8.2.1 Input Data of Regulative Scenarios

Except for TDV and REF(mp), all changed parameters of the REGs compared to the REF scenario are static and listed in Table 8.3. Figs. 8.12 and 8.13 show both time variable parameters and their distinction with regards to REF.

Static

Parameter	Unit	**REF**	**BAU**	**IMO**	**SNOX**	**TDV**	**REF(mp)**
Emission budget	$[kt_{CO2e}]$	**19120**	∞	∞	∞		
Emission target	[%]	**0**	∞	**60**	∞		
Year of emission target	$[a]$	**2050**					
SOx limit in SECA	$[\%_{mass}]$	**0.1**					
SOx limit outside SECA	$[\%_{mass}]$	**0.5**			**0.1**		
Year of Sox limit outside ecas	$[a]$	**2020**			**2017**		
Nox limit in NECAs for new ships	$[Tier]$	**3**					
Year of Nox limit in NECAs	$[a]$	**2021**			**2017**		

Table 8.3: Static parameters of REG scenarios changed compared to REF. (If empty, then same as REF)

Time variable

A future decreasing maritime transport demand is assumed, due to less use of fossil fuels in the energy sector since many countries strive towards CO2 neutral societies. Thus, most of the Danish fossil fuel imports and exports would eventually be substituted by renewable alternatives. However, aviation possibly remains dependent on some sort of mineral product. In this scenario fossil fuel cargo commodities are fully taken out until 2050, except for the share of jet fuel that is even considered to increase significantly. With regard to a Danish kerosene outlook by [Bos18], the fossil based cargo share - excluding jet fuels - equals 32 %.

Figure 8.12: Transport demand, TDV

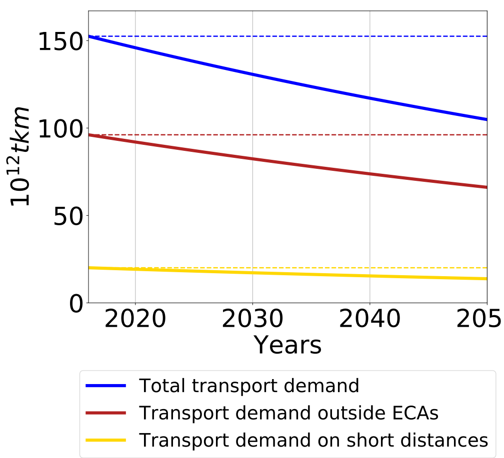
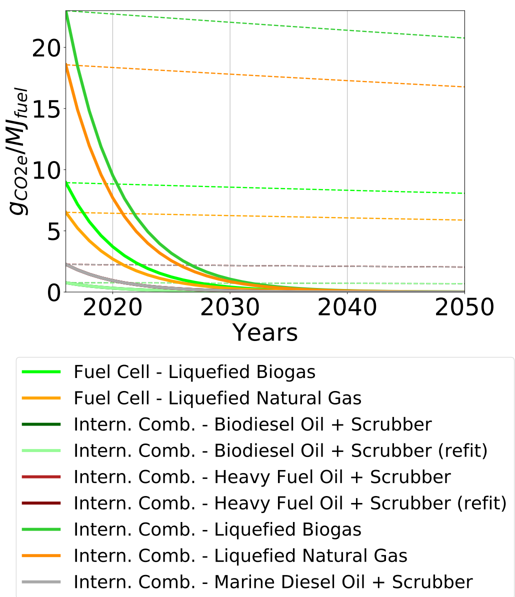


Figure 8.13: CH4(w2p), REF(mp)



8.2.2 Output Data of Regulative Scenarios

The same two key result figures are provided for each of the REGs scenario runs: One for the annually used fuels, the other one for the annually incurred system costs. GHG emissions are not plotted, as they are directly linked to the deployed fuel technologies. For the total cumulative CO2e amounts per scenario see Table 8.5.

REF(mp)

The REF scenario with methane leakage phaseout has a similar fuel technology composition until 2027 as the one without. Afterwards it invests into hydrogen fuel cells, too, but less than in the REF. In turn, BDO is gradually increased at an earlier stage and to a greater extend. In 2050 both fuels have equal shares. The emission budget is fully utilized while system costs have only been slightly reduced.

Figure 8.14: Annual fuels, REF(mp)

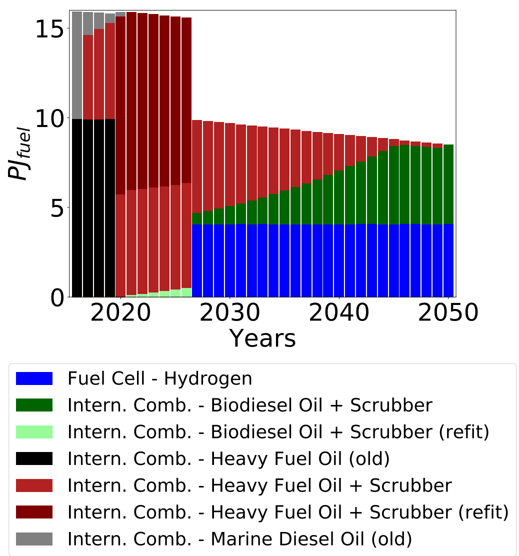
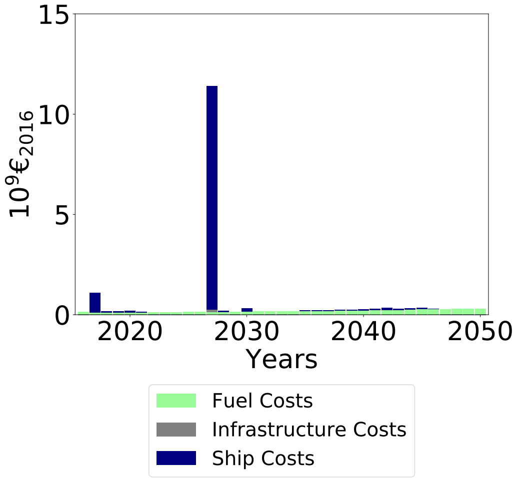


Figure 8.15: Annual costs, REF(mp)



BAU

As no GHG emission regime is in place, no carbon neutral fuel technology is needed. The major fuel utilized is HFO in combination with SOx scrubbers. When old ships are scrapped in 2027, solely HFO supplies all transport demand. Hence, system costs are with less than 10 billion EUR2016 comparably low (see Fig. 8.56), however allowing for more than 44 Mt CO2e emissions. This is more than twice the amount of REF.

Figure 8.16: Annual fuels, BAU

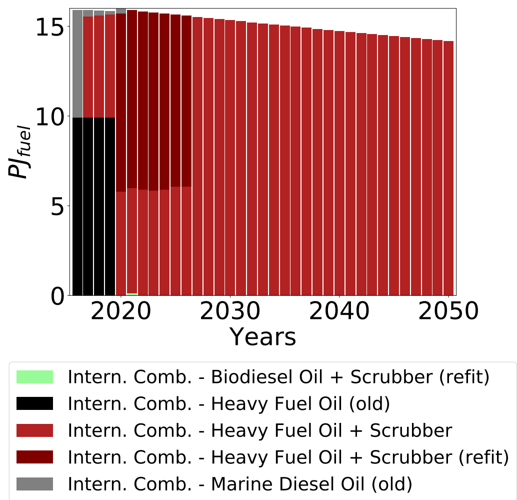
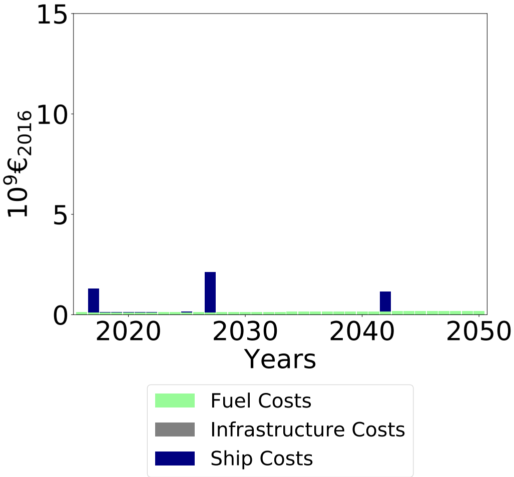


Figure 8.17: Annual costs, BAU



IMO

IMO's and BAU's model results are very similar. The only major difference is an uptake of BDO for IMO from 2046 onwards. Consequently, in comparison to BAU, overall CO2e emissions decrease and system costs increase to small extends. With the later introduction of BDO, IMO's CO2 emission target in 2050 is reached. To comply with the IMO target only a small amount of BDO at a later stage could be sufficient.

