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Pathways to Climate Neutral Shipping - A Danish Case Study

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Abstract

In this paper, we describe pathways for the Danish maritime cargo sector to CO₂e (equivalent) neutrality in 2050 in compliance with the Paris Agreement. In our model approach, we not only include national greenhouse gas emissions, but also suggest a method to assign greenhouse gas emissions from international shipping to countries. Our modelling results indicate, that either strong regulative carbon budgets or a carbon price of 350–450 €₂₀₁₆/t CO₂e would be necessary to induce the urgent transition. This would double today's average cargo transport costs, but increase average import values only by 6–8 %. Regarding fuel technologies, hydrogen, methanol and ammonia are most compatible from a socio-economic cost perspective. Though, due to high cost uncertainties, there is no clear winner. Liquefied natural gas as an alternative intermediate solution would only have a short window of opportunity, due to methane leakage causing high greenhouse gas emissions as well as high fuel and technology costs. If this gaseous fuel is based on renewable sources it can play a role, but only in case of drastically reduced methane leakage.

Keywords: Maritime transport, Marine fuels, Energy modelling, Emission reduction, International cargo, Shipping emissions

1. Introduction

The ambition to reach climate pathways with limited overshoot of 1.5 °C requires global net zero CO₂e emissions by 2050 [1]. This implies a massive reduction of fossil fuels in the energy system. Several studies based on energy system models have shown possible pathways to net zero emissions for the electricity supply from country to continents and the whole world [2] and also for the heat sector. Although transport is more challenging [3, 4], in recent years an increasing amount of studies also includes pathways for this sector to net zero emissions in 2050. However, the majority of scenarios leaves out a significant

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part of the transport emissions, namely international shipping. Due to its international nature, appropriate governance is challenging [5]. So far, countries leave out international shipping in their energy and climate plans, leaving the responsibility to the International Maritime Organisation (IMO). While – to some extent – progress has been made regarding sulphur emission reduction, their goal of 50% greenhouse gas reduction until 2050 of worldwide shipping [6] is neither ambitious enough to reach the goals of the Paris Agreement, nor underpinned with measures and possible pathway descriptions [7].

While liquefied natural gas (LNG) has mainly been in the focus as a conventional alternative marine fuel [8, 9] due to its advantage regarding sulphur oxide (SO_x), nitrogen oxide (NO_x) and particle emissions (PM), its possibility to also reduce climate impact of shipping has increasingly been questioned [10]. This is on the one hand due to its limited CO_2 emission benefit compared to oil [11]. On the other hand, the implications for greenhouse gases (GHG) depend on how the natural gas is extracted, processed, distributed, and used [12]. According to the International Energy Agency, the average global gas methane leakage rate is 1.7% for natural gas [13], while a recent assessment of methane emissions from the U.S. oil and gas supply chain conclude 2.3% [14]. Looking at a global warming potential over a 20-year time frame, a leakage rate of 3-4 % would already use up the climate benefit of natural gas compared to coal, over a 100-year time frame it is 6-7 %. Hagos and Ahlgren [15] state that a 1 % methane slip from a dedicated LNG passenger vessel results, on average, in 8.5 % increase in net GHG emissions. According to measurements and calculations based on [16, 17], methane slip of dual-fuel engines amounted to roughly 4 % and dedicated gas engines to 2.3 % in 2016. Although LNG-specialised engines with high pressure direct injection could lower leakage rates even further, ship owners today prefer dual-fuel engines as they judge flexibility and the resale value of the ship more important than efficiency gains because climate impact is not reflected in any economic value for shipping. In summary, the climate impact of both, LNG and methanol produced from natural gas is assessed to have the same order of magnitude as heavy fuel oil [18, 19].

Independent of the role of LNG, one can generally conclude, that the current concentration on reduction of SO_x , NO_x and PM in shipping is too short-sighted [20], since climate emissions from shipping are the bigger challenge [21]. More radical changes avoiding infrastructure lock-ins and exploring co-benefits of sulphur and carbon reduction are advisable. In line with that, the discussion about climate and other emission compatible future marine fuels has gained momentum in recent years. Indirect electrification via hydrogen or other synthetic fuels could be a promising option [22]. Their potential can be significant if relying on de-carbonised inputs while the potential of bio-derived fuels are strongly related to their respective scarcity [20]. Also wind-energy in form of soft-sails, fixed-sails, Flettner Rotors or kite sails are options being tested [23].

Another important aspect of reducing emissions additionally to fuel switch is energy efficiency, whose potential has not been completely exploited yet [24, 25] and could be further improved applying e.g. waste heat recovery to a greater extent [26]. Furthermore, operational measures like slow steaming [27], hull

design and larger vessels [28] can provide significant contributions to lowering emissions in shipping. However, as Olmer et al. [29] show, shipping will need to move beyond energy efficiency interventions alone to achieve absolute emission reductions.

Calculating different pathways until 2050, a study from Lloyd’s Register [30] comes to the conclusion, that different options are possible, mostly depending on the availability of biomass, the development of transport demand and technology learning, but independent of the pathway, all require a substitute for fossil fuel since operational measures are not sufficient. A meta-study looking at measures and fuels of various studies [31] suggests that a 75% emission reduction is possible until 2050, but only with a combination of various measures. Looking at possible reduction targets, Smith et al. [32] describe the pathway to zero emissions in 2035 in their most ambitious scenario. An initiative from the shipping industry itself is striving for zero emission vessels [33], also worked on by Lloyd’s Register [34]. Additionally to studies taking the general and national perspective, there is ongoing research about specific applications, like e.g. batteries in offshore support vessels [35], specific fuel options, like e.g. slow steaming and wind propulsion [36] or specific areas like emission reduction in port [37].

