Transitions of the Norwegian maritime sector

A quantitative case study

Miguel Chang (IFE), Odd André Hjelkrem (SINTEF), Steffen Bakker (NTNU), Kari Aamodt Espegren (IFE)

Report 02/24

ISBN 978-82-93863-29-8

Contents

1. Introduction

Global climate change action calls for a redesign of the energy system to curb greenhouse gas emissions. One of the most critical areas to address is the transition of the transport sector since it is a significant contributor to carbon emissions due to its energy supply mostly consisting of fossil fuels [1]. Among the different forms of transport, hard-to-abate segments remain, for example in the maritime sector [2].

In this context, the Norwegian government has set ambitious targets to cut down emissions by half in the maritime sector by 2030 (relative to 2005 levels) [3]. This is crucial given Norway's position as a leading seafaring country. In addition to government targets, the Norwegian Shipowners' Association aims to reach climate neutrality by 2050 [4]. Both initiatives go beyond other emission abatement targets from international organizations (e.g., the International Maritime Organizations' actions to reduce GHG emissions from shipping [5,6]).

The transition in the maritime sector faces several challenges to reach ambitious decarbonization targets. Not all solutions will be suitable for all maritime segments, and certain propulsion technologies and fuel replacements will be more suitable for short-distance sea transport, while others will have more relevance for long-distance shipping. For example, unlike other forms of transport, propulsion systems onboard long-distance vessels need enough energy to cover long routes before having any refueling options, both when considering international and domestic shipping and different maritime segments. Moreover, these vessels have restricted carrying capacity in terms of available volume and weight for storing energy. This often requires the need for high-density fuels in order to have an adequate supply of energy for the ships' propulsion system. On the other hand, short-distance ships can utilize harbor infrastructure for more frequent resupplying or recharging. Given the difference within shipping segments, an adequate representation of the technologies and ship types available is needed in order to capture how the transition in the maritime sector could take place. Thus, it is critical to capture the maritime sector in more detail in energy system analysis and in order to adequately understand the potential availability of fuels and energy use depending on volume and weight through different vessel segments. Ultimately, detailed model representations of these segments can provide the necessary insight into which long-term investment options are needed to decarbonize the current fossil fuel-based propulsion systems and which of these are to be replaced [7].

Technological advances are making green fuels, such as biofuels, hydrogen, ammonia, and electrification, more viable and accessible for the maritime sector [8]. However, it is still uncertain how these technologies will develop under different transition scenarios and what the impacts of these will be once they are integrated into the energy system. Therefore, this study presents a long-term energy system scenario analysis for Norway, with a focus on different technology options in the maritime sector. Given Norway's leading position in the shipping industry, it presents a good illustrative case of how the transition in the maritime sector can take place. Thus, the study will illustrate the case of Norway's energy transition.

1.1. NTRANS Transition pathway scenarios

The maritime case study presented in this report utilizes different socio-technical transition pathways scenarios developed as part of FME NTRANS [9]. These scenarios constitute different perspectives on societal and technological change leading to different energy system configurations.

Technology choices and allowed fuel options in the maritime sector can differ across the scenarios, due to differences in underlying assumptions regarding the adoption of technologies, penetration of variable renewables, and other energy infrastructure. A high-level overview of the four scenarios is presented in Figure 1, and a detailed qualitative and quantitative description of the NTRANS transition pathway scenarios and their underlying assumptions is provided in [9]. The current quantitative case study corresponds to Step 5 in NTRANS' 10-step approach, while a parallel qualitative study (NTRANS report-nr: 03/2024) [10] delves deeper into the socio-technical perspectives analyzing recent developments and potential transition bottlenecks and challenges in the maritime sector.

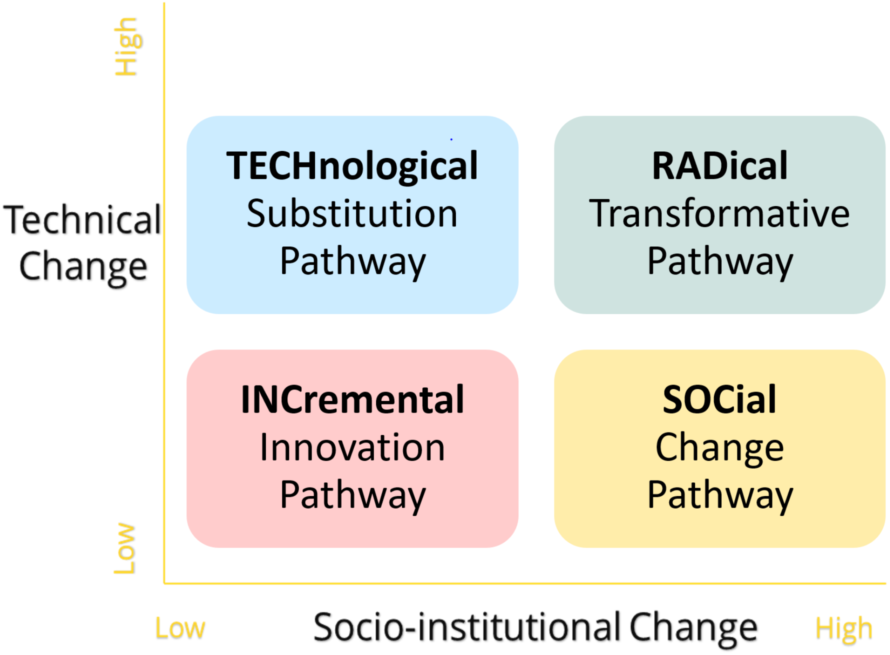


Figure 1. Overview of NTRANS scenarios [9].

1.1. Aims and contributions of the maritime case study

The aim of this case study is to improve the understanding of the role of the maritime sector in the transition of the Norwegian energy system, based on the four NTRANS scenarios. Moreover, this study aims to explore the impact of modeling vessel segments with a higher resolution in an energy system model. The analysis shows technology and fuel alternatives available in each segment and enables the option of investigating geospatial differences.

This additional insight into the maritime sector is provided by combining the analysis of an energy system model of Norway (IFE-TIMES-Norway [11]), which has a technological and geospatial aggregated representation of the maritime sector, with a tool that has a high level of geospatial detail and provides estimates of energy consumption for different maritime vessel segments (Energy Map [12]). Further details on these tools are provided in the following sections.

The analysis presented in this case addresses the following research questions with a focus on freight vessels:

- What is the benefit and value of modeling the maritime sector with a higher resolution, including a more detailed representation of different ship segments?

- What added insight into the energy transition is provided by combining analysis from an energy system modelling tool with estimates of maritime energy consumption having a high level of geospatial detail?

2. Approach and Methodology

2.1. Energy system model: IFE-TIMES-Norway

This section provides an overview of the IFE-TIMES-Norway model [11], developed in the TIMES modelling framework. Then, a more detailed view of the current representation of maritime sector is presented as well as the updates to the model conducted as part of this case study.

2.1.1. General model description

The IFE-TIMES-Norway model provides a detailed bottom-up representation of the Norwegian energy system, to provide operation and investment decisions towards 2050. The geographical resolution of the model matches the country's five current spot price regions of the electricity market. The model is developed using the TIMES modelling framework [13]. TIMES is a long-term and energy system optimization model that includes different energy resources, technologies, carriers, and energy demands. The main outputs of the model are total system costs, investment costs in supply and demand technologies, estimated energy production and trade volumes [13]. An overview of the model is provided in Figure 2.

TIMES provides endogenous investment decisions, minimizing the total costs of the energy system, while ensuring that all the specified energy service demands in the system are met. The model is formulated as a linear optimization problem, which means that the technologies included in the model may be implemented at any capacity, within some lower and upper bound values, rather than having discrete incremental values. Therefore, the estimates generated by the model can provide an approximation of the expected investments in capacities and demand technologies in the energy system. Looking explicitly at the transport sector, this means that for the different scenarios, the model can provide estimates of the optimal mix of fuels based on investments in different propulsion systems and conversion technologies [13].

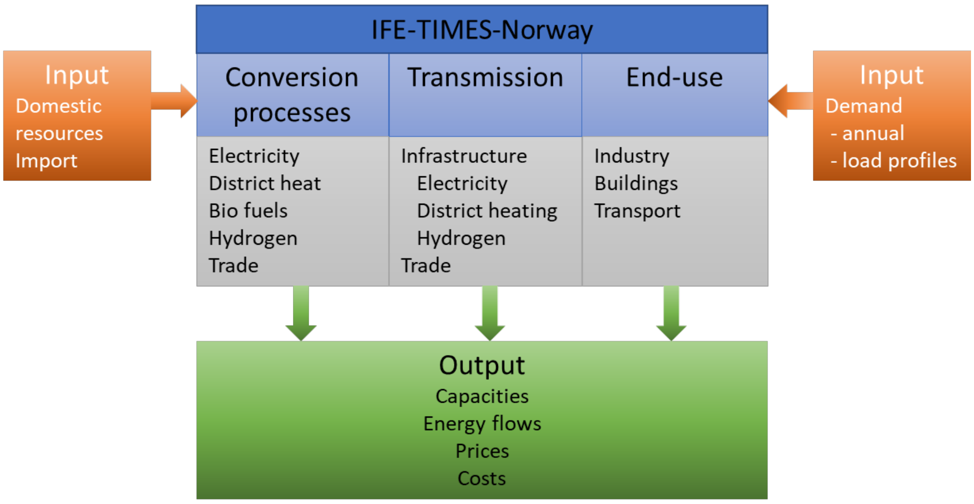


Figure 2. Schematic of the IFE-TIMES-Norway model [9].