Figure 8.18: Annual fuels, IMO

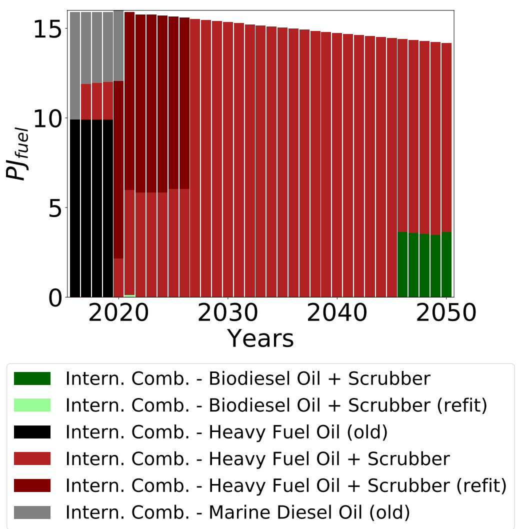
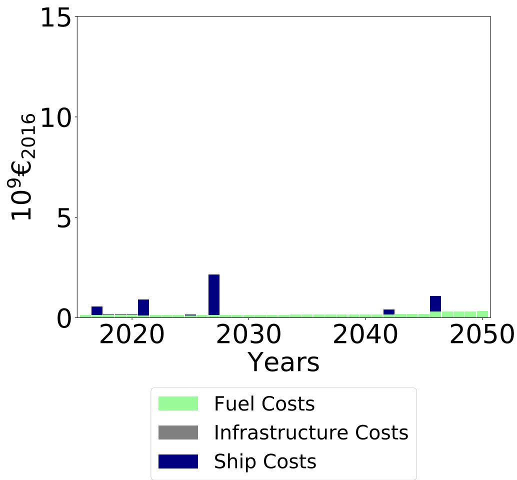


Figure 8.19: Annual costs, IMO



SNOX

Likewise to the preceding scenario, SNOX' overall results are fairly in line with BAU. Unique, though, is the period until 2027 as all IC HFO ships are refitted with scrubbers and IC MDO ships scrapped straight away. By 2017, HFO with exhaust gas cleaning is the cheapest possible fuel option that meets stricter and earlier ECAs restrictions.

Figure 8.20: Annual fuels, SNOX

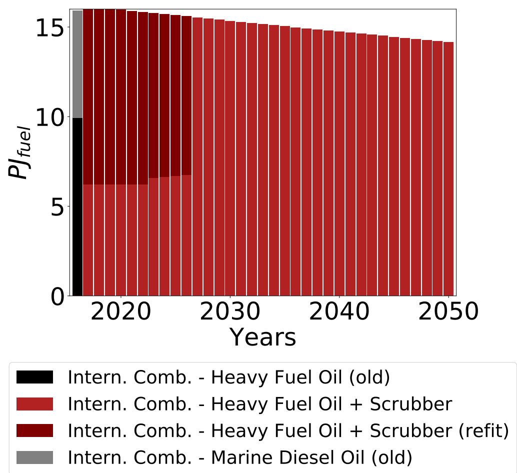
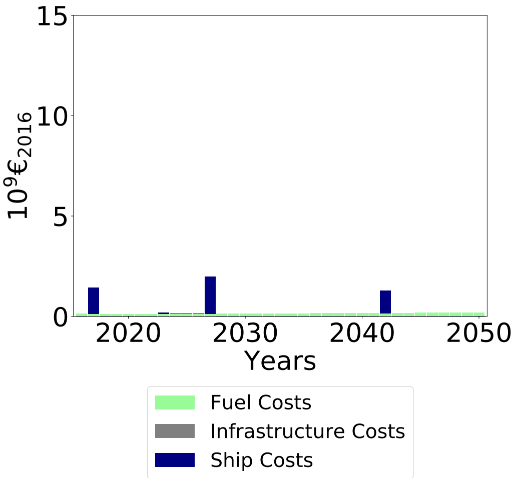


Figure 8.21: Annual costs, SNOX



TDV

Notably, transport demand reduction and methane leakage phaseout present similar effects to the reference system. Gradually less transport demand as well as an equal CO2e budget compared to REF allow for an earlier usage and higher share of BDO. The additional BDO ousts out some of both H2 and HFO. Since transport demand declines over time, less investments are needed so that the system costs fall by 25 % to 15 billion EUR2016. These overall cost reductions are much greater than the entire transport demand reduction of 17 %. The faster the demand curves in Fig. 8.12 fall before it reaches the year of major investments into new fuel technologies, the greater this cost benefit would be.

Figure 8.22: Annual fuels, TDV

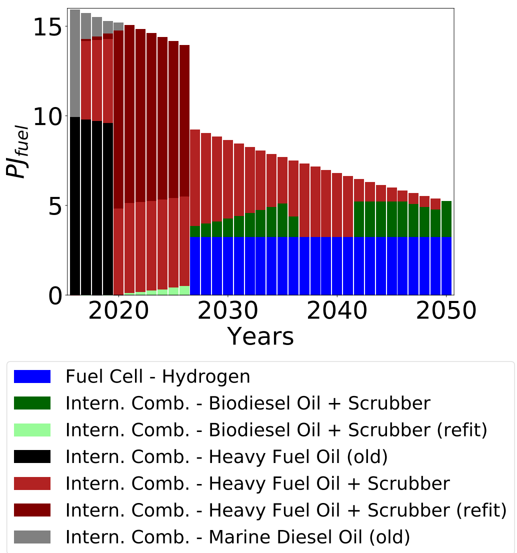
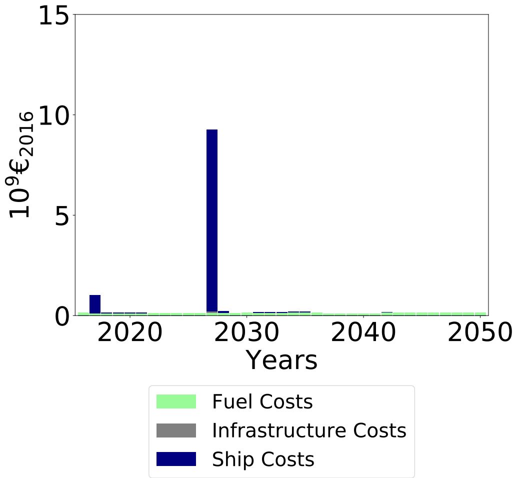


Figure 8.23: Annual costs, TDV

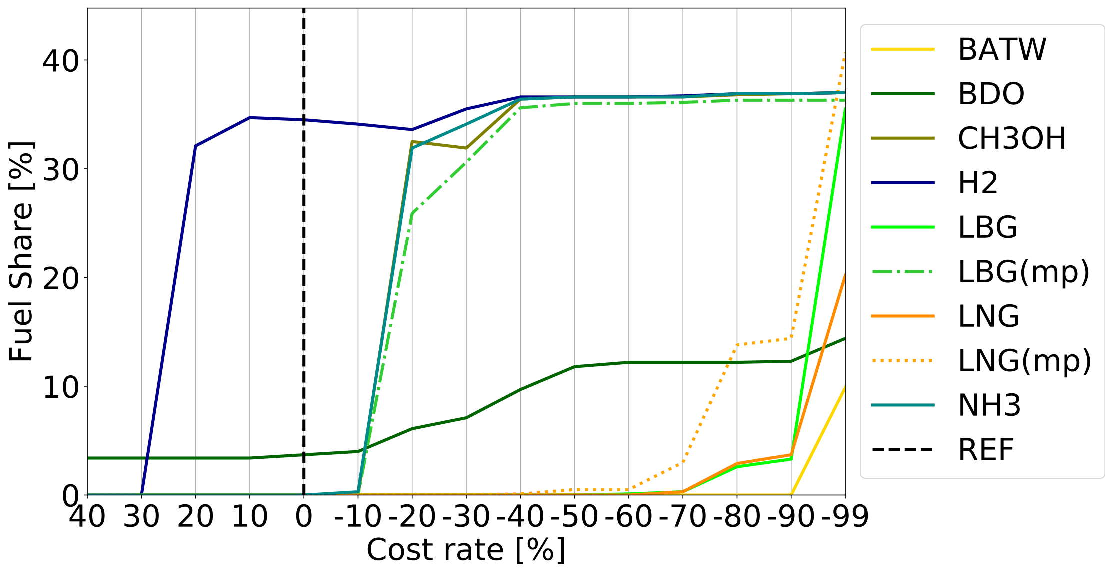


8.3 Cost Scenarios

Cost scenarios are referred to as CSTs. As stated in Table 8.1 on page 38 they all change one or more cost related parameters compared to the REF scenario (fuels, infrastructure and ships). The main purpose of the CSTs is to analyze first at what cost rates market entry thresholds exist for several different fuel technologies. Second, the model results of the scenarios with the respective variation rates are displayed and discussed. For clarity, scenarios are named after the specific fuel technology under investigation. E.g. in the NH3 scenario cost parameters that affect ammonia utilization are subject to variation. If these parameters are likely to influences other fuel technologies simultaneously, then they are subject to the same variation, too. The total changing rates are applied to the final values in 2050 of the REF. If - for example - the finale value in 2050 of any cost parameter is 1 EUR2016 per MJ and the variation is -40 %, then the new final value for this scenario is 0.6 EUR2016 per MJ. The starting value in 2016, which could have been 2 EUR2016 per MJ, is left untouched. Consequently, the negative price spread between 2016 and 2050 then increases from 1 to 1.4. With this difference, the annual cost rate that increase or decrease a specific parameter is calculated. Every year the preceding value is multiplied by the annual rate, so that a continuous curve is formed towards the new final value.

In order to retrieve the most relevant cost variation rates per scenario a meta analysis is conducted. For this reason, all CST scenarios are calculated for a range of rates from -99 % to +40 % in steps of 10 %. Fig. 8.24 shows cost variation rates and associated total accumulated system fuel shares of the privileged fuel in each cost scenario. The rates alternate the 2050 cost parameters of REF for the specific scenario's fuel technology. Rate zero refers to REF. Dashed and/or dotted lines present the results of scenarios with a methane leakage phaseout for all affected fuel technologies. Notably, there exists a significant difference of up to 80 % regarding market entry rates, if a scenarios is calculated with methane leakage phaseout or not. Thus, the scenario versions without methane leakage phaseout are disregarded hereafter. Sections 8.3.1 and 8.3.2 present the selected rates per scenario.