Looking at the regulative side, Shi [38] suggests a scheme of market-based measures that can be adopted by means of an international convention under the auspices of the International Maritime Organisation (IMO) and the UN-FCCC. This could be a global emission trading scheme including shipping and aviation [39], while Gritsenko [5] suggests polycentric governance. Although the technical, economical and regulative options for shipping to take its share in the climate responsibility have risen, regarding its importance and urgency, it is still under-represented in current discussions and studies assessing energy transformation. Its importance is due to (1) the general efficiency of shipping compared to other means of transport, (2) its large share in worldwide transported goods and (3) the wide range of GHG emission predictions. According to the upper bound of predictions, future maritime transport emissions would increase by 250% in 2050 [40]. However, other predictions actually assume a decrease in transport demand due to less fossil fuel transported, as well as increased circular economy and effects from 3D-printing [41].

The urgency is due to mainly three reasons: (1) Very long investment cycles of ships. This leads to the situation, that decisions about the fuels to reach net zero emissions in 2050 are just around the corner. (2) Infrastructure requirements being essential and requiring long planning horizons and (3) the increasing interdependence between fuels applied in shipping and our land-based energy systems (electricity, heat, fuels for transport). Developments in shipping fuels will affect decisions on energy infrastructure on land and vice versa. Examples are future refineries providing fuels for shipping and land-based heavy transport, producing excess heat during the fuel production. Thus, options have to be intensively looked at and also optimised in combination with the rest of the energy system.

This paper contributes to fill the research gap between studies on inland

shipping with a high level of detail but limited scope on the one side and international shipping in low resolution regarding technology and fuels on the other side. Our modelling approach takes emissions from international shipping into account but can still be applied to single or several countries. It could thus be integrated in national energy and climate modelling scopes. Although we exemplify model Danish shipping, the methodology can be applied to other countries as well. Unlike most other studies, data and model not only include costs for fuels and technologies but also infrastructure costs. Emission-wise, the whole picture is covered by taking well-to-propeller climate emissions including methane leakage into account while complying with current and future SO_x and NO_x emission restrictions. In this holistic approach, today's and possible future fuels and technologies are evaluated by an optimisation model, minimising total system costs while reaching net zero GHG emissions in 2050. Due to high uncertainty regarding cost development, we perform a threshold analysis providing an overview of fuel-technology combinations likely to play a role in the future.

In section 2, we describe the model scope (subsection 2.1), structure (subsection 2.2), the mathematical formulation (subsection 2.3), data sources and processing (subsection 2.4) and explain our scenario approach (subsection 2.5). The underlying data collection, model and scenario development is based on and further described in [42]. Subsequently, we present the scenario and threshold analysis results and discuss their relevance, also describing strengths and weaknesses of the model approach (section 3) and finally draw conclusions (section 4).

2. Materials and Methods

2.1. Model Scope

The framework developed for this study minimises total system costs in compliance with constraints like emission restrictions. It can be applied to illustrate potential pathways of maritime transport in annual resolution. Costs include fuel, ship and infrastructure costs and are seen from a socio-economic perspective, excluding externalities. Since it is combined with a stock model of existing ships and infrastructure, components at the end of their lifetime are replaced by new endogenous model investments. At its current status, the model framework distinguishes ship-technology combinations by their main engine and fuel type. Operational patterns like varying speed or ship design like hull-shapes are not considered. Regarding emissions, SO_x , NO_x , CO_2 and methane (CH_4) limitations can be set.

In our model application, the temporal scope is chosen until 2050 since this is the target year for reaching net zero emissions in compliance with the Paris Agreement. To be able to include Danish national and international cargo, we developed an approach for distributing international shipping to countries as illustrated in Figure 1. The route and thus fuel usage and associated emissions of each trip from or to a Danish port and half of the international trips are

assigned to Danish shipping. Regarding SO_X and NO_X emissions, regional and global legal restrictions defined in Marpol Annex VI regulations 13 and 14 [43, 44] are applied. GHG emissions are summarised as CO_2e , including CO_2 and CH_4 . Inline with the IPCC [45], we assume that the radiative forcing over a 100-year time horizon for CH_4 compared to CO_2 is 25 times higher. This can be seen as the lower bound for global warming potential of CH_4 since this factor has been increased in more recent reports.

The overall remaining GHG emission budget is derived from the IPCC's RCP2.6 scenario [46, p. 27], which is further explained in subsubsection 2.4.3. Table B.4 illustrates the combination of technologies and fuels that are available in our model application striving for GHG emission free Danish shipping in 2050.

Figure 1: Model boundary: The model considers the specifications inside the green box. Figure taken from [42]

2.2. Model Structure

While the core components of the model are the equations describing the objective equation and constraints of the optimisation, pre-processing of the input and post-processing of the output data also constitute an important part of the modelling framework. Figure 2 illustrates the model flow with white boxes representing data instances and blue arrows representing processes. These scripts are written in Python with the pre-processing applying the data package *panda*, the optimisation utilising the optimisation package *pyomo* and the output processing additionally to *pandas* *matplotlib* for illustrating the results in plots. All scripts, raw and processed data including documentation are available on GitHub [47], where further development of the model takes place. To allow for barrier-free reproducibility of the presented results, the entire deployed software is open-source and the version of data and code deployed for this research is available at [48]. Both are published under the GNU general public license version 3.