2.2. Representation of the maritime transport segment in IFE-TIMES-Norway

2.2.1 Traditional representation

The existing configuration of the maritime sector in the IFE-TIMES-Norway model considers three broad fleet categories: passenger, fishing, and others (the latter representing freight and coastal vessels). In the model, the current distribution of energy demands is derived from Statistics Norway (SSB) and DNV-GL based on the shares of CO_2 emissions for the different ship segments, as presented in [14]. These shares assume that the current fuel consumption is solely based on marine gas oil (MGO), and that existing shares of liquified natural gas (LNG) are negligible. Then, the shares from emissions are scaled proportionally to the energy demands reported in the statistics.

In IFE-TIMES-Norway, the technology options are differentiated by the type of propulsion system and fuel. Namely, the current available options are assumed to be ships with internal combustion engines used with either MGO or LNG as fuels, while propulsion with new fuels and technologies is assumed to be available in the future. Ships with PEM fuel cells running on hydrogen or ammonia in ICE are not fully matured propulsion options; thus, these are available from 2025 onwards in the model. Meanwhile, battery electric vessels are also considered for short-distance freight vessels, having maximum allowable shares linearly interpolated from 0% to 5% (of the total for the freight vessel category) from 2018 to 2030. The maximum market share of each technology for the different vessel types follows the assumptions in [11], shown in Table 1.

Table 1. Input assumptions for the maximum share of each fuel to serve the maritime demands [11].

Group	Type of vessel	Year	Fuel used/propulsion system				
			ICE	LNG	Battery	H2	Ammonia
1	Passenger vessels	2018	no limits	0%	0%	-	-
		2025		*	*	0%	0%
		2030		86%	50%	13%	38%
		2040		86%	50%	13%	38%
2	Fishing vessels	2018	no limits	0%	0%	-	-
		2025		*	*	0%	0%
		2030		*	5%	5%	5%
		2040		50%	25%	25%	50%
3	Other vessels (Freight & Coastal)	2018	no limits	0%	0%	-	-
		2025		*	*	0%	0%
		2030		*	5%	5%	5%
		2040		90%	10%	10%	90%

**: denotes periods where values are interpolated and not explicitly defined.*

The IFE-TIMES-Norway model presents ICE propulsion with alternative fuels (biofuels and ammonia) as well as propulsion with hydrogen fuel cells. The efficiency of these options is assumed to be similar to conventional ICE operating on MGO. A 100% efficiency is assumed for these propulsion options, as a way to represent the transport demands in terms of the total fuel consumption from the different segments. In the case of ammonia, losses are found upstream of the fuel production process, like in the conversion of hydrogen to ammonia with 17% losses. Similarly, battery-electric propulsion systems are assumed to have an efficiency of 80% [14].

The investment costs originally assumed in the model take the assumption of a representative vessel type, based on vessel types within the segment with the largest shares of emissions based on the statistics. Thereafter, [14] identifies a cost per demand in GWh. The assumptions and results can be seen in Table 2. Looking specifically at the "other vessel" aggregated category, the investment costs are derived from estimates for platform supply vessel (posing as a representative vessel), with an investment cost of 22,260 kNOK/GWh, and a lifetime of 25 years.

Investment costs in ships are also differentiated by propulsion system and fuel. The original assumption considers that LNG ships are 20% more expensive than MGO ships, based on DNV-GL estimates [15]. For the other fuels and propulsion systems, 50% higher costs are assumed today. For future investments by 2030, the additional costs were originally assumed to be 20% higher than MGO-based ICE ships. The lifetime of all ship groups is assumed to be 25 years.

2.2.2. Detailed representation of freight transport - Model updates and data assumptions for vessel segments

The maritime sector modelled in this study, expands on the previous assumptions presented above by considering a more disaggregated view of the different vessel segments in the "Other vessels" grouping. Namely, this grouping is split into 5 different vessel segments based on the data flows from the Energy Map tool to IFE-TIMES-Norway, which is further explained in Section 2.3. The ship segments considered are Containers, Bulk carriers, Cargo, Tankers, Other (grouping of portside and coastal supply vessels).

This additional level of detail requires updated assumptions for differentiating the investment costs of new-build ships found across the different vessel segments and their respective options of propulsion systems. Updated investment costs for the ships with different propulsion fuel options with ICEs were derived from a recent maritime sector study in the MarE-fuel [16]. This included ships running on MGO, LNG, and Ammonia. Additional costs for different vessel segments with fuel cells were obtained from Taljegard et al. [17].

The base costs documented in [11] are used as the starting reference costs representing the "Other" vessel segments. In the original setup, the "Other" segment corresponds to Passenger Supply Vessels (PSV) with propulsion based on MGO ICE. To derive the updated costs in the other vessel segments under the new categories, the percent differences of the vessel segments reported in [16] and [17] are calculated relative to the original data. Then, this factor is used to scale up the original reference investment costs and to propagate the resulting differences across the different vessel segments in the new categories. Table 2 presents the updated lifetime and earliest availability year (for immature technologies) for different ship segments based on the MarE-fuel report [16].

In addition, [16] also presents the potential use of multifuel ICE starting from 2031. This assumption is used in the analysis to present a differentiated case that represent a potential convergence in costs of the different ICE propulsion options. Meanwhile, another scenario case is considered where these costs do not converge.

Table 2. Cost data assumptions (in kNOK/GWh) applied to the different vessel segments. Derived from [16,17].

	Vessel cost by propulsion fuel, *kNOK/GWh*				
Vessel Segment	MGO	LNG	NH_3	H2 Fuel cells	Ave. Lifetime (existing). year
Container	19,960	22,629	21,976	30,350	25
Bulk	18,682	24,247	23,154	28,407	28
Cargo	23,850	30,051	29,256	36,265	35
Tanker	23,850	30,051	29,256	36,265	25
Other	22,260	29,812	27,427	33,847	33

Available start year	2020	2020	2025	2025

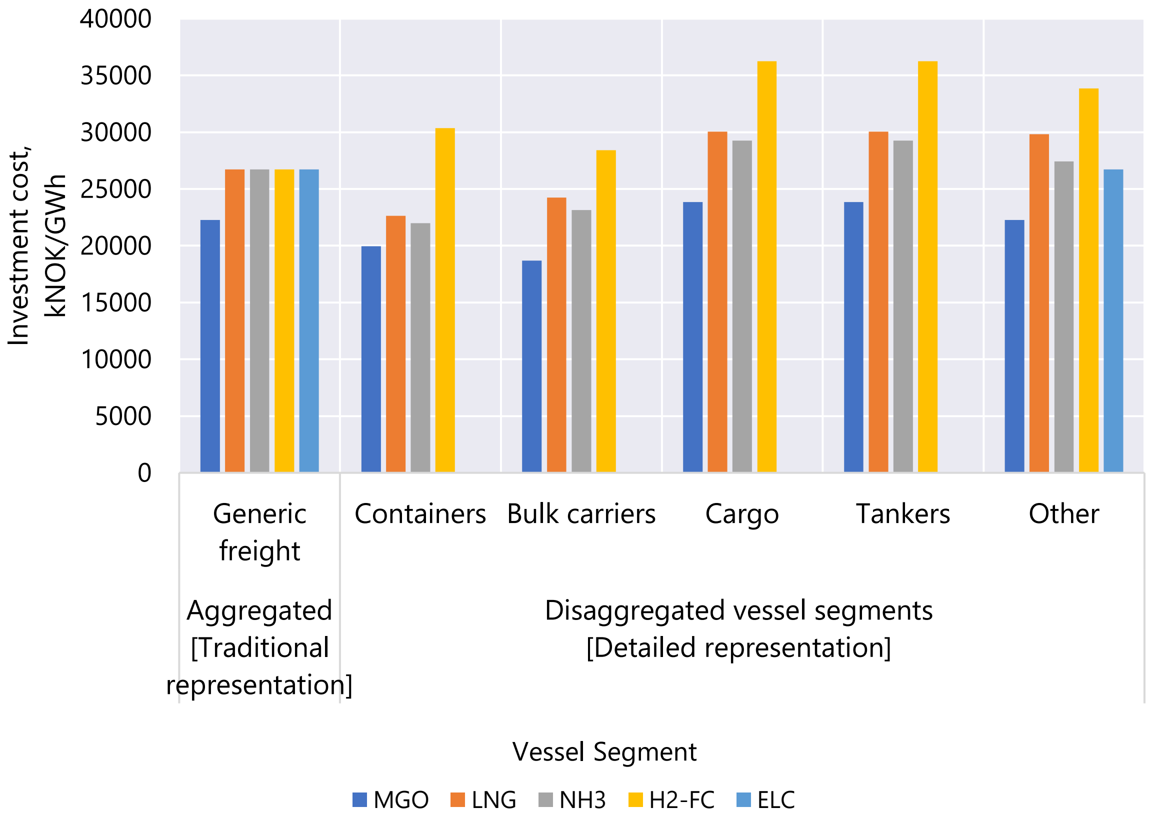


Figure 3. Comparison of investment cost for different freight vessel segments.

Figure 3 gives an overview of the investment costs as it was when the freight ships was aggregated into one large ship subsector (old version), and the updated investment costs when freight is divided in different segments.

In addition to updating the costs of the different vessel segments, additional investment costs and technical assumptions are also added to account for the fuel production pathway of green ammonia based on data from [18]. This means, that the model considers a new additional process using hydrogen and electricity as feedstock for ammonia production. However, refueling infrastructure is not yet included under the new cost assumptions. Prior to this update, the model had a simplified representation of ammonia as a direct feed of centralized hydrogen production with no additional embedded investment costs or auxiliary electricity consumption, and the losses were modelled as a lower propulsion efficiency of the vessels.