Figure 8.24: Cumulative fuel shares per cost variation rate

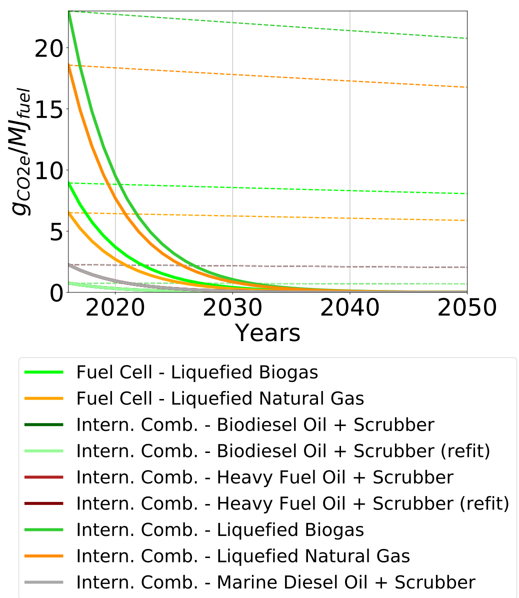


8.3.1 Input Data of Cost Scenarios

Derived from the REF's model results (see Fig. 8.10), mainly fuel and ship costs influence the system setups and total costs, unlike infrastructure. Therefore, this chapter focuses merely on these two parameters in comparison to the REF scenario. It provides an overview about selected rates, affected fuel technologies and resulting cost curves. Dashed lines represent the reference curves for comparison.

Each of the following scenarios that is indicated to have a methane leakage phaseout until 2050 is using the reduction curves of Fig. 8.25. Old ships are excluded from this improvement. MDO (grey) and HFO follow the same curve, so that the red curves of HFO are covered by the grey one. The highest two leakage rates in 2016 belong to IC LBG and IC LNG ships. Besides, new and refitted IC BDO ships follow identical curves.

Figure 8.25: CH4 leakage phaseout



BATW

The BATW scenario changes the cost parameters of battery and wind hybrid technologies. Cost-variable fuel is electricity (ELEC) that also impacts fuel production costs of electro-fuels (CH3OH, H2, LBG, NH3). Hence, their fuel costs are subject to variation, too. The affected ship types are full-electric and sailing ships with battery support (yellow lines).

The selected rate from Fig. 8.24 is -99% and therefore some values in 2050 are close to zero. Figs. 8.26 and 8.27 display the resulting cost curves. In 2023, electricity undercuts the remaining fuel's costs. On the ship site, in 2033 and 2037 costs fall later below all other new ship types as the initial values are ten- to twenty-fold as high.

Figure 8.26: Fuel costs, BATW

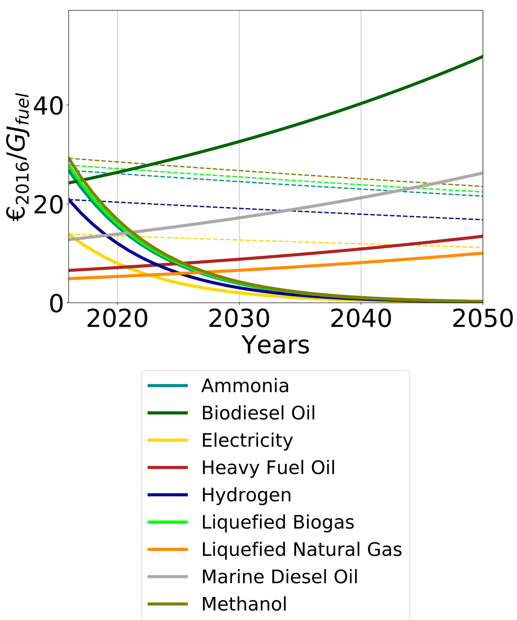
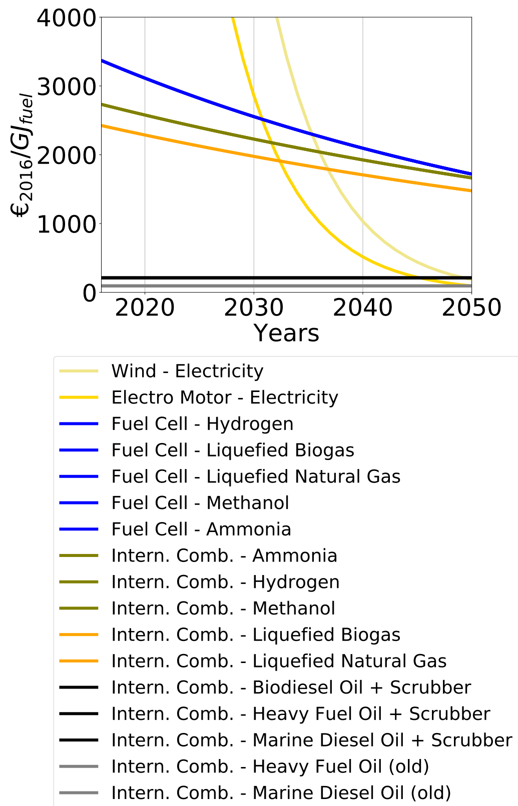


Figure 8.27: Ship costs, BATW



BDO

In this scenario solely the BDO fuel cost parameter is changed, since diesel engines are a well established technology with limited cost reduction potential. The selected rate from Fig. 8.24 is -50 %. With this rate BDO fuel costs stay at a similar level compared to renewable electro-fuel options.

Figure 8.28: Fuel costs, BDO

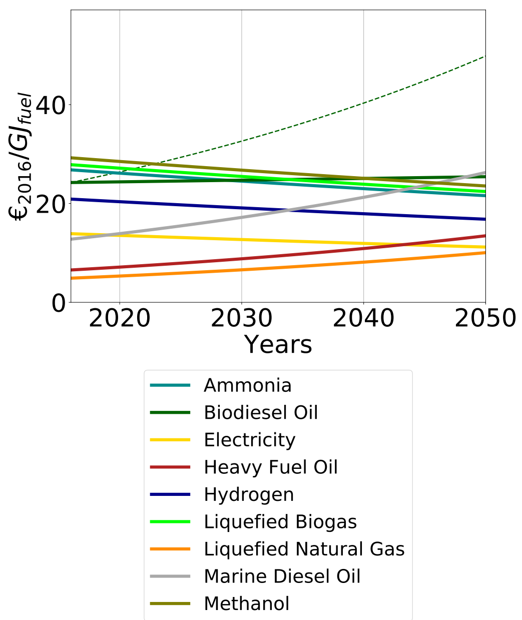
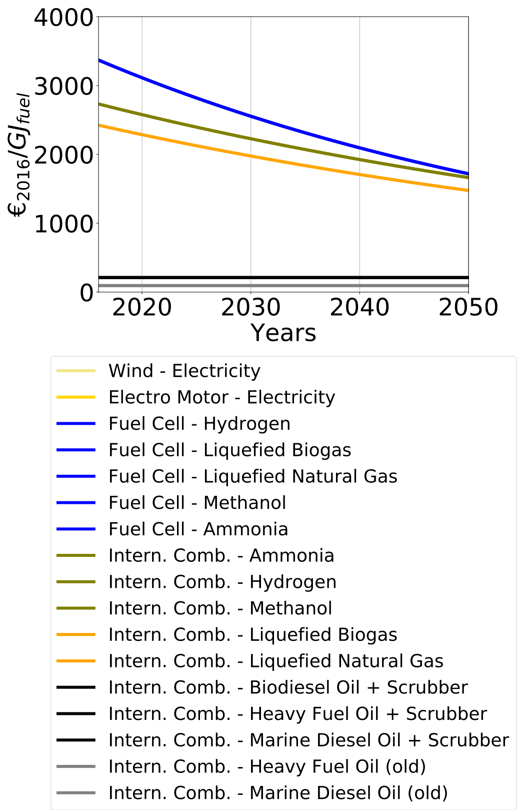


Figure 8.29: Ship costs, BDO



LNG(mp)

The scenario rate at which the share of LNG shoots up remains with -80 % at a high level, even when a methane leakage phaseout is implemented (see Fig. 8.24). A cost advantage for both, IC and FC ship types is reached around 2023 (see Fig. 8.30) while the already low fuel cost's are decreased even further (see Fig. 8.30). Finally, in 2050 LNG ship costs decrease to a similar level of current IC HFO and MDO.

Figure 8.30: Fuel costs, LNG

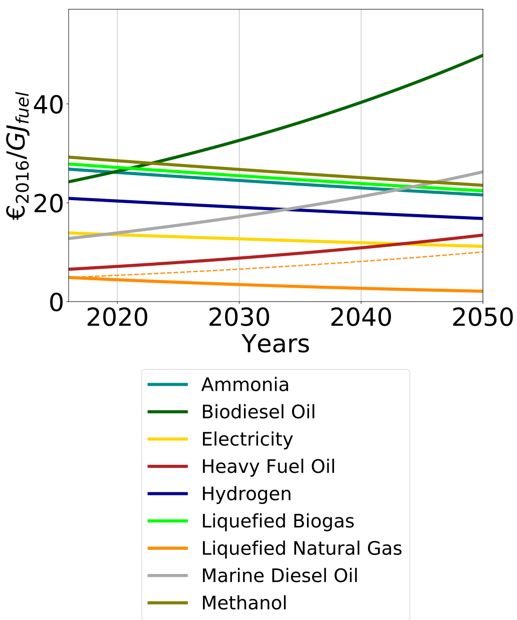
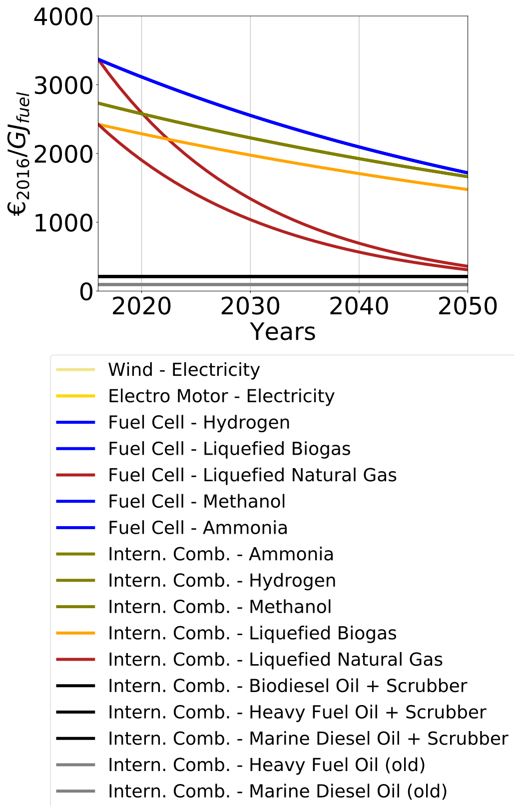


Figure 8.31: Ship costs, LNG



CH3OH, H2, LBG(mp), NH3

Since CH3OH, H2, LBG and NH3 are considered as electro-fuels, the clustering of fuel costs is done in the same way as electricity in BATW. The ship costs variation however is only applied to IC and FC ship types per scenario. Table 8.4 holds the changing rates per scenario that is of most interest. Further, it states the years in which the changed ship cost curves undercut the others for fuel cells and internal combustion engines respectively. They are plotted as red lines in Figs. 8.33, 8.35, 8.37 and 8.39.