2.3. Mathematical Formulation

The problem is formulated in a linear, non-integer manner, aiming to minimise the objective equation. Model variables in the first time step are initialised

Figure 2: Model boxflow: The core model consists of the components inside the green box. (NB: Notebook; GLPK: GNU Linear Programming Kit)

with data compiled for the current shipping fleet. For the following time steps, different constraints trigger the necessary investment decisions for new technologies and lead to decommissioning of existing ships that are not in compliance with legal obligations or emission targets. Since the objective is to minimise total system costs (Equation 1a), investments are interpreted as conflicting, yet inevitable actions to cope with the constraints, such as lowering emissions to air (Appendix A.0.5) and supplying the transport demand in each time step (Appendix A.0.4). All model variable domains are within non-negative real numbers, including zero (R_0^+). The nomenclature of sets, variables and parameters used in the equations can be found in the nomenclature list (Appendix A.0.1). Below, subsection 2.3.1 illustrates exemplarily the formulation of the objective equation. The entire mathematical formulation is described in Appendix A.

2.3.1. Objective equation

The objective equation (obj. eq.) minimises total system expenditures over all time steps and ship types (aggregated by main engine and fuel). It comprises the sum of costs for fuel consumption, additional infrastructure as well as ship capacity for all years (35 time steps in the described application). Costs for fixed assets – fuel infrastructure (CI) and ships (CS) – are given as annuities and account only with the annual added capacities. The value of the existing amount in the start year ($finit_{t,s}$ in T_0) is not included in CI and CS .

$$\min. \sum_{\forall t \in T} \sum_{\forall s \in S} (CF_{t,s} + CI_{t,s} + CS_{t,s}) \quad (1a)$$

subject to (s.t.)

$$CF_{t,s} \geq f_{t,s} \cdot cf_{t,s} \quad (1b)$$

$$CI_{t,s} \geq (iup_{t,s} - finit_{t,s}) \cdot li_s \cdot ci_{t,s}, \forall t \in T_0 \quad (1c)$$

$$CI_{t,s} \geq iup_{t,s} \cdot li_s \cdot ci_{t,s}, \forall t \in T_{>0} \quad (1d)$$

$$CS_{t,s} \geq (sup_{t,s} - finit_{t,s}) \cdot ls_s \cdot cs_{t,s}, \forall t \in T_0 \quad (1e)$$

$$CS_{t,s} \geq sup_{t,s} \cdot ls_s \cdot cs_{t,s}, \forall t \in T_{>0} \quad (1f)$$

Nomenclature – Obj. eq.	
$CF_{t,s}$ Fuel costs for t and s , [€ ₂₀₁₆]	$cs_{t,s}$ Ship costs (specific) for t and s , [$\frac{€_{2016}}{MJ_{fuel} \cdot a}$]
$CI_{t,s}$ Infrastructure costs for t and s , [€ ₂₀₁₆]	$f_{t,s}$ Fuel amount for t and s , [MJ]
$CS_{t,s}$ Ship costs for t and s , [€ ₂₀₁₆]	$fin_{t,s}$ Initial fuel amount for t and s , [MJ]
S All ships	$iup_{t,s}$ Added infrastructure capacity for t and s , [MJ]
$\mathcal{T}$ All time steps (years)	$li_{t,s}$ Infrastructure lifetime for t and s , [a]
$ci_{t,s}$ Infrastructure costs (specific) for t and s , [$\frac{€_{2016}}{MJ_{fuel} \cdot a}$]	$ls_{t,s}$ Ship lifetime for t and s , [a]
	$sup_{t,s}$ Added ship capacity for t and s , [MJ]

2.4. Data

Main input data for the model are fuel and ship type specifications for the initial set of the start year as well as future options for ship-technology combinations. For fuel data, the unique identifier is the fuel type, for ship data it is the ship type. Ship types can use the same fuel, but different engine types like internal combustion (IC), fuel cell (FC), electric motor (EM).

2.4.1. Fuel data

The fuel parameters (Table B.3) include CO₂ and CH₄ emission factors from well-to-tank (w2t), sulphur content as well as cost parameters. Costs are specified for fuel and infrastructure and along with that, the respective lifetime. For fuels that are currently applied on a large scale – heavy fuel oil (HFO), marine diesel oil (MDO), bio-diesel oil (BDO) – the bunker index prices are used. It is assumed that these include all cost components from well to tank including fixed costs for a sufficient supply infrastructure. Thus, for these, infrastructure and fuel costs are not further specified. In contrast, new fuel technology costs are divided into fixed and variable components, since sufficient supply infrastructure has not been installed yet. If fuel upgrading is required, it is assumed to be done at berth to avoid additional grid investments. In the case of Denmark, the gas grid could handle any conceivable amount of natural gas and transport of upgraded biogas.

2.4.2. Ship and technology data

Ship type input parameters (Table B.4) include emission factors, compliance with sulphur and NO_x regulation, lifetime, options for refit, costs, transport supply as well as application options regarding range. The amounts of fuels used today are additionally provided in the tables since these are applied as the starting point in the modelling, while future amounts are determined endogenously by the model.

The emission factors for CO_2 and CH_4 only include the tank-to-propeller emissions, since the upstream emissions are already covered by the fuel parameters. Regarding sulphur and NO_x compliance, Tier rating defines if a ship complies with IMO NO_x regulations and can thus be operated in a NECA. Old ships in the model do not have sufficient TIER rating and thus either have to be scrapped or refitted when the regulation enters into force in 2021. New built ships are generally assumed to have a TIER 3 rating. Scrubber installations for sulphur are defined for each ship type.

The average remaining lifetime for existing ships is 11 years since the average age of the current fleet is 14 years, when considering bulk, container and tanker ship types which dominate the Danish cargo fleet [49, Tab. 2.2, p. 27]. Retrofitting an old ship to comply with new regulation can possibly be an option to reduce costs. A typical refit currently ongoing to comply with sulphur regulations is the installation of a scrubber for ships with internal combustion engines running on HFO. It has to be mentioned that this results in a reduction of specific transport per fuel due to efficiency losses caused by the scrubber. Ships with internal combustion engine using HFO can also be refitted for the use of BDO, which is relatively straightforward and thus does not imply much costs. These kind of refits do not extend the lifetime of the ship or technology, but just provide different functionality.