The new assumptions for green ammonia consider that 95% of the energy input comes from centralized hydrogen production and 5% from electricity, and that the ammonia production process has an 82% efficiency. In addition to these, the model has been updated with investment costs for green ammonia production plants (including additional investments in air separation units) from the Danish Energy Agency's Technology Catalogue [18]. In the original model, an additional energy loss is considered in ammonia consumption from the ships to account for the efficiencies in the production process specified above, since these were not present priorly. Therefore, these losses are removed in the updated version of the model to reflect the ammonia consumption more adequately prior to combustion in the propulsion system, as is the case with the other propulsion fuels considered.

2.2. Energikart (Energy Map)

To include the energy demand from transport on a more detailed level, the results from the Energy Map [12] were used. The Energy Map is a visualization tool based on a detailed estimation of the energy consumption in the Norwegian transport sector. The main input is a set of results from regional and national transport models, which estimate the amount of transport in a given sector.

The transport models differentiate between the transport of people and freight. For persons, the trips are estimated based on trip generation and attraction, mode choice and route choice. All start- and endpoints are in "Grunnkrets", the basic statistical unit in terms of spatial classification of areas in Norway. The freight transport demand is calculated by describing the flow of goods between a set of nodes in the Norwegian transport network. This is further linked to vehicles and vessels to estimate the traffic flow.

The Energy Map is made up by combining the results from all the different model results, especially with regards to boundaries between model areas to avoid overlaps. Then, an energy model is applied to estimate the energy demand, fuel consumption and emissions for all trips modelled in the transport models.

The maritime sector is the most varied in terms of fleet size, including 38 different ship types. The vessels are mainly classified by the type of cargo they transport and differ in terms of physical characteristics and engine size. Figure 4 illustrates the different types of vessels considered by Energy Map, presenting their distribution by weight class.

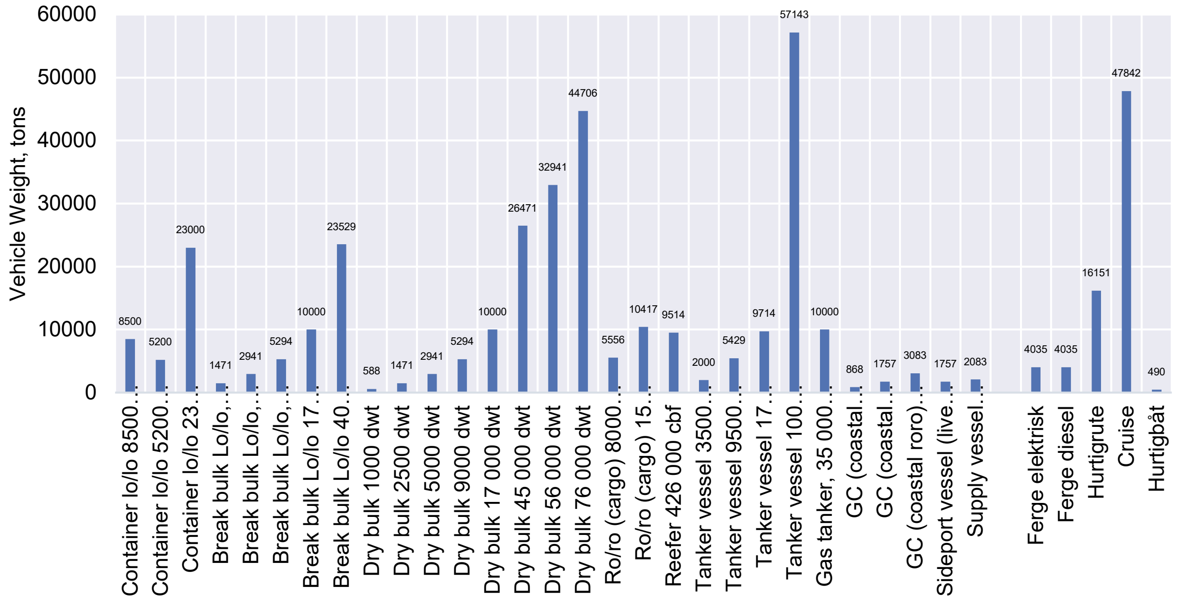


Figure 4. Overview of ship types by weight considered in Energy Map.

The output from the energy map for the maritime case is the total amount of fuel used in geographic areas by ship type. The results are estimated for an average day and are aggregated to get yearly values. In Figure 5, a snapshot of the Energy Map is presented.

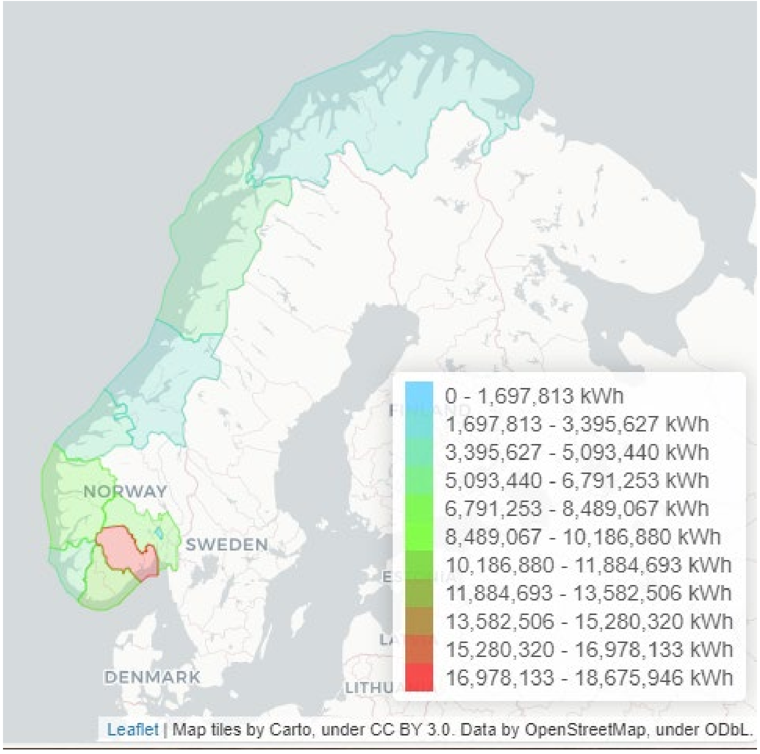


Figure 5. Snapshot of Energy Map with energy consumption for sea freight (in kWh/day) by county (2020 county division) [11].

2.3. Model linking and data flows

The data provided by Energy Map provides significant detail about the different types of ships and various parameters associated with this. In order to reduce the complexity of inputs going into the energy system model, the different types of ships had to be aggregated. In Section 2.1.3, groupings were made for the different ships under different vessel activity segments, which consisted of: Bulk carriers, Containers, Cargo, Tankers, and Others (including coast and portside supply vessels). Estimates for energy consumption of each of the aggregated vessel segments then served as inputs into the energy system model, IFE-TIMES-Norway [11]. The estimated shares of each vessel segment based on their total energy consumption are presented in Table 3.

Table 3 Estimated shares of energy consumption by vessel segment in group 3.

Vessel segments, group 3	Container	Bulk	Cargo	Tanker	Other
Shares	1.1%	16.8%	3.0%	69.8%	9.3%

The data flow between the Energy Map and IFE-TIMES-Norway allows to capture additional resolution of the shares of energy consumption across different vessel segments. In addition to this, the connection could enable subsequent conversions of energy demand estimates to transport demands (in terms of ton-kilometers), by using the details on distance travelled and payload weight for the vessels. These data flows are illustrated below in Figure 6.

Moreover, the results of IFE-TIMES-Norway, which include future projections for fuel mixes across different scenarios, can also be fed back to the Energy Map. This can be used in subsequent studies to propagate these estimates on a more geographically detailed level, to assess required infrastructure needs for the different future fuel options.

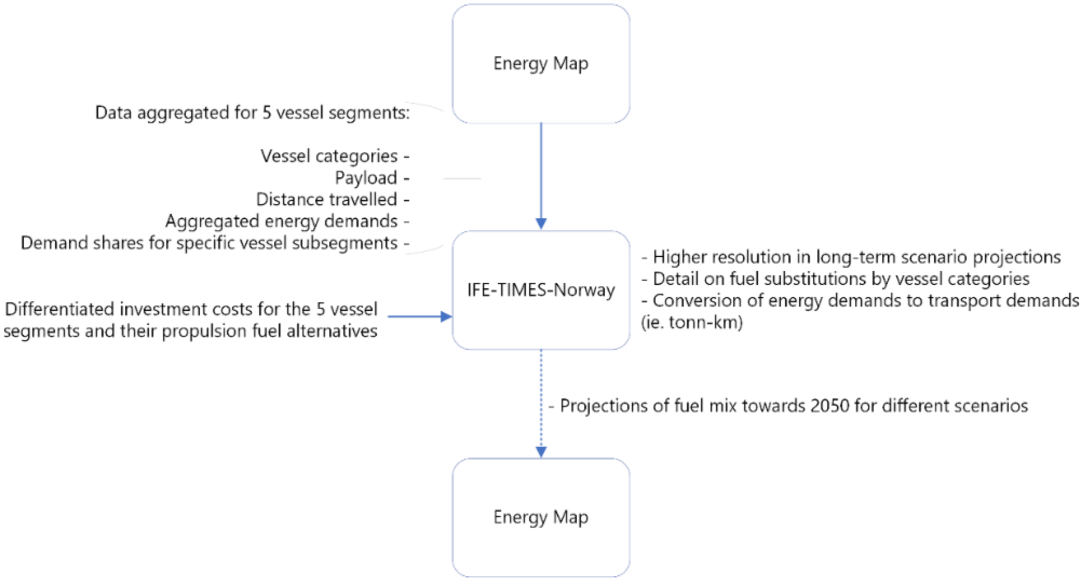


Figure 6. Data flow between Energy Map and IFE-TIMES-Norway applied to the maritime shipping case