Electro-fuel scenario	Rate [%]	1^{st} year of ship type cost advantage Internal combustion	Fuel cell
CH3OH	-20	2035	2048
H2	20	-	-
LBG(mp)	-40	2017	2033
NH3	-20	2036	2046

Table 8.4: Electro-fuel cost changing rates and years of cost advantage.

Figure 8.32: Fuel costs, CH3OH

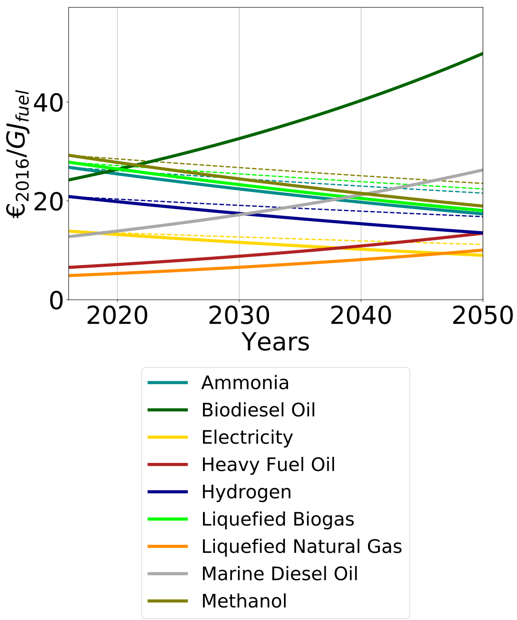


Figure 8.33: Ship costs, CH3OH

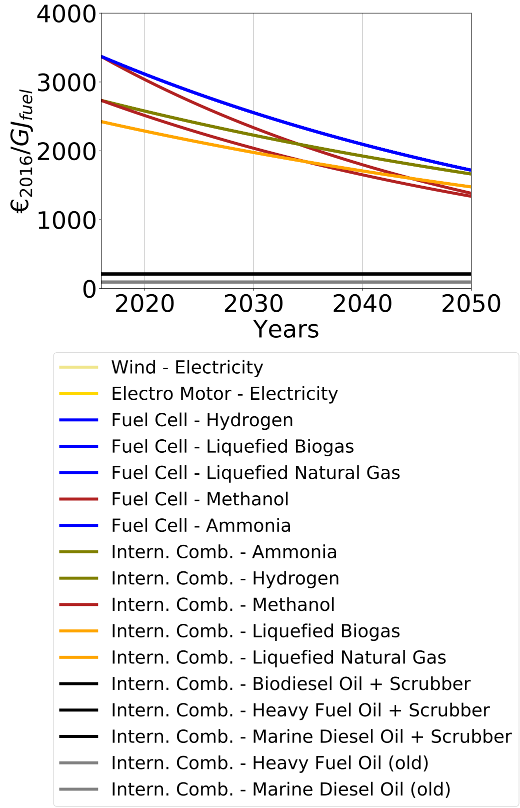


Figure 8.34: Fuel costs, H2

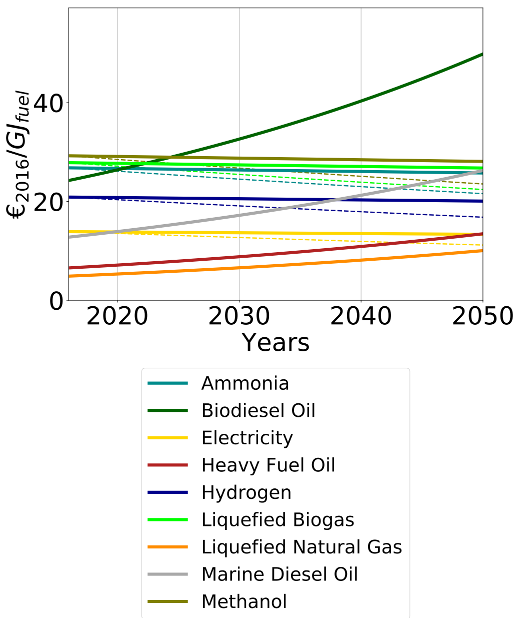


Figure 8.35: Ship costs, H2

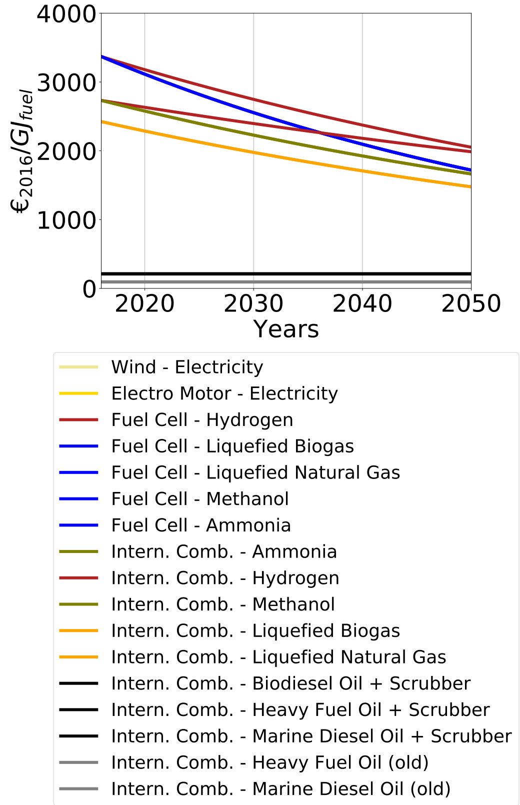


Figure 8.36: Fuel costs, LBG

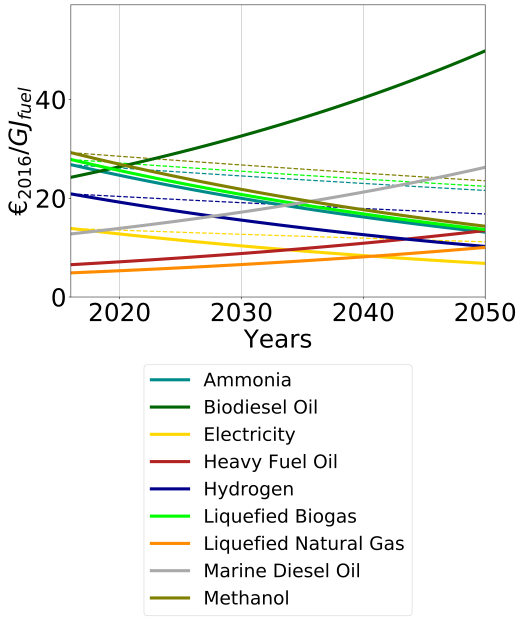


Figure 8.37: Ship costs, LBG

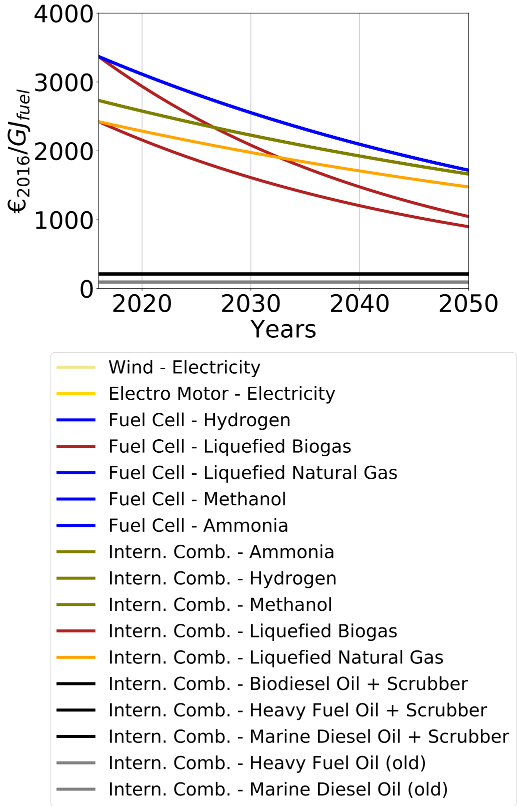


Figure 8.38: Fuel costs, NH3

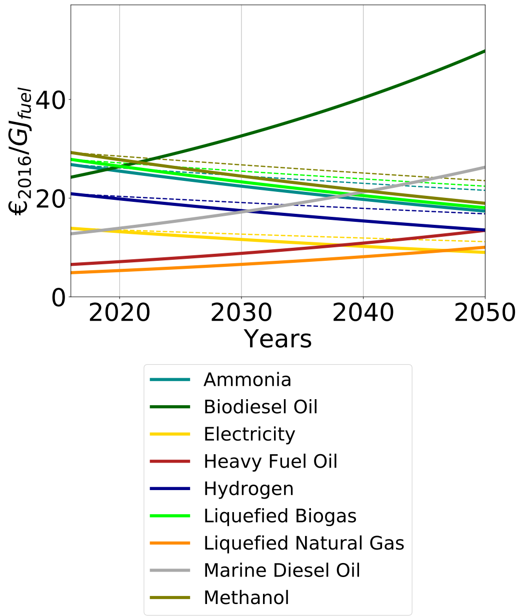
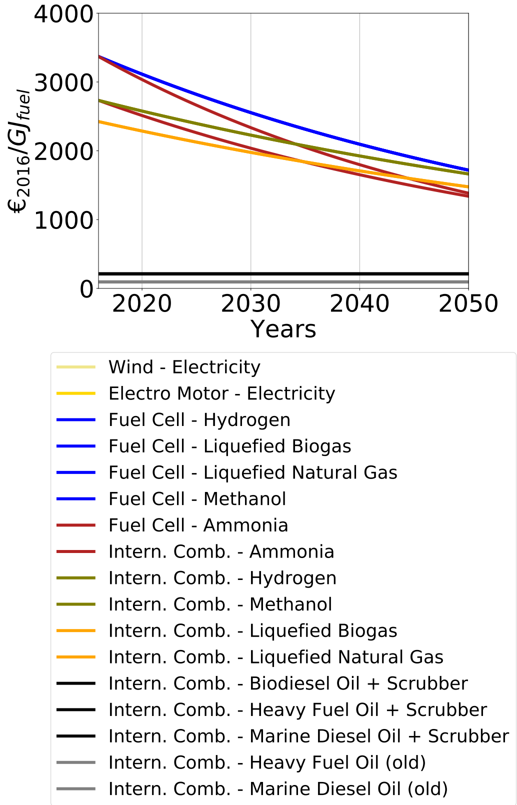


Figure 8.39: Ship costs, NH3



8.3.2 Output Data of Cost Scenarios

The same two figures as for the REGs are shown for each CST scenario in order to provide sufficient information about the results: Annually consumed fuel amounts and incurred system costs. GHG emissions are not plotted, as they are again directly linked to the deployed fuel technologies. For the total calculated CO2e amount see Table 8.5.

BATW(-99)

In the BATW scenario with -99 % cost reduction occure two investment periods. First, from the start to 2021, where investments are made in IC HFO with scrubbers and FC H2. Besides, most exiting IC HFO ships are refitted with scrubbers. The second period is from 2040 to 2046, when ship costs for WIND ELEC vessels have dropped enough to become cost compatible (see Fig. 8.27). H2 is built up once and used until its ship lifetime expires. From that moment onwards WIND ELEC is the single remaining ship type.