Regarding the range options, only full electric ships are restricted to radius of 500 nautical miles, equivalent to 926 km (derived from [50]), all other have an unlimited range.

2.4.3. Emission budget

The remaining emission budget of CO_2e for the temporal scope of the model is a decisive constraint in the calculation. Since there are no agreed or standardised ways of attributing GHG emissions from international shipping to countries, we have devised a method for distributing global shipping emissions and the respective remaining carbon budget to countries 2.1). We apply a global emission budget estimate by the IPCC [46, Tab. SPM.3, RCP2.6] and derive the shipping's budget by its annual estimated global GHG emission share from Olmer et al. [29].

The comparison of global maritime CO_2e emissions in 2012 with the Danish emissions in 2016 and its application to the global maritime budget leads to the Danish GHG budget (Table 1). The absolute level of Danish cargo shipping emissions of 1.2 Mt CO_2e in 2016 is derived from the fuel specific emission operation factors, multiplied by total fuel consumed in that year. The relation of global maritime emissions in 2012 with the Danish ones in 2016 leads to a

rather over-estimated Danish budget since the global transport demand was increasing in that period [49, Tab. 3, p. 5]. Keeping the resulting emission level constant would deplete the budgets within the next 15 years and allows for less GHG emissions compared to a linear decrease from today until 2050.

	Unit	CO ₂ emissions	References
Global budget	[Mt]	510000	[46]
Global maritime budget share	[%]	3	[29]
Global maritime budget	[MT]	15300	
Global maritime emissions in 2012	[Mt]	961	[51]
Danish maritime emissions in 2016	[Mt]	1.2	[52, 53, 54]
Danish maritime emission share	[%]	0.125	
Danish budget	[Mt]	19.12	

Table 1: Derivation of CO₂e emission budget from global to Danish level.

2.5. Scenarios

In general, all scenarios except the business as usual (BAU) and IMO-scenario are modifications of the reference scenario’s input parameters. The reference scenario and its modifications all comply with the carbon budget restriction. In the variations, one or a cluster of parameters are changed in a ceteris paribus manner and by the same percentage. If appropriate, changing rates are clustered due to market coupling effects. For example, electro-fuel cost parameter are all changed in the same way in the respective variation scenarios, as they all depend primarily on electricity. Additionally, the transport demand variation (TDV) scenario illustrates the possible effects of a decreasing transport demand by 30% until 2050 – else it is kept constant.

2.5.1. Scenario data

The development of cost and other parameters is decisive for the model results. To make the assumptions behind that transparent, the variations are expressed as percentage change rates from 2016 to 2050 (Table B.5). Derived from that number, equal annual changing rates are applied. Table B.5 shows the parameter changes and thus future development of the reference scenario.

Other decisive parameters are bio-fuel availability and transport demand. Bio-fuel availability increases from 0 % in 2016 to 40 % in 2050 in relation to the total fuel consumption in 2016 [55]. The transport demand stays constant based on [41, p. 18] and [56, p. 19].

2.5.2. Scenario overview

Table 2 provides an overview of the fourteen scenario variations and the respective modified parameters. The extent to which the respective scenario parameters are modified is stated alongside the results in section 3.

Scenario	Description	Modified parameters
REF	Reference scenario, based on literature	-
REF(mp)	Reference scenario + methane leakage phaseout	em
BAU	Business as usual	eb, et
IMO	International Maritime Organization	eb, et
TDV	Transport demand variation	tdtotal
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 2: Scenario overview with description and modified parameters. For additional information about scenarios see [42]. (cf: fuel costs; ci: infrastructure costs; cs: ship costs; eb: emission budget; em: CH₄ emissions; et: emission target; tdtotal: total transport demand)

3. Results and Discussion

In the business as usual scenario (BAU) no GHG regime is in place. Although SO_x- and NO_x-restrictions are applied, no major change in fuel usage can be detected. Figure C.9 displays BAU’s fuel consumption and cumulative CO_{2e} emissions. It shows, that scrubbers instead of fuel switch are the most cost-efficient solution if no GHG restrictions are implemented. Applying the IMO goal to halve climate emissions of shipping in 2050 does not lead to significant changes except a minor switch to BDO instead of HFO (Figure 3). In comparison, the climate emission budget restriction in the reference scenario results in a significant fuel switch: Mainly hydrogen in fuel cells and BDO with scrubber in internal combustion engines are chosen (Figure 4). The comparison shows, that without any kind of climate emission restriction, the total cumulative emissions are twice as high and the IMO plans do not have a significant impact.

Due to the high level of uncertainty of cost development of infrastructure, fuel and propulsion technology of different marine fuel options, we apply a wide range of cost variations to test for its effect on fuel composition. The results are summarised in Figure C.10. Depending on the cost rate change of a specific fuel technology (x-axis), while keeping all other parameters constant, its share in the total fuel consumption from 2016-2050 (y-axis) changes significantly. The black dashed line at a cost rate change of zero represents the reference scenario. Already at a -10% cost change rate (including fuel, ship and infrastructure costs), methanol and ammonia respectively gain relevance, reaching a dominant role at a -20% cost change rate. Thus if the costs of either methanol or ammonia drop by -20%, these would take over the role of hydrogen as the main renewable fuel of the future. These scenario variations are illustrated in Figure 5 and Figure 6.

Figure 3: Fuel consumption (y-axis left) and cumulative emissions (y-axis right) in the IMO scenario, applying the climate emission target of the International Maritime Organisation for 2050.