3. Results

In this section, we analyze the impact of considering more detailed vessel segments in IFE-TIMES-Norway across all four NTRANS scenarios. Throughout the analysis, three sets of results are considered based on the different modelling assumptions:

- Aggregated results with a traditional representation: considering the original assumptions and grouping of all freight vessels without differentiation of the different costs across vessel segments nor additional costs for ammonia production. This case presents ship types under a single generic freight vessel aggregation.
- Updated results with detailed representation of sea freight – disaggregated by vessel segment: considering differentiated costs for the 5 freight vessel segments, and details on ammonia production. Additionally, two further cases are considered which account for different potential developments in terms of the technology availability and costs. This is split into:
  a) Differentiated costs for all ICE-based ships throughout the modelling horizon; This portrays a limited rollout of multi-fuel technologies that could be used in the future (i.e., engines capable of operating with MGO, ammonia, or LNG) and less convergence in future investment across propulsion options.
  b) Converging costs for ICE-based ships by 2040; This portrays more extended cost reductions in new options and the rollout of e.g., multi-fuel technologies, which allow the investment on ships with propulsion systems that can readily facilitate fuel replacements.

3.1. Traditional representation of sea freight in the NTRANS scenarios

Figure 7 shows the estimated energy consumption for each fuel technology across the different NTRANS scenarios, considering the aggregated modelling approach. Similar results can be observed for INC and SOC, as well as TECH and RAD due to the underlying common assumptions across the pair of scenarios, defined in [9]. Namely, in both INC and SOC, the use of both domestic and imported biofuels is allowed, with no restrictions from 2040 onwards. At the same time, it is assumed that investments in hydrogen supply remain expensive in the future, having low technology learning and that no hydrogen-based options are available in sea transport. Meanwhile, in TECH and RAD, biofuels are restricted to only the domestic potentials (with specific bounds by region) and expensive imports; while hydrogen use is allowed and investments are cheaper by 2050, with high learning rates for all technologies. As a result, the levels of biofuel use are more predominant in INC and SOC than in TECH and RAD. Since the use of biofuels in sea transport is unrestricted, a rapid phase-out of MGO for biofuels is seen from 2040. On the other hand, with limited availability of biofuels in TECH and RAD, the shares of biofuels in transport are lower, while the use of hydrogen-based fuels, in this case ammonia, is more cost-optimal than in INC and SOC.

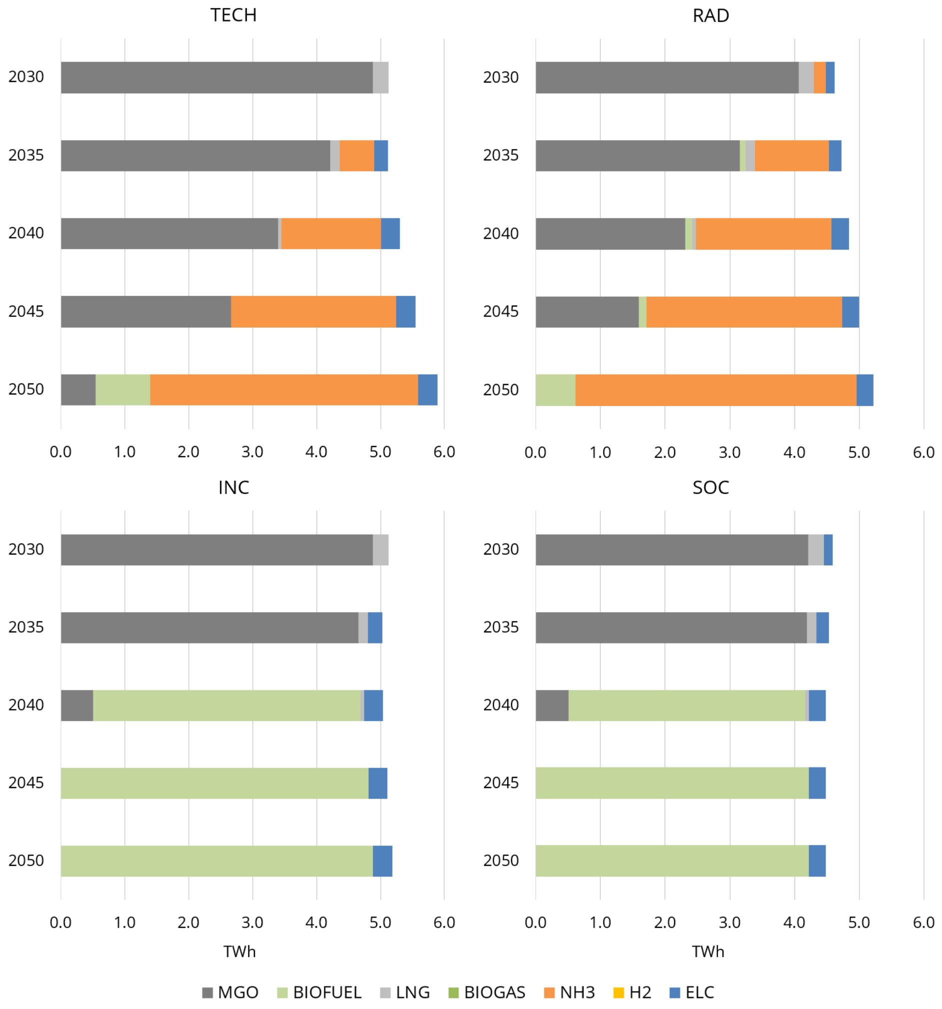


Figure 7. Distribution of maritime freight transport energy consumption (in GWh) for the different NTRANS scenario pathways in the aggregated modelling approach.

3.2. Comparison between the traditional and detailed representations

The impacts of including additional detail in the maritime sector manifest differently across the four scenario pathways, as presented in Figure 8 and Figure 9. In the case of the Incremental (INC) and Social (SOC) scenarios presented in Figure 8, it is possible to see that the new assumptions lead to only modest changes in the results at a national level. When comparing the original assumptions with case a), where costs remain differentiated for ships with different propulsion fuels, it is possible to see that the biggest difference is in a slightly higher use of MGO and LNG in 2040. Nevertheless, this plays a very small role from that year onwards due to the additional costs required for these fuels. Overall, the results in case *a) (Differentiated costs for all ICE-based ships)* and *b) (Converging costs for ICE-based ships)* and the original assumptions observed in the INC and SOC scenarios do not show substantial differences. This is mostly due to the assumptions limiting the fuel alternatives in these two scenarios, leaving the options of biofuels across all vessel segments and electrification in short-distance vessels as the preferred least-cost options.