Figure 8.40: Annual fuels, BATW

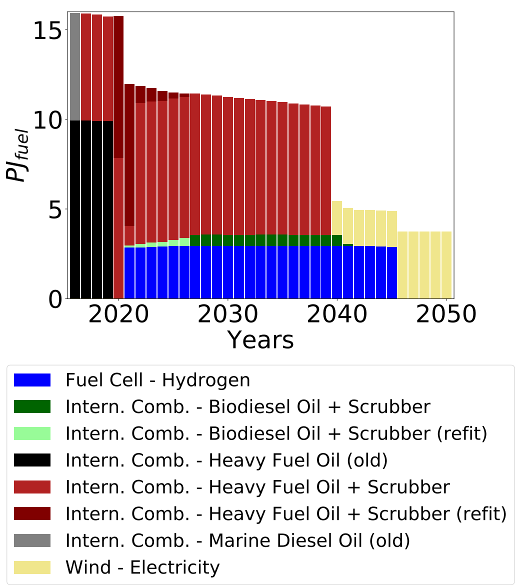
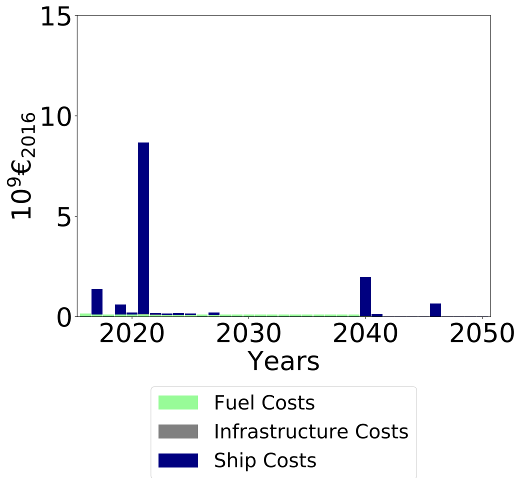


Figure 8.41: Annual costs, BATW



BDO(-50)

Likewise to BATW occur two investment periods. Though, they both shift closer to the middle on the time-line (see Fig. 8.43). At first the model invests mainly into FC H2 and afterwards it increases the share of IC BDO. Both, in order to replace IC HFO vessels. In 2050, IC BDO and FC H2 allocate all transport demand among themselves.

Figure 8.42: Annual fuels, BDO

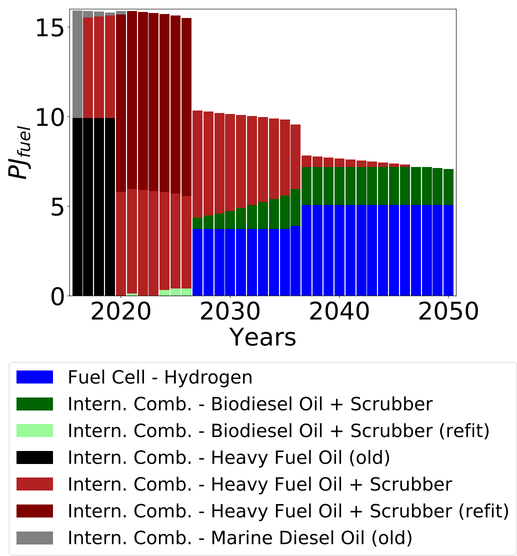
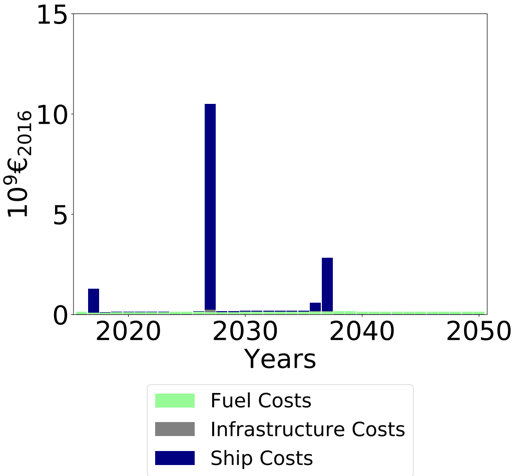


Figure 8.43: Annual costs, BDO



LNG(mp, -80)

LNG(mp) with -80 % cost reduction shows the same pattern in the first section unitl 2027 as BDO. From then on IC BDO, FC LNG, but mainly FC H2 subsequently oust out the remaining IC HFO. LNG faces a limited window of opportunity of 23 years. Again, IC BDO and FC H2 are the two remaining ship types in 2050 to comply with the net zero CO2e target.

Figure 8.44: Annual fuels, LNG(mp)

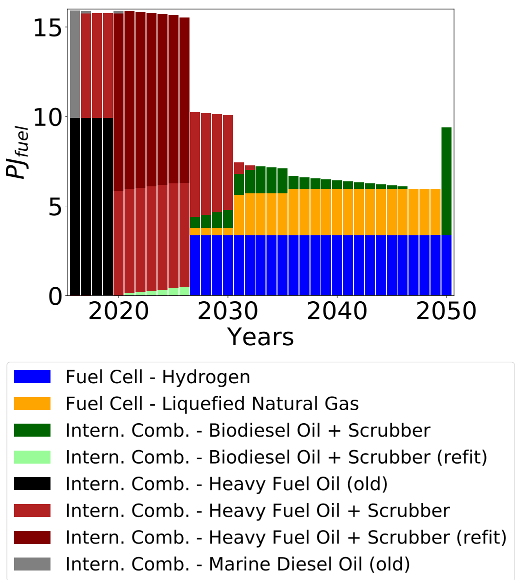
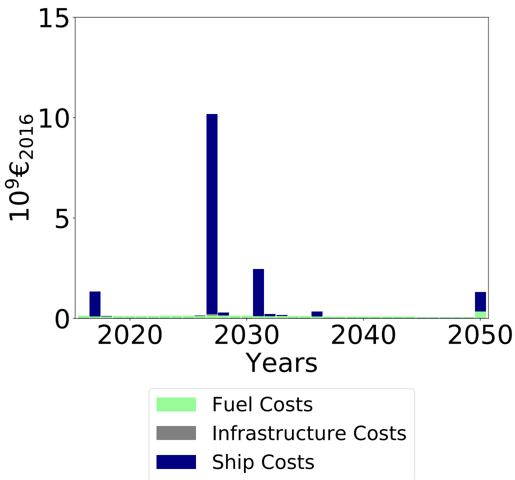


Figure 8.45: Annual costs, LNG(mp)



H2(20)

H2 can cope with a disadvantageous cost increase of 20 % compared to REF, whilst not loosing significant market share. The annual fuels of REF and H2(20) displayed in Figs. 8.14 and 8.46 resemble each other quite strong. But, at the bottom of Fig. 8.46 FC NH3 is just about to emerge. As for many other scenarios, the one major investment period takes place in 2027 (see Fig. 8.47).