Figure 4: Fuel consumption (y-axis left) and cumulative emissions (y-axis right) in the reference scenario with a limited carbon budget.

Figure 5: Fuel consumption (y-axis left) and cumulative emissions (y-axis right) in the ammonia scenario (NH₃, r-20) with a limited carbon budget.

Figure 6: Fuel consumption (y-axis left) and cumulative emissions (y-axis right) in the methanol scenario (CH₃OH, r-20) with a limited carbon budget.

For LBG, the development of the methane leakage problem is of outstanding importance. Under the assumption that methane leakage can be coped with until 2050 (dashed line in (Figure C.10) and a cost reduction of -40% (Figure C.11), LBG is close to hydrogen, methanol and ammonia as choice to be the dominate fuel in 2050. Contrary to that, LNG would not only require a methane leakage phase out, but also a very favourable cost development to play a major role.

Sailing cargo ships, driven by a combination of wind and electricity from batteries seem to only be cost efficient in case of a very strong drop in costs. However, the influence factors have more dimensions than just the pure battery and ship costs. In this model, it is assumed that one third of the propulsion of wind driven ships is still done by electricity. For long distance cargo, that mainly has to use the engine for manoeuvring into and out of the harbour, the wind share and potentially additional solar input can be significantly increased and thus the required battery and electricity costs reduced. Thus the conditions in our model application are rather unfavourable for wind propulsion.

For comparison, the total fuel use of all scenarios for 2016-2050 is displayed in Figure 7 and the fuel composition in the target year 2050 in Figure 8. A general efficiency increase can be seen for all carbon budget scenarios. Due to higher operational tank-to-propeller efficiency and thus a higher Tkm/GJ fuel - rate, less fuel is applied in the carbon budget scenarios. Except in the transport demand scenario all supply the same transport demand.

Figure 7: Total fuel use from 2016-2050

Figure 8: Fuel composition in 2050

Derived from the cost differences for fuel, ship and infrastructure, a carbon price in the range of 350–450 €/2016/ton CO₂e would be required for a renewable transition of the Danish shipping sector. There are no directly comparable

studies, but, to put our results in perspective, Raucci [57, p.197] reports similar prices of around 430 \$/ton CO₂ for a global transition with a global shipping carbon budget double as high as in our case. In that setting, he concludes, that hydrogen requires an emission price of 1400 \$/ton CO₂ to become an economic option. In contrast, a global study on country- and sector-wise CO₂ abatement costs [58] represent the lower range: Although shipping is not included, road transport is indicated with about 200 €/ton CO₂. Specific costs for climate emission abatement costs in shipping can be expected to be higher than that, since shipping poses special challenges due to high range requirements. More specifically on CO₂ abatement costs for shipping, Chryssakis et al. [59], assumes costs in the range of 150–200 €/avoided ton CO₂ if using LBG, methanol based on renewables or BDO.

The model code and most of the data references and pre-processing can also be applied for other countries, especially Europe. However, since shipping has a global perspective, the case study for Denmark already gives a good indication of the fuel shares chosen for a cost-optimal path to carbon neutrality in 2050 for the worldwide shipping. Conditions for shipping are similar, the basic parameters, technology, fuel and infrastructure costs are considered as world prices rather than reflecting local particularities.

Compared to other sectors like electricity and heat, these mitigation costs per ton CO₂e seem high, but one has to consider several points. First, our results can be interpreted as the upper bound of cost: Technologies considered are all applicable today, developments in other sectors applying similar technology options could further decrease costs and additional alternatives could evolve. Second, as shown in the demand reduction scenarios, any decrease in transport demand would save costs even beyond the proportional saving. This is due to not only fuel savings (proportional) but, also due to avoided investments in new ships (disproportionate). A decrease in transport demand especially has an effect in the period, in which new investments in ships are required and can thus avoid costs over-proportionally. And third, refits and hybrid solutions have not been considered to a great extent in the model functionality and could further decrease costs and ease the shift to different fuels.

Transport costs in the BAU scenario amount to roughly 3 €₂₀₁₆/ton cargo. For climate compatible pathways they are likely to more than double. With UNCTAD [60, p. 50] reporting average transport costs of around 5 €/ton and including more detail, our results seem to be acceptably precise. Further, [60, p. 55] states that transport costs in developed countries are equal to 7 % of the cargo’s import value. Under the assumption of an equal share in BAU, cargo import values for the climate compatible pathways would increase by 6 – 8 %.

Thus, costs could get lower for the transition, but the question is also whether to talk about mitigation costs. Co-benefits like reduced air pollution have not been quantified on a monetary basis in the model and were thus not part of the optimisation. However, these could have essential health benefits, maybe even reaching mitigation gains instead of mitigation costs.

The necessary transition will not happen under current market conditions. Regulation is required urgently to bring shipping on the pathway to carbon neu-

trality in 2050, in line with the Paris Agreement. A carbon budget for shipping worldwide, broken down to countries is a viable option to consider. Additionally, more research for alternative fuels and technologies, as well as solving crucial questions on security, infrastructure and methane leakage issues are important contributions to implement the transition to climate neutral shipping in 2050.