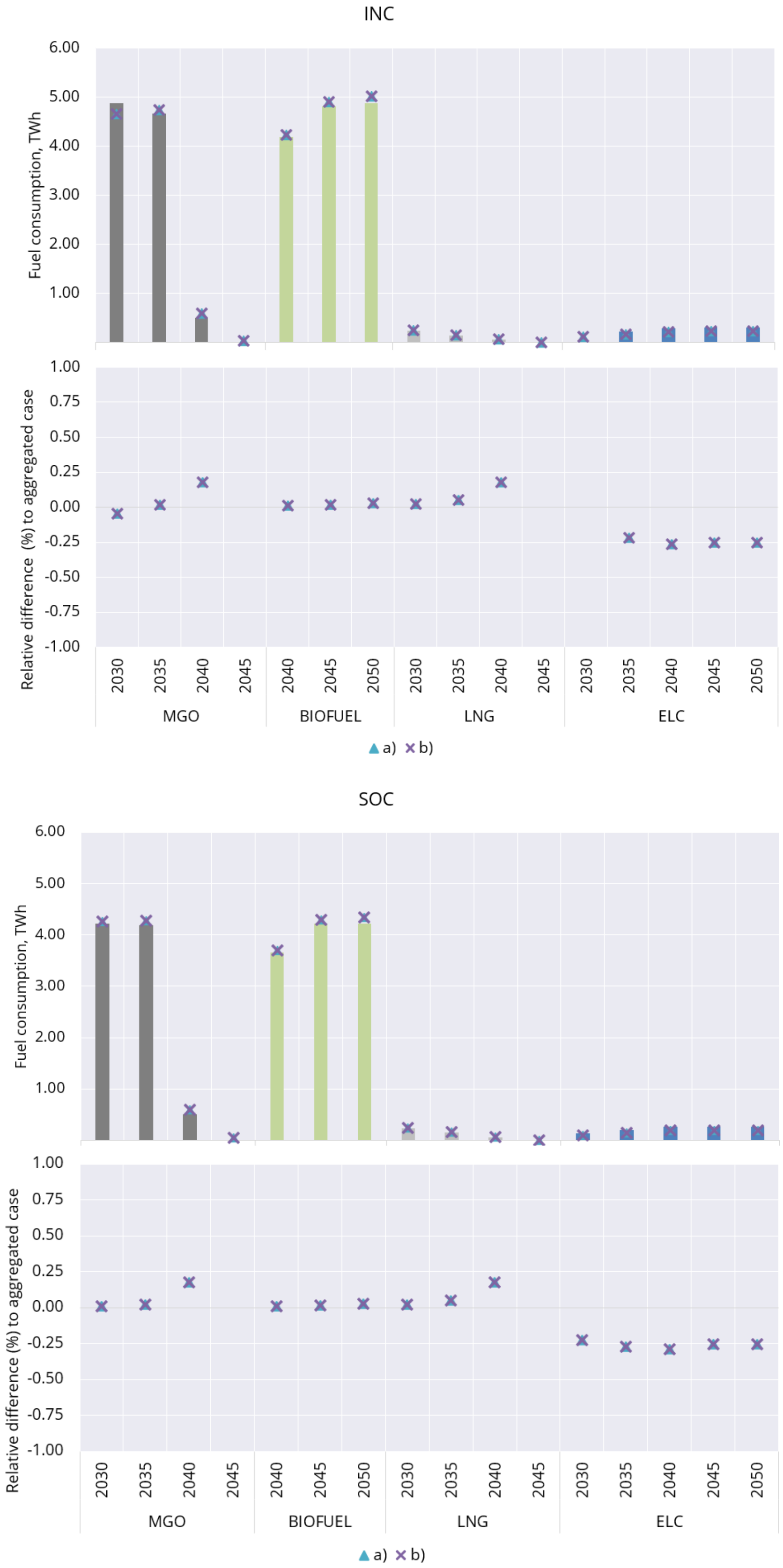


Figure 8. Difference plots for the Incremental and Social scenarios. The bars in the Fuel consumption plot represent the aggregated; the triangle and cross marks in the plots represent Case a and b, respectively.

In contrast, both scenarios with high technological change – the Technological (TECH) and Radical (RAD) scenarios – do present more noticeable changes in the composition of propulsion fuel demands as presented in Figure 9.

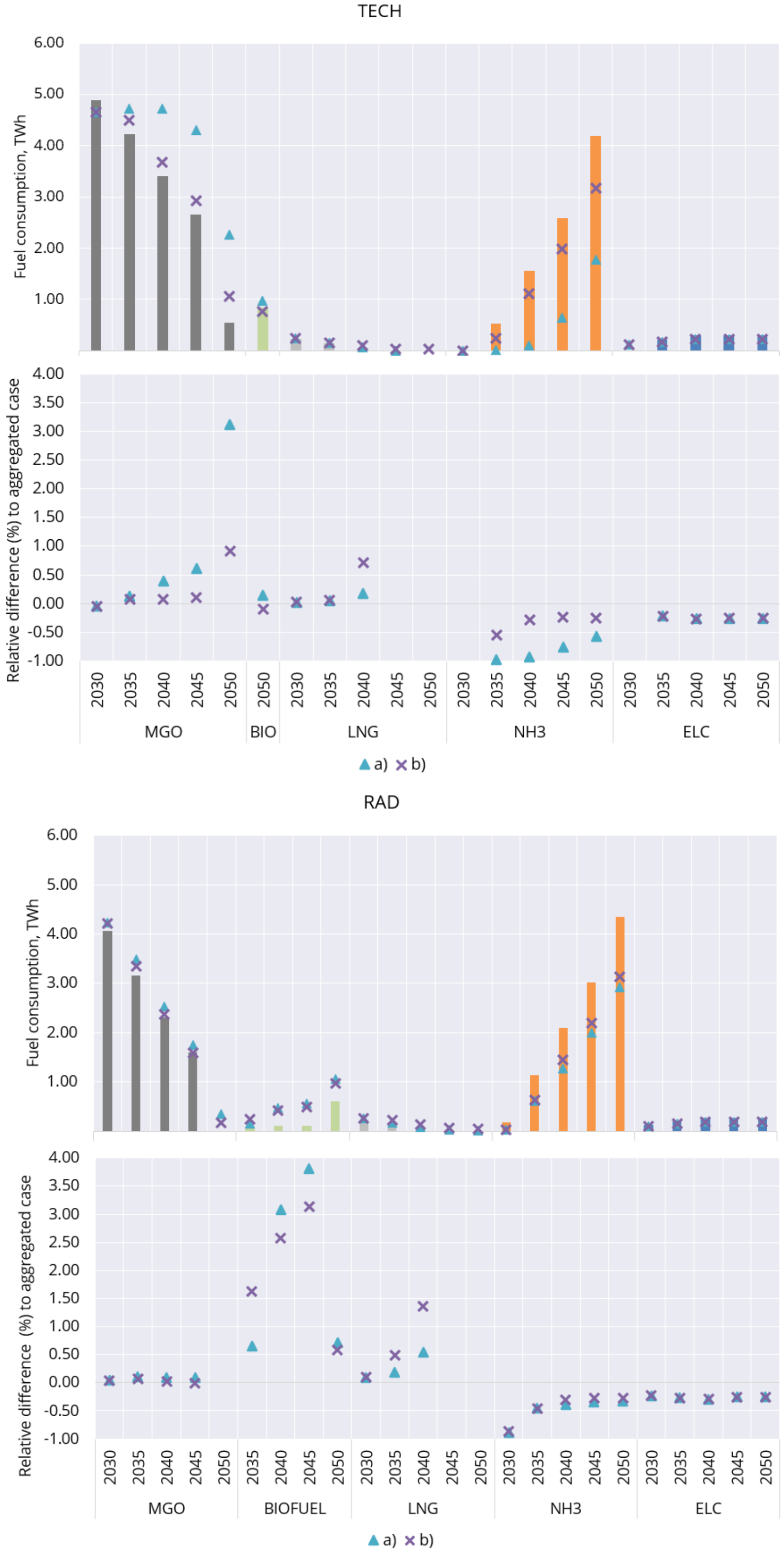


Figure 9. Difference plot for the Technical and Radical scenarios.

Figure 9 shows that these technological driven scenarios already had a much larger uptake of ammonia (NH_3) relative to the socially driven scenarios (i.e., INC and SOC). However, when considering the updated assumptions in case *a)* and *b)*, the additional costs included for ammonia production and the different vessel costs lead to lower penetration of ammonia-based propulsion, especially in the TECH scenario. Instead, NH_3 is substituted with larger shares of biofuels in the RAD scenario, while MGO consumption remains present to an extent in the TECH scenario. Interestingly, in case *a)* for the TECH scenario, a larger consumption of MGO can be expected in the latter years due to earlier investments in MGO-based ICE vessels given the assumptions that the cost in other propulsion options remains differentiated and more expensive throughout the transition rather than converging. In contrast, case *b)* – which assumes converging costs for the different propulsion options, shows only modest differences in the use of MGO relative to the traditional representation (about 1% more). These results highlight the need of support to new propulsion technologies and higher technology learning to reach lower costs in order to be cost-competitive with MGO-based propulsion across the different segments.

Finally, across all the scenarios, smaller shares of battery-electric vessels are considered relative to the original aggregated assumptions. This is due to the fact that in the original assumptions, these were bounded up to a maximum share of 10% of total freight ships by 2040; whereas in the updated analysis, battery-electric vessels are limited by only being available in one vessel segment with a higher maximum market share potential (assumed as 80%), namely in the "Other" category encompassing supply and coastal vessels, since shorter trips occur in a share of ships in this segment.

3.3. Details on specific vessel segments and regions

While the results on a national level show differences in fuel consumption across the different scenarios, a more nuanced view is provided when looking specifically at the different types of vessels. For example, as illustrated in Figure 10 and 11 for the RAD scenario, the share of propulsion fuels will be different across the different vessel segments relative to the trends in the aggregated representation. Moreover, differences appear also when considering differentiated cost assumptions, illustrated in Figure 10 and 11 with the results from case *b).*

Under this scenario, ammonia is projected to play a significant role as a fuel replacement in the different vessel segments. However, when considering case *b)*, biofuels are projected to play a larger role in the Cargo and Bulk ship segments, replacing MGO. This differs from the aggregated representation, which estimated a larger replacement based on ammonia. While the differences in biofuels are large in these segments, the relative differences in biofuel consumption relative to the total for sea freight – as seen earlier in Figure 9 – is only at around 3% since the differences are more modest in the other segments, like in the Tankers segment which comprises the biggest share of fuel consumption, or negligible as in the case of the *Other* segment.

For Container ships, LNG is also projected to be an option in 2030 and 2040, though its consumption in this segment is reduced by 2050 in favor of ammonia. Under case *b)*, LNG could have a more prominent role in the intermediate steps of the transition for container ships, covering up to around 40% of total consumption in 2040, and above 20% by 2050. The remaining 80% of the fuel consumption in this segment in 2050 is expected to be from ammonia. Similarly, ammonia in the RAD scenario is estimated to be the predominant fuel option in the Container, Cargo, and Tanker segments by 2050, covering over 70% of the fuel consumption, although MGO is expected to still cover a significant share of the consumption in 2040 (over 60%). Meanwhile, similarly large shares – over 60% - can be observed in the Cargo and Bulk segments by 2050, with additional use of biofuels and LNG covering the remaining fuel mix.

Already in 2030, big differences can be observed in the uptake of battery-electric ships, allowed only in the *Other* segment and continuing in subsequent years. By 2050, the rollout of electric propulsion in this segment reaches shares of about 70%. In the results, this is explained by the imposed constraints on electric propulsion being limited to shorter distance sea transport, mostly seen in this segment category. For both 2040 and 2050, it is possible to see varying degrees of penetration of ammonia and biofuels to replace MGO and LNG.