Figure 8.46: Annual fuels, H2

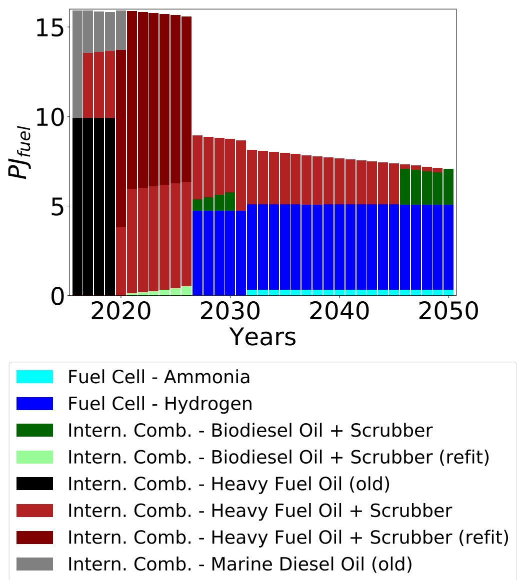
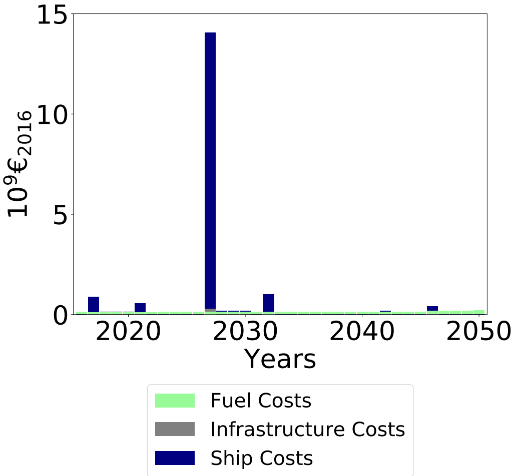


Figure 8.47: Annual costs, H2



CH3OH(-20), LBG(mp, -40), NH3(-20)

Apart from H2, the outputs from all three model runs of the other electro-fuel scenarios (CH3OH, LBG(mp), NH3) with the respective cost variation rates show strong consistency. The first ten years appear virtually identical. Also the subsequent periods show similar shapes, where only the electro-fuel type is switched. In each case, IC HFO with scrubber is again oust out in two investment steps (see Figs. 8.49, 8.51 and 8.53). In the case of CH3OH and NH3, since their cost are reduced by just -20 %, BDO complements the fuel mix. Also here are the major investment periods in 2027.

Figure 8.48: Annual fuels, CH3OH

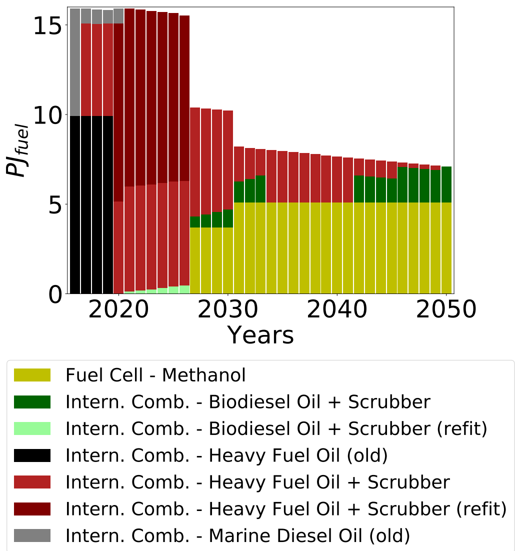


Figure 8.49: Annual costs, CH3OH

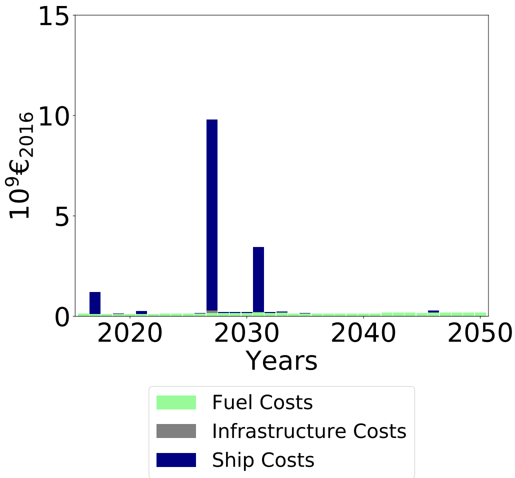


Figure 8.50: Annual fuels, LBG(mp)

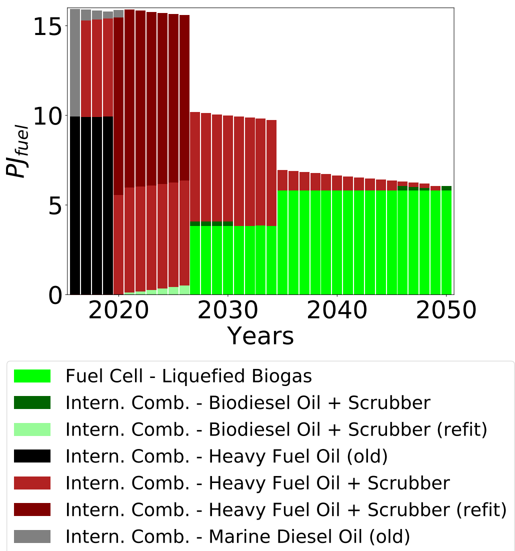


Figure 8.51: Annual costs, LBG(mp)

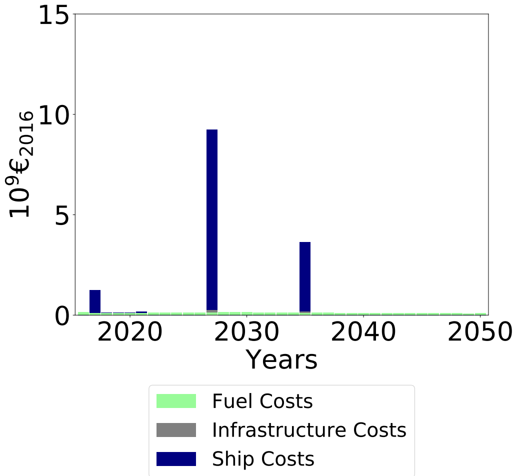


Figure 8.52: Annual fuels, NH3

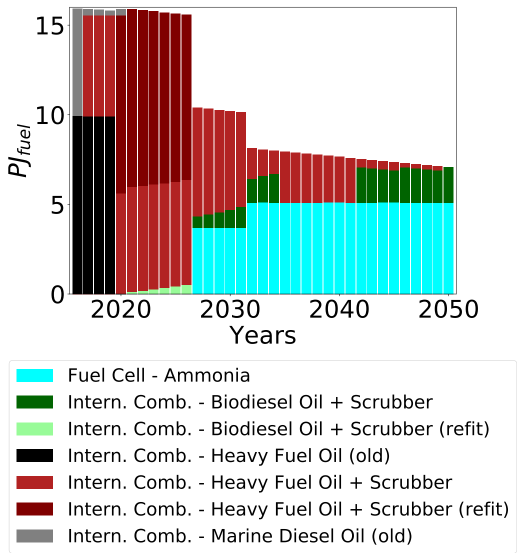
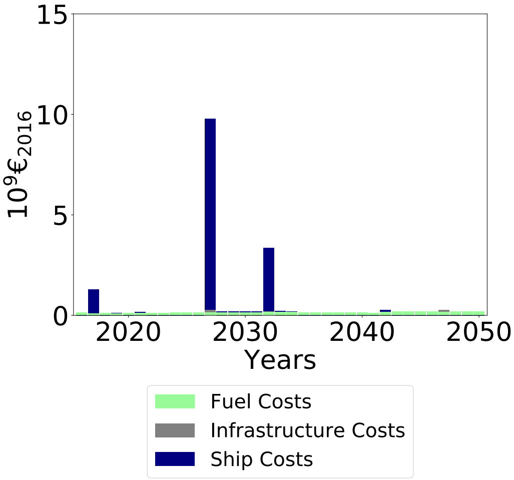


Figure 8.53: Annual costs, NH3



8.4 Scenario Comparison

In order to allow for a general scenario comparisons, the following Figs. 8.54 to 8.56 provide total stacked fuel amounts, GHG emissions and system costs of all analyzed scenarios. Besides, Table 8.5 holds the respective numbers on which the figures based, a calculated CO2e prices and total transport costs.

8.4.1 Fuels

The displayed cumulative fuel amounts for shipping per scenario and type range from 340 to 540 PJ fuel. All scenarios with GHG emission constraints are at the lower end around the REF's amount that is additionally indicated by a dashed line.