4. Conclusion

The achievement of CO₂e-neutrality in the shipping sector is of great importance for reaching the targets of the Paris Agreement. Although this goal is underrepresented in the current discussion, this study shows, that it is possible for the Danish part of international shipping to become CO₂e-neutral until 2050 with existing technologies. Regarding fuels, hydrogen, methanol and ammonia are from a socio-economic cost perspective the most compatible. Due to high uncertainties regarding future cost developments and safety requirements (esp. ammonia), there is no clear winner. Regarding technologies, fuel cells are chosen for these fuel options, the decisive parameter being the higher fuel efficiency. Although LNG is the fuel option most prominently discussed as an alternative today, it would only have a short window of opportunity, mainly because of leakage problems of methane causing high GHG emissions, and high fuel and technology costs. If this gaseous fuel is based on renewable sources, the so-called LBG can only play a role if methane leakage can be drastically reduced until 2050. The option of cargo-ships driven by a mixture of wind and electricity stored in batteries could not adequately be represented in the model setting. The evaluation of their role would need a further refinement of the calculations. The model itself has shown to be a valid tool for assessing pathways for shipping under emission restriction obligations and for assessing the threshold of different fuel options. Although the has been applied to Danish international shipping, it already gives a good indication of potential fuel shares for worldwide shipping.

The presented modelling approach indicates that either strong regulative carbon budgets or a carbon price of 350–450 €/t CO₂e would be required to induce the necessary changes for a carbon neutral Danish shipping in 2050. This would double today’s average cargo transport costs. However, due to the low share of transport cost on the value of transported goods, the average transported good would only increase by 6 – 8 %. This can be considered as the upper limit, since new fuel possibilities not reflected in this study might evolve.

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Appendix A. Equations

Appendix A.0.1. Nomenclature

Abbreviations	Parameters
ECA Emission control area	ba_t Bio-fuel availability for t , [% ₂₀₁₆]
ECAN Nitrogen emission control area	$cft_{t,s}$ Fuel costs (specific) for t and s , $\left[\frac{\text{€}_{2016}}{MJ_{fuel} \cdot a}\right]$
ECAS Sulphur emission control area	$cft_{t,s}$ Fuel costs (specific) for t and s , $\left[\frac{\text{€}_{2016}}{MJ_{fuel} \cdot a}\right]$
Sets	$cit_{t,s}$ Infrastructure costs (specific) for t and s , $\left[\frac{\text{€}_{2016}}{MJ_{fuel} \cdot a}\right]$
SB Ships burning bio-fuel	$cst_{t,s}$ Ship costs (specific) for t and s , $\left[\frac{\text{€}_{2016}}{MJ_{fuel} \cdot a}\right]$
SN$\mathcal{G}$S Ships not global-SECAs compliant	$dnoneca_t$ Transport demand outside ECAs for t , [Ttkm]
SN$\mathcal{N}$ Ships not NECAs compliant	$dshort_t$ Transport demand on short range for t , [Ttkm]
SN$\mathcal{S}$ Ship not SECAs compliant	$dtotal_t$ Total transport demand for t , [Ttkm]
SR$\mathcal{O}$(s) Refit option per ship type s	eb Emission budget (absolut), [gCO _{2e}]
SS$\mathcal{R}$ Ships for short range	$ect_{t,s}$ CO ₂ emissions (specific) for t and s , $\left[\frac{gCO_2e}{MJ_{fuel}}\right]$
S All ships	$emt_{t,s}$ CH ₄ emissions (specific) for t and s , $\left[\frac{gCO_2e}{MJ_{fuel}}\right]$
T All time steps (years)	et Emission target (relative to start year), $\left[\frac{gCO_2e_{et}}{gCO_2e_{T_0}}\right]$
Variables	$lit_{t,s}$ Infrastructure lifetime for t and s , [a]
$CF_{t,s}$ Fuel costs for t and s , [€ ₂₀₁₆]	$lst_{t,s}$ Ship lifetime for t and s , [a]
$CI_{t,s}$ Infrastructure costs for t and s , [€ ₂₀₁₆]	$stst_{t,s}$ Transport supply for t and s , $\left[\frac{Ttkm}{MJ_{fuel}}\right]$
$CS_{t,s}$ Ship costs for t and s , [€ ₂₀₁₆]	$teca$ Inception year of global ECA, [a]
$EC_{t,s}$ CO ₂ emissions for t and s , [gCO _{2e}]	tet Emission target year, [a]
$EM_{t,s}$ CH ₄ emissions for t and s , [gCO _{2e}]	$tneca$ Inception year of NECAs, [a]
$f_{t,s}$ Fuel amount for t and s , [MJ]	
$finit_{t,s}$ Initial fuel amount for t and s , [MJ]	
$icap_{t,s}$ Infrastructure capacity for t and s , [MJ]	
$iupt_{t,s}$ Added infrastructure capacity for t and s , [MJ]	
$scapt_{t,s}$ Ship capacity for t and s , [MJ]	
$supt_{t,s}$ Added ship capacity for t and s , [MJ]	

Nomenclature list.

Appendix A.0.2. Objective equation

The objective equation minimises total system expenditures over all time steps and ship types (aggregated by main engine and fuel). It comprises the sum of costs for fuel consumption, additional infrastructure as well as ship capacity for all years (35 time steps in the described application). Costs for fixed assets – fuel infrastructure (CI) and ships (CS) – are given as annuities and account only with the annual added capacities. The value of the existing amount in the

start year ($finit_{t,s}$ in T_0) is not included in CI and CS .

$$\min. \sum_{\forall t \in T} \sum_{\forall s \in S} (CF_{t,s} + CI_{t,s} + CS_{t,s}) \quad (\text{A.1a})$$

subject to (s.t.)

$$CF_{t,s} \geq f_{t,s} \cdot cf_{t,s} \quad (\text{A.1b})$$

$$CI_{t,s} \geq (iup_{t,s} - finit_{t,s}) \cdot li_s \cdot ci_{t,s}, \forall t \in T_0 \quad (\text{A.1c})$$

$$CI_{t,s} \geq iup_{t,s} \cdot li_s \cdot ci_{t,s}, \forall t \in T_{>0} \quad (\text{A.1d})$$

$$CS_{t,s} \geq (sup_{t,s} - finit_{t,s}) \cdot ls_s \cdot cs_{t,s}, \forall t \in T_0 \quad (\text{A.1e})$$

$$CS_{t,s} \geq sup_{t,s} \cdot ls_s \cdot cs_{t,s}, \forall t \in T_{>0} \quad (\text{A.1f})$$

Appendix A.0.3. Constraints on fuel utilisation, infrastructure and ship capacity

Fuel constraints may apply for a selection of ship types and years in the model (Equation A.7). With regard to infrastructure and ships, only the incremental capacity is cost effective while taking into account expiry dates of existing capacities. The expiry dates relate to the technical lifetimes, which differ between ships and infrastructure of same type.