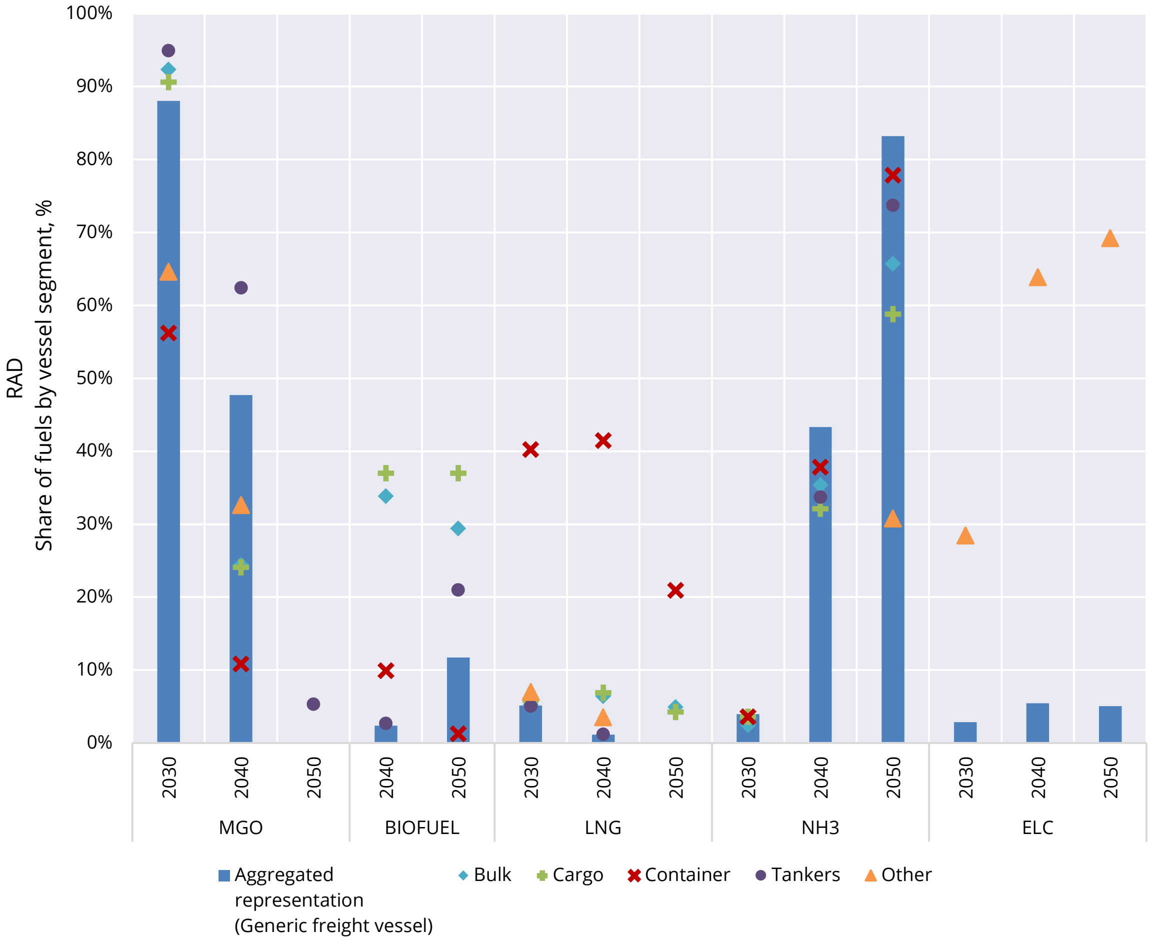


Figure 10. Share of propulsion fuels by vessel segment for the RAD scenario (case b.) relative to the aggregated case.

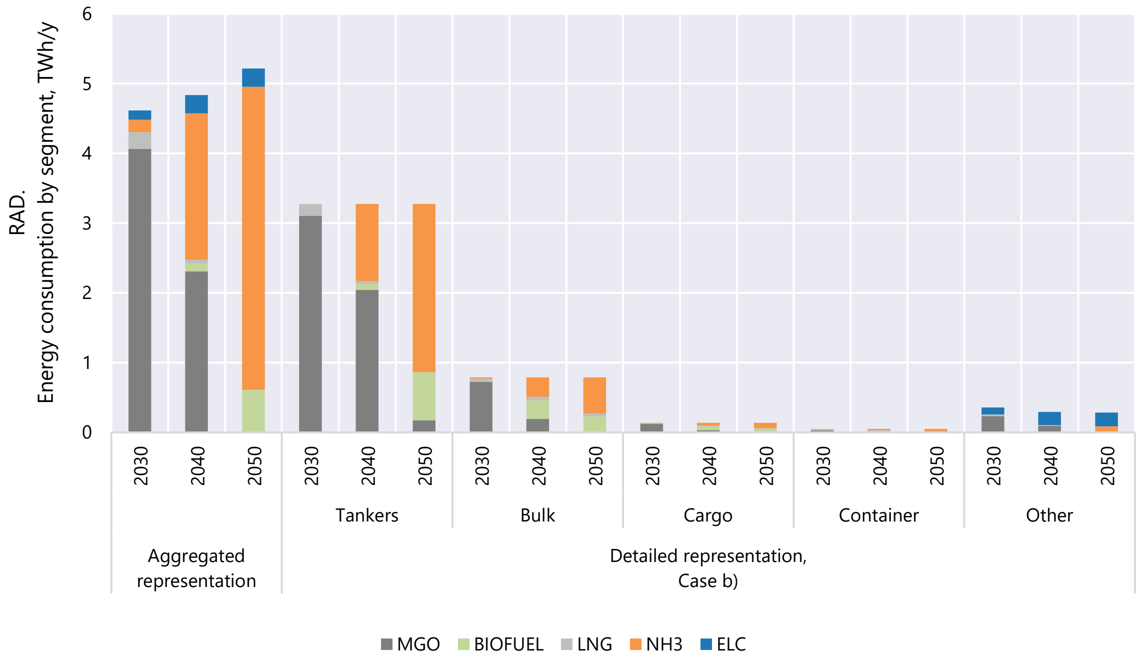


Figure 11.Propulsion fuels by vessel segment for the RAD scenario in the aggregated case and detailed case b.

The benefits of additional modelling detail can be further illustrated when looking at a more detailed geographical aggregation level. In the case of IFE-TIMES-Norway, a more granular view of the system can be provided when looking – for example – at different spot market regions. In Figure 12, this is illustrated for the case of the TECH scenario in 2050.

As illustrated in Figure 12, the overall fuel consumption mix changes from the original aggregated assumptions to the more detailed case *b)*. Moreover, slight differences can also be observed in the total fuel use due to changes in the propulsion mix and the different efficiency of the technologies. These changes in the consumption mix carry over to the fuel segments and regions. For example, in the latter, the adoption of ammonia is more predominant in the NO5 region than in NO1, however, its distribution varies widely when also considering the different segments as already mentioned. In some cases, the ammonia covers a relatively larger share than in the nationally aggregated results. On a national aggregated level biofuel plays a modest role, however, the shares of biofuels cover a relatively large share of the fuel consumption across the NO1 region and in some specific segments in NO5. Likewise, LNG which has a small share in the overall national fuel mix, appears as a more predominant option in NO1 along with biofuels. Meanwhile, this same fuel mix is not foreseen in NO5 by 2050. These differences could be attributed to uncertainties in the input assumptions; for example, regarding the upper bounds on biofuel imports and use of bioresources for each region (with NO1 having a nominally higher limit than NO5) and fuel import prices.

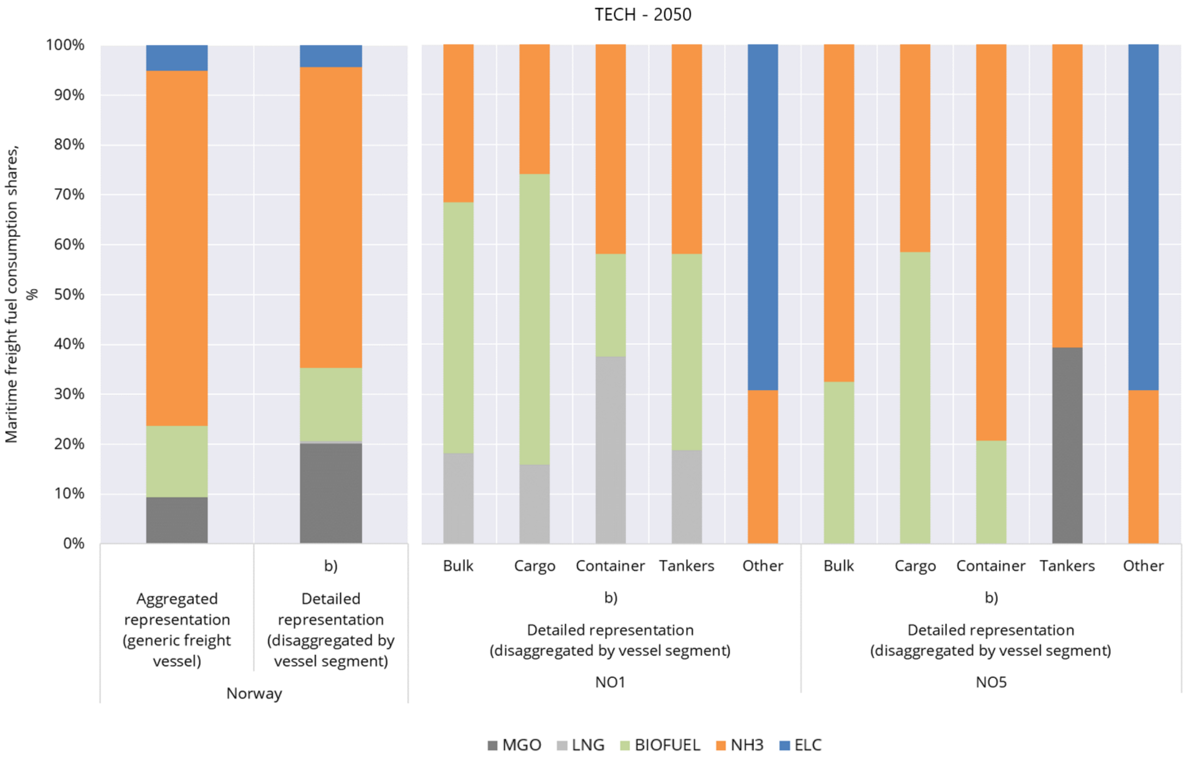


Figure 12. Fuel consumption shares for the Technical scenario by 2050 for the aggregated case and case b) at a national level, and the updated representation in two selected regions (NO1 and NO5).