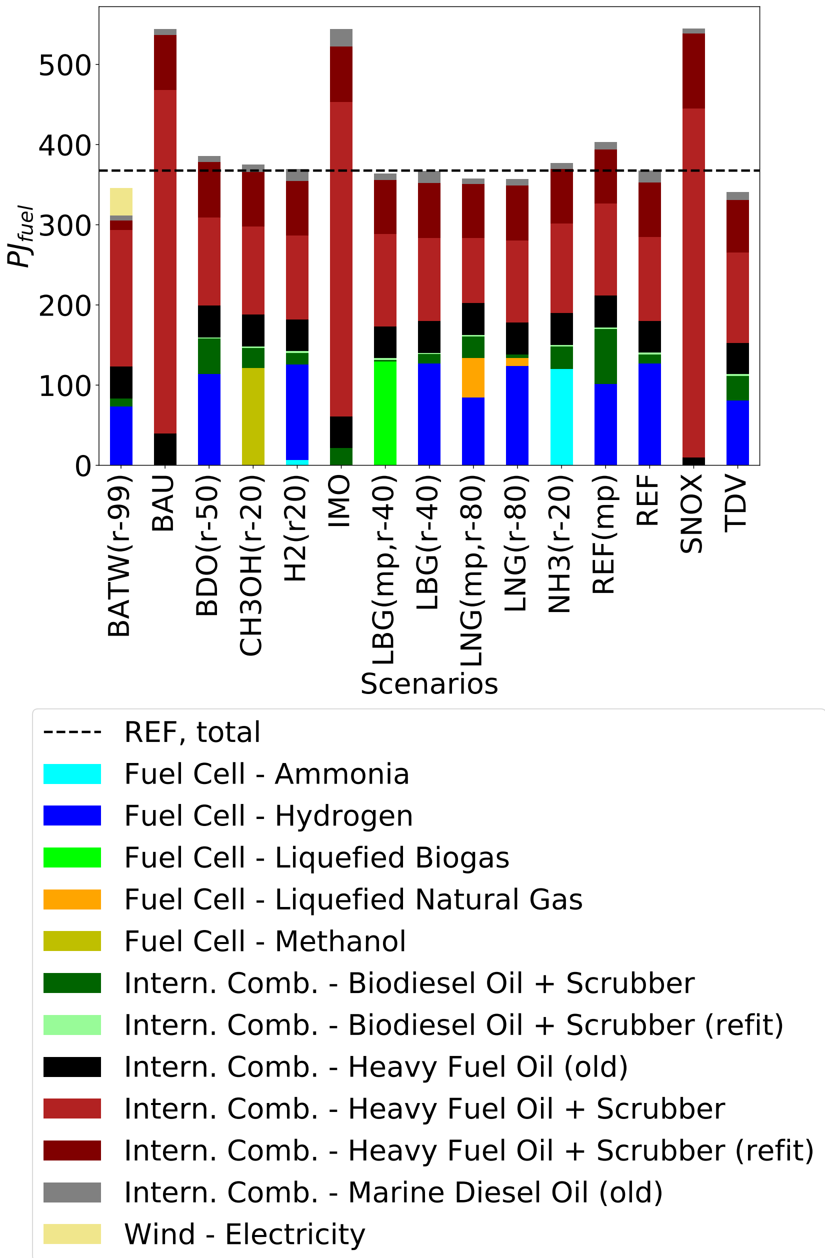


Figure 8.54: Total fuel for shipping per scenario and type.

8.4.2 Emissions

Fig. 8.55 shows the cumulated system emissions in Mt CO2e and for each scenario. It is broken down to CH4 and CO2 shares. All scenarios except for BAU, IMO and SNOX comply on the point with the emission budget of 19.12 Mt constraint, which is indicated by the dashed line. These three scenarios have GHG emission levels that are more than twice as high as allowed by the budget constraint.

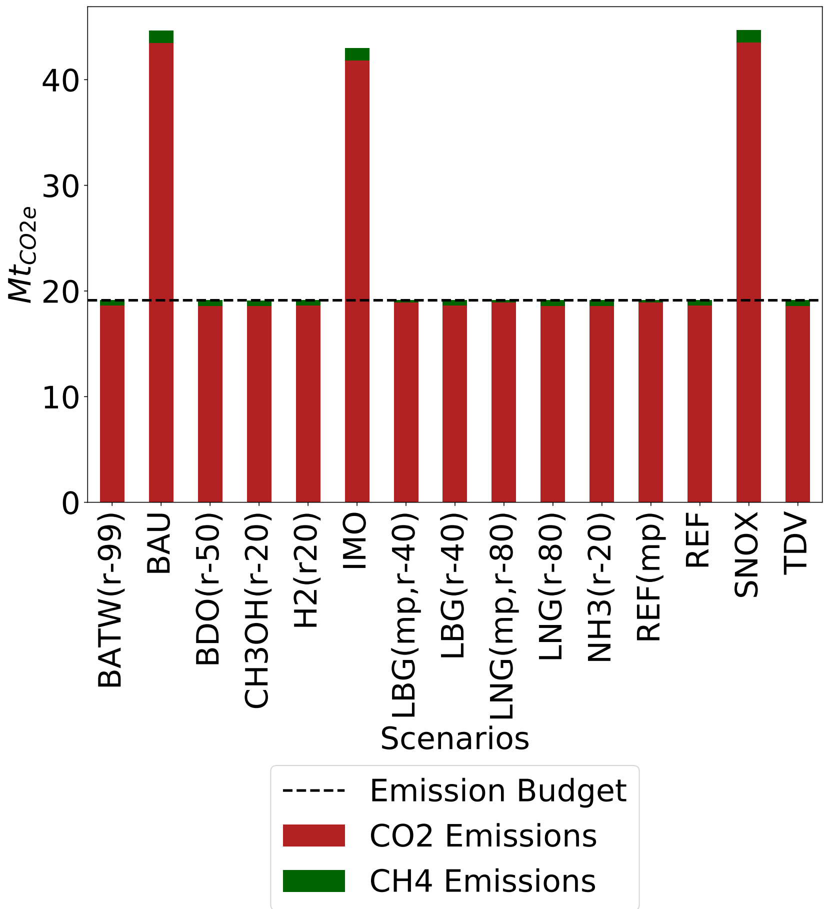


Figure 8.55: Total emissions per scenario and type.

8.4.3 Costs

In contrast to the emissions BAU (dashed line in Fig. 8.54), IMO and SNOX have by far the lowest total system costs. Among them fuel costs pose the highest cost share. As for the other scenarios ship costs have the largest share. In total, the costs range from 9.5 to 21.5 billion EUR2016. Infrastructure costs are insignificantly small throughout the entire scenario set.

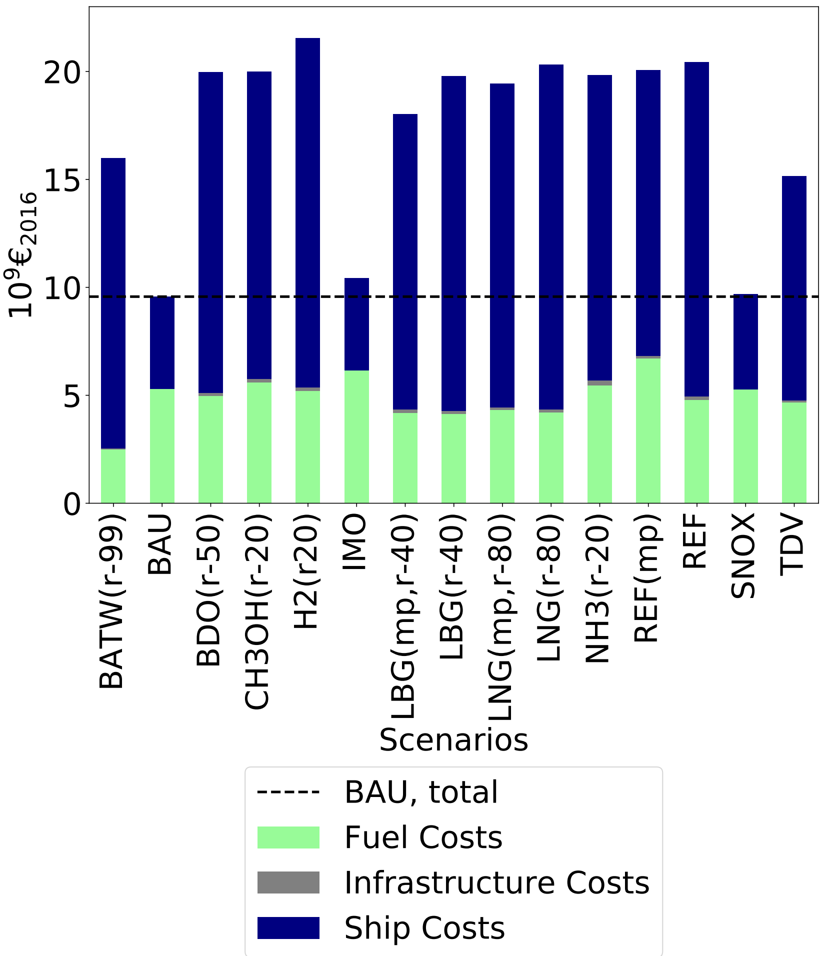


Figure 8.56: Total costs per scenario and type.