Infrastructure capacity: Defined as the sum of all additional fuel infrastructure built during the elapsed technical lifetime.

$$icap_{t,s} \leq \sum_{\mathbf{x}}^{t-1} (iup_{x,s}), \forall t \in T_{>0}, \forall s \in S \quad (\text{A.2a})$$

s.t.

$$x = T_0, \forall t \leq (li_s + T_0 - 1) \quad (\text{A.2b})$$

$$x = t - li_s + 1, \forall t > (li_s + T_0 - 1) \quad (\text{A.2c})$$

Additional infrastructure: Additional fuel infrastructure in order to supply the fleet.

$$iup_{t,s} \geq f_{t,s} - icap_{t,s}, \forall t \in T_{>0}, \forall s \in S \quad (\text{A.3})$$

Existing ships: Defined as the sum of all additional shipping capacity build during the elapsed technical lifetime.

$$scap_{t,s} \leq \sum_{\mathbf{x}}^{t-1} (sup_{x,s}), \forall t \in T_{>0}, \forall s \in S \quad (\text{A.4a})$$

s.t.

$$x = T_0, \forall t \leq (ls_s + T_0 - 1) \quad (\text{A.4b})$$

$$x = t - ls_s + 1, \forall t > (ls_s + T_0 - 1) \quad (\text{A.4c})$$

Additional ships: Additional ships in order to supply the cargo transport demand.

$$sup_{t,s} \geq f_{t,s} - scap_{t,s}, \forall t \in T_{>0}, \forall s \in S \quad (A.5)$$

Refit capacity: Defines for each year the old ships' capacity possible to refit.

$$f_{t,s} + f_{t,r} - f_{T_0,s} \leq 0, \forall t \in T_{<(T_0+ls_s)}, \forall s, r \in SRO \quad (A.6a)$$

$$f_{t,s} + f_{t,r} = 0, \forall t \in T_{\geq(T_0+ls_s)}, \forall s, r \in SRO \quad (A.6b)$$

Bio-fuel capacity: Defines for each year the upper limit of bio-fuel available – based on own assumptions.

$$\sum_{\forall s \in SB} (f_{t,s}) - ba_t \cdot finit_{T_0} \leq 0, \forall t \in T \quad (A.7)$$

Appendix A.0.4. Constraints on transport demand

Transport demand constraints may apply for a selection of ship types and years in the model, depending on the range category – either short or long – and the emission regulations – in- or outside emission control areas (ECA).

Total transport demand: Defines for each year that the total transport supply by all ships must be greater or equal to the total transport demand.

$$dtotal_t \leq \sum_{\forall s \in S} (f_{t,s} \cdot sts_{t,s}), \forall t \in T \quad (A.8)$$

Short transport demand: Defines for each year the maximum transport supply of all ships categorised as short range (926 km).

$$dshort_t \geq \sum_{\forall s \in SSR} (f_{t,s} \cdot sts_{t,s}), \forall t \in T \quad (A.9)$$

Non-ECAS transport demand: Defines for each year the maximum transport supply of all ships only allowed for operation outside of the ECAs.

$$dnoneca_t \geq \sum_{\forall s \in SNS} (f_{t,s} \cdot sts_{t,s}), \forall t \in T \quad (A.10)$$

Appendix A.0.5. Constraints on emissions

Emission constraints may apply for a selection of ship types and years in the model. The constraint set imposes limitations to the deployment of certain fuel types in the model based on the defined CO_{2e} budget and target as well as the legal restrictions for SO_X and NO_X as defined by the IMO.

Emission budget: Defines the maximal amount of accumulated total GHG emissions.

$$eb \geq \sum_{\forall t \in T} \sum_{\forall s \in S} (EC_{t,s} + EM_{t,s}) \quad (\text{A.11a})$$

s.t.

$$EC_{t,s} = f_{t,s} \cdot ec_{t,s}, \forall t \in T, \forall s \in S \quad (\text{A.11b})$$

$$EM_{t,s} = f_{t,s} \cdot em_{t,s}, \forall t \in T, \forall s \in S \quad (\text{A.11c})$$

Emission target: Defines the amount of GHG emissions allowed in the target year, based on a percentage reduction from the start year.

$$\frac{\sum_{\forall s \in S} (EC_{T_0,s} + EM_{T_0,s})}{\sum_{\forall s \in S} (EC_{t,s} + EM_{t,s})} \cdot et \geq 1, \forall t \in T_{\geq (tet-T_0)} \quad (\text{A.12})$$

Global SO_X regulations: Defines the set of ships as of 2020 prohibited to operate globally with respect to global SO_X regulations.

$$f_{t,s} = 0, \forall t \in T_{\geq teca-T_0}, \forall s \in SNGS \quad (\text{A.13})$$

NO_X regulations: Defines the set of ships as of 2021 prohibited to operate within ECAN.

$$f_{t,s} = 0, \forall t \in T_{\geq tneca-T_0}, \forall s \in SNN \quad (\text{A.14})$$