These results suggest that by having the additional level of detail on the different vessel segments and regions, additional insight can be gained regarding the potential infrastructure required in different geographical areas related to the different fuel types, as well as for the specific vessel types considered across the different scenarios.

4. Summary and further work

This study presents low-carbon transition pathway scenarios for Norway's future energy system, focusing on the modelling of the maritime sector. The results of the analysis illustrate fuel and propulsion options in maritime freight under different cost-optimal configurations of the energy system, and how with different overall developments, different options will be available for the maritime sector, looking specifically at the different vessel segments for freight transport. Moreover, the analysis also illustrates the benefits of using more precise models, and when these can be beneficial for national or regional analyses, e.g. if a country wants to investigate the energy needs for decarbonizing their maritime transport.

As shown in the analysis, an added value of modeling the maritime sector with a higher resolution, includes the possibility of addressing specific developments in individual vessel segments and having a more detailed outlook on the potential fuel replacements available in the maritime sector. Moreover, this also translates into additional geographical differentiation that could potentially outline infrastructure requirements for the advent of new fuels and charging demands covering the energy consumption of the different freight vessel segments. However, smaller segments characterized in the model can also be grouped together to reduce modelling complexity, without major differences in the total aggregated results at the national level.

Furthermore, an additional connection is expected from the results of the energy system modelling scenarios back to Energy Map. Given that the different demand technologies for new propulsion systems are part of the outcomes of the energy system model optimization, these new technology mixes are planned to be used as inputs in Energy Map to have a disaggregated view of where these technologies could be implemented throughout Norway, relative to the actual transport demands in the country.

Although the focus of this case presents mostly methodological findings, the insight gained from additional modelling detail can also inform policy and decision-makers about the potential transition pathways across the maritime sector and the different target segments. For example, in short sea shipping realizing the electrification of the vessel fleet will require specific enabling measures (e.g., subsidies) to successfully rollout new battery-electric ships. Meanwhile, the use of new carriers, like ammonia or hydrogen, will likely need adequate support mechanisms to be in place which can foster the build-up of the related value chains and infrastructure for these pathways to be realized. Having tools and scenarios capable of providing details on these developments is thus critical for decision-support.

4.1. Further work

As an extension to the feedback of scenario results from IFE-TIMES-Norway to the Energy Map, it is possible to estimate the use of different propulsion systems in a very detailed geographical scope for future scenarios (especially in areas where the scenario outcomes present similar solutions). This enables the opportunity to map and allocate the energy use from trips to ports and hubs. By applying a certain rule-based behavior for refueling and charging, the demand for portside facilities can be estimated. This will further enable detailed area studies where the required capacities can be evaluated from a practical level concerning e.g., grid constraints or production facilities.

Another possible research area could be to create a feedback loop even further, where the scenario results from TIMES affect the transport demand by introducing new data for trip costs, travel times and so on. It is not necessarily straightforward to apply the feedback loop without experiencing some unexpected issues. Hence, we propose to perform a test of a controlled area to assess the process.

In addition to the above, a potential area of further development can be in updating the IFE-TIMES-Norway with specific transport demands (i.e., in ton-km and person-km) with updated data from the Energy Map. The major update frequency of the Energy Map is dependent on input data from transport models, which are updated at least every four years with each new NTP. However, changes in other inputs such as technical data or fleet prognosis, or even smaller transport model updates, can result in minor updates of the Energy Map independently of the work related to NTP. Updated estimates of the number of trips, payload, and distance travelled in the different vessels can be readily used to update this transport demands in TIMES, thereby improving the representation of the transport sector in the model.

Similar updates can be conducted for IFE-TIMES-Norway using data from other transport models and other interdisciplinary studies to improve the representation of the sector. Some potential areas of improvement could be to supplement the energy system model assumptions with additional inputs regarding relevant costs related to the expected fuel replacements; for instance, the costs of refueling infrastructure and retrofitting of ships. Additionally, uncertainty in the investment costs and technology learning of some less mature options could be further assessed via additional sensitivity analysis. For instance, this could be done as additional analyses of how converging costs in new propulsion fuel options and perhaps subsidies to these technologies and other mechanisms can make these more competitive and rapidly replace MGO as an option. Likewise, some of the options have abrupt uptakes, which could be improved by considering maximum shares in the allowed fuel shares, or growth constraints for specific propulsion options in the vessel segments, similar to related work in road transport segments (e.g., [19]). Finally, additional feedback loops from qualitative socio-technical studies on the maritime sector, such as that presented by Damman et al. [10], could be established to better capture and quantify the impacts of potential transition bottlenecks and the uncertainty of these across the different transition pathways.

References

[1] Shukla PR, Skea J, Reisinger A, Slade R, Fradera R, Pathak M, et al. Climate Change 2022 - Mitigation of Climate Change - Summary for Policymakers - Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2022.

[2] UNCTAD. Review of Maritime Transport 2021. United Natrions Conference on Trande and Development (UNCTAD); 2021.

[3] Regjeringen. Regjeringens handlingsplan for grønn skipsfart. 2019.

[4] Norwegian Shipowners' Association. Zero emissions in 2050. 2020.

[5] IMO. INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS. International Maritime Organization (IMO); 2018.

[6] IMO. Fourth IMO Greenhouse Gas Study. International Maritime Organization (IMO); 2020.

[7] DNV. Maritime Forecast to 2020 - Energy Transition Outlook 2022. 2022.

[8] Korberg AD, Brynolf S, Grahn M, Skov IR. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renewable and Sustainable Energy Reviews 2021;142. https://doi.org/10.1016/j.rser.2021.110861.

[9] Espegren KA, Haaskjold, Kristina, Rosenberg, Eva, Damman, Sigrid, Mäkitie, Tuuka, Andersen, Allan Dahl, et al. NTRANS Socio-technical pathways and scenario analysis. vol. Report 02/2023. 2023.

[10] Damman S, Mäkitie T, Wardeberg M, Chang M, Espegren KA. Socio-technical transition pathways and bottlenecks for Norwegian maritime transport A qualitative case study. NTRANS rapport-nr: Rapport 02/2024; 2024.

[11] Haaskjold K, Rosenberg E, Seljom P. Documentation of IFE-TIMES-Norway v3. 2023.

[12] Hjelkrem OA, Rennemo OM, Dahl E, Malmin OK, Babri S, Karlsson H. Energikart: Et verktøy for å beregne, visualisere og analysere energibruk i transportsektoren i Norge. 2022.

[13] Loulou R, Goldstein G, Kanudia A, Lettila A, Remme U. Documentation for the TIMES Model. IEA-ETSAP; 2016.

[14] Danebergs J, Rosenberg E, Merethe P, Seljom S, Kvalbein L, Haaskjold K, et al. Documentation of IFE-TIMES-Norway v2. 2022.

[15] DNV GL. Analyse av tiltak for reduksjon av klimagassutslipp fra innenriks skipstrafikk Miljødirektoratet. Rapportnr. 2018-0181, Rev.2; 2018.

[16] Franz SM, Shapiro-Bengtsen S;, Campion NJB, Backer M;, Münster M. MarE-Fuel: ROADMAP for sustainable maritime fuels. APA; 2021.

[17] Taljegard M, Brynolf S, Grahn M, Andersson K, Johnson H. Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. Environmental Science & Technology 2014;48:12986–93. https://doi.org/10.1021/es5018575.

[18] Danish Energy Agency. Technology Data - Renewable Fuels. 2022.

[19] Rosenberg E, Espegren : K, Danebergs J, Fridstrøm L, Beate Hovi I, Madslien A. Modelling the interaction between the energy system and road freight in Norway. Transportation Research Part D: Transport and Environment 2023;114:103569. https://doi.org/10.1016/j.trd.2022.103569.

Appendix - Supplementary figures

Result comparison relative between aggregated and disaggregated updated cases across the different NTRANS scenarios.