				Regulative Scenarios					Cost Scenarios								
		Unit	REF	REF(mp)	IMO	SNOX	TDV	BAU	BATW	BDO	CH3OH	H2	LBG	LBG(mp)	LNG	LNG(mp)	NH3
Cost rate		[%]	0	0	0	0	0	0	-99	-50	-20	20	-40	-40	-80	-80	-20
fa	BDO	$[PJ_{fuel}]$	14	71	22	0	33	0	11	46	27	17	13	4	5	29	30
	CH3OH		-	-	-	-	-	-	-	-	122	-	-	-	-	-	-
	ELEC		-	-	-	-	-	-	34	-	-	-	-	-	-	-	-
	H2		127	102	-	-	81	-	74	114	-	119	127	-	124	85	-
	HFO		212	222	501	539	217	537	222	219	217	212	212	222	211	189	220
	LBG		-	-	-	-	-	-	-	-	-	-	-	130	-	-	-
	LNG		-	-	-	-	-	-	-	-	-	-	-	-	10	49	-
	MDO		15	9	22	6	10	7	6	7	9	15	15	8	8	6	7
	NH3		-	-	-	-	-	-	-	-	-	7	-	-	-	-	120
	Total		**368**	**403**	**544**	**545**	**341**	**544**	**347**	**386**	**375**	**370**	**367**	**364**	**358**	**358**	**377**
CF	Total	$[10^6\ EUR_{2016}]$	4800	6710	6140	5290	4670	5290	2500	4980	5590	5210	4150	4180	4210	4340	5450
CI	Total		140	110	-	-	90	-	50	140	180	150	120	170	140	100	250
CS	Total		15490	13240	4280	4410	10390	4280	13440	14860	14220	16180	15510	13670	15960	14990	14140
	Sum		**20439**	**20060**	**10420**	**9700**	**15150**	**9570**	**15990**	**19980**	**19990**	**21540**	**19780**	**18020**	**20310**	**19430**	**19840**
EC	Total	[kt CO2e]	18609	18925	41812	43504	18596	43456	18611	18587	18600	18607	18610	18908	18571	18934	18598
EM	Total		511	195	1141	1171	524	1169	509	533	520	513	510	212	549	196	522
	Sum		**19120**	**19120**	**42952**	**44674**	**19120**	**44626**	**19120**	**19120**	**19120**	**19120**	**19120**	**19120**	**19120**	**19120**	**19120**
CO2e price		$[EUR_{2016}/t_{CO2e}]$	426	411	508	-2624	219	0	252	408	409	469	400	331	421	387	403
Transport cost		$[EUR_{2016}/t]$	7	7	3	3	6	3	5	7	7	7	7	6	7	6	7

Table 8.5: Scenario results including CO2e prices based on BAU and transport costs per ton.

CHAPTER 9

Discussion

This chapter discusses results and observations of the conducted scenarios described in Chapter 8. Besides, reliability and robustness of the results are analyzed by means of calculated transport costs per metric ton cargo and CO2e prices compared to the BAU scenario.

The model shows a ”the winner takes it all” behaviour. It tends to max out old and new ship’s lifetimes and to invest mainly in one single renewable alternative fuel technology. This indicates a satisfactory reflection of actual asset management. Until 2027 the system setups look mostly similar in terms of fuel types and shares taken into account. While IC MDO is scrapped straight away, refitted and new IC HFO ships take over. Throughout all scenarios where GHG emissions are constraint in the same way, HFO maintains its overall share, regardless of cost reduction rates. Without these constraints, HFO is very likely to remain the predominant maritime fuel (Fig. 8.55). Note, though, that the developed model neither includes co-benefits or risk of fuels, nor are cost reduction rates of technologies comparable.

Since the shipping stock’s remaining lifetime is an average estimation, the year 2027 just represents the perennial transformation period. But, old ships are scrapped and new ships built today that shape the future Danish fleet for the coming decades. E.g. LNG does not hold much potential to lower CO2e emission sufficiently, these investments might obstruct an integral transformation of the shipping sector. Though, regardless of which alternative fuel-technology prevails, total energy demands are reduced significantly in all scenarios that are subject to a CO2e regime (see Fig. 8.54) and new ship types are predicted to be far more energy efficient than current internal combustion engines burning HFO or MDO (see Table 6.3). Concerning the methane leakage phaseout phenomena, it shows significant impact on the scenario results. In particular for LNG and LBG technologies it is a decisive factor. A fast and complete elimination of methane leakage up- and downstream could potentially lower system costs ceteris paribus by approximately 10 % (Table 8.5).

Why are fuel-electric ships never chosen? Possible explanations could be that in the BATW scenario battery-only ships are in direct competition with sail-battery hybrids, where they are disadvantaged due to shorter operation range and lower transport supply. Though, battery-only ships are able to provide very high level of transport quality, but such detail is not provided in the model and therefore not rewarded. The averaging of input parameters promotes investments into larger, long range operating ship-types, which might not be able to satisfy all cargo shipping applications. Especially, when considering transport of smaller cargo volumes without too much dead space, or more divers operation profiles like high shares of speed changes, maneuvering during operation or berthing regularly at small ports.

In order to evaluate the reliability and robustness of the model behaviour, three key indicators are put into global perspective. First carbon prices in comparison to BAU scenario, second transport costs per metric ton cargo and third emission peak periods. Additionally, anticipated relations between cost reduction rates, total system costs and GHG emissions are consulted for valuation.

The model suggests carbon prices ranging from 350 to 450 EUR2016 per ton CO2e for a renewable transition of the Danish shipping sector. [Rau17, p. 198] reports similar prices of around 430 EUR2013 per tonne for a global transition. Thus these costs are in the same range. Further, transport costs for Danish shipping in the BAU scenario amount to 3 EUR2016 per tonne cargo. For climate compatible pathways transport costs likely more than double with around 6 to 7 EUR2016 per ton. Compared to [TD15, p. 50], that states average transport costs of around 5 EURO per ton and a greater level of detail, Danish costs seem in an acceptable range, too. Further, [TD15, p. 55] states transport costs in developed countries are equal to 7 % of the cargo's value. For Denmark it would increase to approximately 13 % for any renewable pathway. With regards to GHG emissions, e.g. [Smi+16, p. 9] estimates a peak in 2025 necessary to comply with the Paris agreement. In the present study however, transport demand stays constant and energy efficiency improves, so that carbon emissions constantly decrease. Thus, they should have peaked already. In the Danish case and with a carbon regime towards zero emissions in 2050, GHG emissions would fall drastically from 2027 on-wards.

Finally, as stated in Section 5.4 on page 23, the calculated average 16 PJ fuel consumption for 2015 and 2016 holds high potential of uncertainty, since the underlying energy demand per ship is highly sensitive to its maximum dead-weight capacity [Kri12]. Though, it is believed that a change in fuel consumption would not lead to qualitatively different results.

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CHAPTER 10

Conclusion

Considering the entire spectrum of conducted scenarios, it turns out that fuel compositions from 2016 to 2027 resemble each other. Due to the entry into force of global SOx limits in 2020 old vessels burning IC MDO are scrapped, whilst heavy fuel oil IC HFO ships are being refitted with exhaust gas cleaners (EGC) to utilize their full technical lifetime. After the entire old stock of ships is scrapped around 2027, crucial future maritime fuel technology choices have to be made. It appears, that the fuel technology decision is likely to be based on ship costs in this particular period, rather than on infrastructure or fuel prices. On the basis of the scenario results and according to the systems fuel shares, the following cost hierarchy can be derived: First ships, second fuels and with limited impact third infrastructure. Investing in carbon neutral ships would create a pull effect towards the required fuel infrastructure. Most scenarios show that after the first investment decision no further technology competition is emerging. Economies of scale could reinforce this effect. Only in the course of increasing bio-fuel availability, renewable bio-diesel is added. But not just costs influence investment choices. The methane leakage problem poses a great threat for LNG and LBG to gain market share. If not all up- and downstream leakage is gradually eliminated towards 2050, these fuels can hardly constitute compatible compatible pathways. Moreover, fossil based LNG has even under privileged cost and emission conditions only a limited window of opportunity available. Pursuant to the model calculations, it is at maximum 23 years long, which would be less than its assumed technical ship lifetime. In contrast,

H_2, CH_3OH and NH_3 are most competitive and their respective financial impacts are similar.

In order to take on climate compatible pathways towards a carbon neutral cargo shipping sector - in line with Paris agreements - either a carbon cap and ambitious mandatory reduction targets, or a carbon price ranging from 350 to 450 EUR2016 per ton CO_2e would be necessary. With respect to the model results, this would increase the specific shipping costs per ton by roughly 5 to 7 EUR2016 that corresponds to 6 % of current average freight values. Further, by eliminating GHG emissions the overall tank-to-propeller fuel efficiency could be significantly increased. IMO's commitment to bisect emissions compared to the 2008 level seems unsatisfactory and too conservative to serve the purpose of a thorough maritime system transformation that actually opposes global warming to a fair share. When transport demand declines by 32 % as for the TDV scenario, this reduction is equal to cost savings of 25 % with cumulative 14 % less cargo transported. Hence, cost savings outpace transport reduction, which indicates higher transport cost efficiency.

The year 2027 represents just the average investment period. Old ships are scrapped and new ships build today, which will influence the future systems fuel composition and its capability for a timely change. Therefore, it soon needs adequate frameworks which encourage a climate compatible transformation that leads to a carbon neutral Danish and global shipping sector. Without any political action, this goal will either become very expensive or in the worst case unreachable. So, what this research finally conveys is the fact, that time is rapidly approaching to increase the pressure on the maritime industry. In face of the large investment volumes that would be required, it is rather inappropriate to wait for an intrinsic system transformation.

CHAPTER 11

Further Work

Evidence for improvements and further research was found in the following:

1. Data
   - Deploying AIS data to add accuracy to the data stock.
   - More precise differentiation between different ship types, based on range or transport capacity.
   - Considering design and operational aspects that impact the ships fuel efficiency.
   - Allowing for further refit options, like new sail technologies.
   - Investigation of non-linear effects in the input data, e.g. ship size compared to new-build costs.
2. Modelling
   - Including particular matter to the emission constraints for US ECAs.
   - Allowing for mixed integer programming as ships and infrastructure components have fixed sizes.
   - Applying the model to further countries.
3. Results
   - Conducting a global sensitivity analysis.
   - Comparing the levelized cost of energy per fuel type.
   - Comparing results with production costs of ambient carbon based designer fuels.

APPENDIX A

Appendix

All supplementary material including model source code, data preparation notebooks and plotting scripts are published under the DOI of [Bra18].

For a quick access use the following link, which points directly to the research projects GitHub repository: `https://github.com/futuremarinefuels/denmark`.

Or, contact the author directly: till-sebastian.brahim@studierende.uni-flensburg.de.

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Flensburg, September 17, 2018

T. ben Brahim

Till Sebastian ben Brahim