Appendix B. Tables

Fuel type	cf $\left[\frac{EUR_{2016}}{GJ_{fuel}}\right]$	ci $\left[\frac{EUR_{2016}}{GJ_{fuel}}\right]$	cf + ci $\left[\frac{EUR_{2016}}{GJ_{fuel}}\right]$	ec(w2t) $\left[\frac{gCO_2}{MJ_{fuel}}\right]$	em(w2t) $\left[\frac{gCH_4}{MJ_{fuel}}\right]$	sulphur content [% _{mass}]	li [a]	References
HFO	-	-	6.547	8.148	0.090	2.9525	40	[61, 62, 63, 18]
MDO	-	-	12.775	7.728	0.090	0.7500	40	[61, 62, 63, 64]
BDO	-	-	24.240	0	0.030	0.1498	40	[33, 63]
LNG	4.888	0.139	-	6.600	0.033	0.0500	36	[65, 62, 18, 64]
LBG	27.847	1.599	-	0	0.130	0.0750	25	[66, 63]
H2	20.885	1.199	-	0	0	0	25	[66]
CH3OH	29.240	1.679	-	0	0.042	0.0912	25	[66, 18]
NH3	26.803	1.802	-	0	0	0	20	[67]
ELEC	13.889	2.929	-	0	0	0	20	[68]

Table B.3: Fuel type data for each parameter (for abbreviations see the nomenclature list in appendix Appendix A.0.1). Further explanation of data can be found in [42].

Ship-type	Range	ls [a]	fa ₂₀₁₆ [PJ _{fuel}]	ts $\left[\frac{Tkm}{GJ_{fuel}}\right]$	cs $\left[\frac{EUR_{2016}}{GJ_{fuel}}\right]$	ec(t2p) $\left[\frac{gCO_2}{MJ_{fuel}}\right]$	em(t2p) $\left[\frac{gCH_4}{MJ_{fuel}}\right]$	Refit	Refit opt.	Tier	Scrubber	References
IC HFO (old)	long	11	9.93	9.69	8.72	76.06	0.00045	yes	IC HFO (refit)	0	no	[49, 53, 54, 52, 56]
IC MDO (old)	long	11	5.99	9.40	8.45	74.36	0.00045	yes	IC BDO (refit)	0	yes	[49, 53, 54, 52, 56]
IC HFO	long	25	0	9.40	8.45	75.90	0.00045	no	-	3	yes	[49, 52, 56]
IC MDO	long	25	0	9.40	8.45	74.32	0.00045	no	-	3	yes	[49, 52, 56]
IC HFO (refit)	long	11	0	9.40	0.02	75.90	0.00045	no	-	3	yes	[49, 69]
IC BDO (refit)	long	11	0	9.40	0	0	0.00045	no	-	3	yes	[49, 54]
IC BDO	long	25	0	9.40	8.45	0	0.00045	no	-	3	yes	[49, 63]
IC LNG	long	25	0	10.13	96.98	54.36	0.71000	no	-	3	no	[49, 52, 56]
IC LBG	long	25	0	10.13	96.98	0	0.79000	no	-	3	no	[49, 63]
IC H2	long	25	0	10.13	109.29	0	0	no	-	3	no	[49, 70]
IC CH3OH	long	25	0	10.13	109.29	0	0.79000	no	-	3	no	[49, 64, 18]
IC NH3	long	25	0	10.13	109.29	0	0	no	-	3	no	[49]
FC LNG	long	25	0	22.47	134.80	54.36	0.22763	no	-	3	no	[49, 71]
FC LBG	long	25	0	22.47	134.80	0	0.22763	no	-	3	no	[49, 71]
FC H2	long	25	0	22.47	134.80	0	0	no	-	3	no	[49, 72]
FC CH3OH	long	25	0	22.47	134.80	0	0.22763	no	-	3	no	[49, 71]
FC NH3	long	25	0	22.47	134.80	0	0	no	-	3	no	[49]
EM ELEC	short	30	0	11.86	1,047.05	0	0	no	-	3	no	[9]
WIND ELEC	long	30	0	35.58	2,094.11	0	0	no	-	3	no	

Table B.4: Ship type data for each specific parameter (for abbreviations see the nomenclature list in Appendix A.0.1). Further explanation and references of data can be found in [42].

Modified parameters	Percentage change 2016-2050	Affected Technologies	References
ic	-20	LNG,LBG,H2,CH3OH,NH3,ELEC	[66, fig. 6, p. 13]
cf	110	HFO,MDO,BDO,LNG	[73, fig. 13, p. 3]
	-20	LBG,H2,CH3OH,NH3,ELEC	[66, fig. 6, p. 13]
cs	-40	Internal combustion: LNG,LBG,H2,CH3OH,NH3	[56]
	-50	Fuel cell: LNG,LBG,H2,CH3OH,NH3	[56]
	-75	Electric motor, WIND: ELEC	[56]
ts	+15	All except old ships	[51, tab. 51, p. 282]
ec	-10	IC: HFO,MDO,LNG; FC: LNG	[51, tab. 51, p. 282]
em	-10	IC: HFO,MDO,BDO,LNG; FC: LNG,LBG	[51, tab. 51, p. 282]

Table B.5: Change of fuel and ship specific parameters from 2016 to 2050 in the Reference scenario (for abbreviations see the nomenclature list in Appendix A.0.1). For additional information about scenarios see [42].

Appendix C. Figures

Figure C.9: Fuel consumption (y-axis left) and cumulative emissions (y-axis right) in the business-as-usual scenario without carbon restrictions.

Figure C.10: Total fuel shares from 2016-2050 (y-axis) in relation to different cost range changes (x-axis) compared to the reference case.

Figure C.11: Fuel consumption (y-axis left) and cumulative emissions (y-axis right) in the bio-methane scenario (LBG(mp), r-40) and assuming methane leakage phase-out.