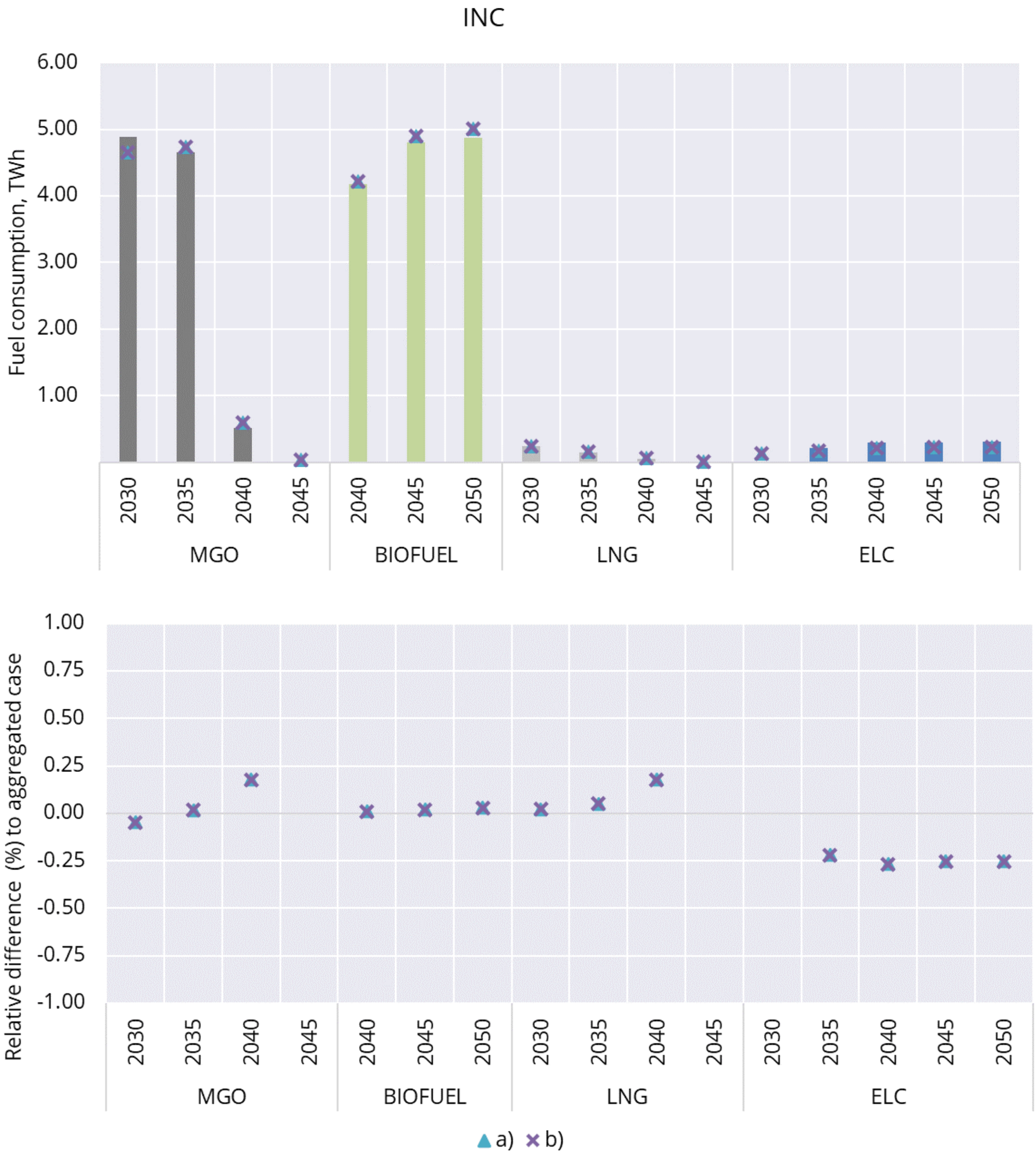


Figure 13. Difference plots for the INCremental. The bars in the Fuel consumption plot represent the aggregated case; the triangle and cross marks in the plots represent Case A and B, respectively.

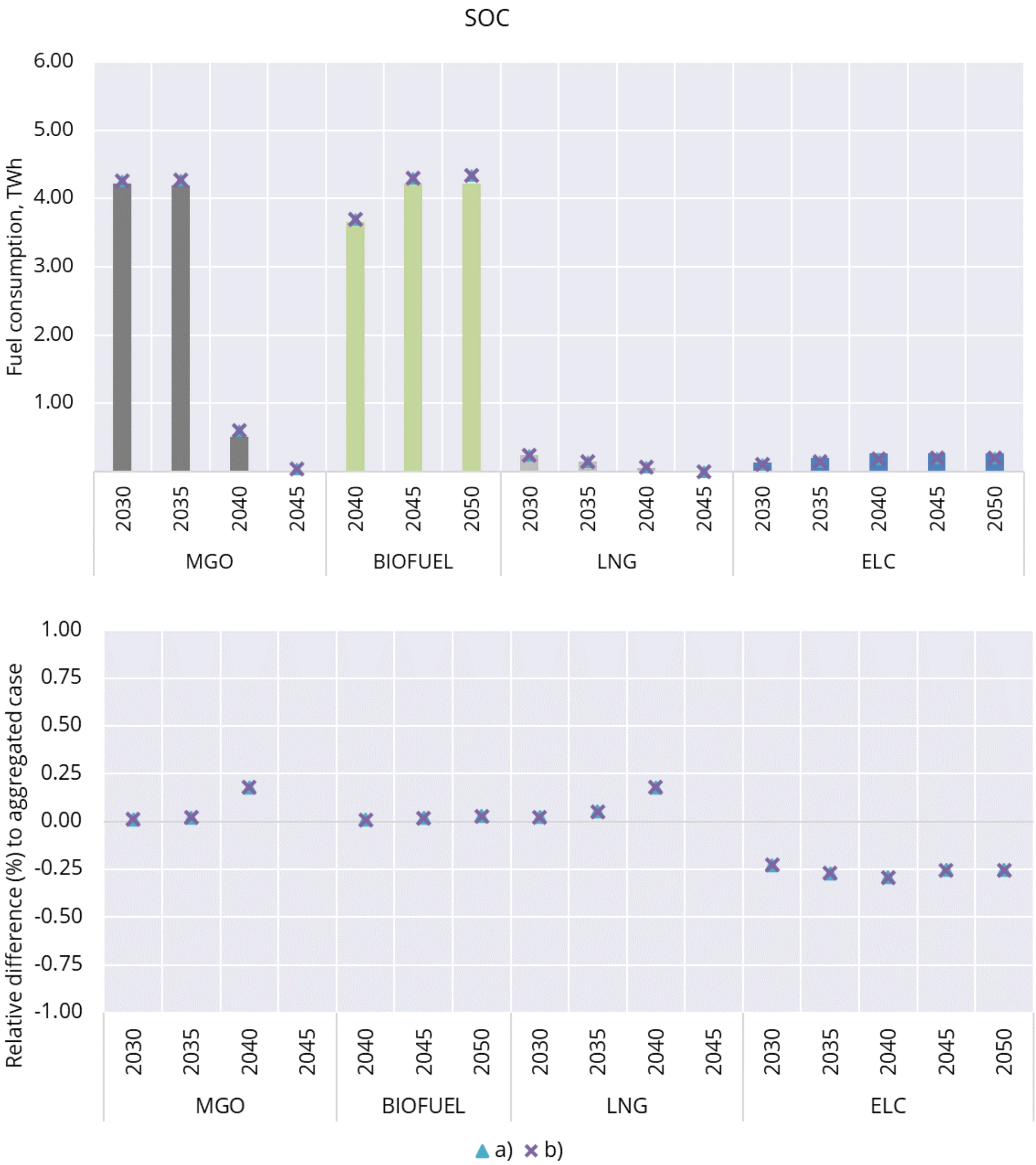
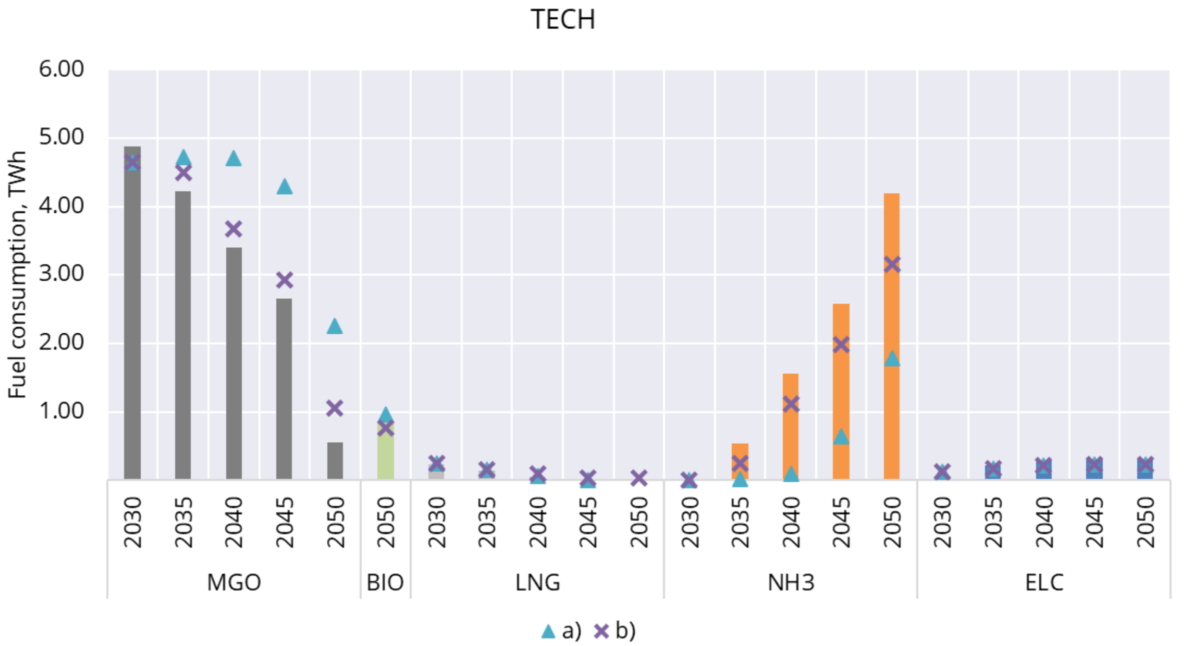


Figure 14. Difference plots for the SOCial scenario. The bars in the Fuel consumption plot represent the aggregated case; the triangle and cross marks in the plots represent Case A and B, respectively.



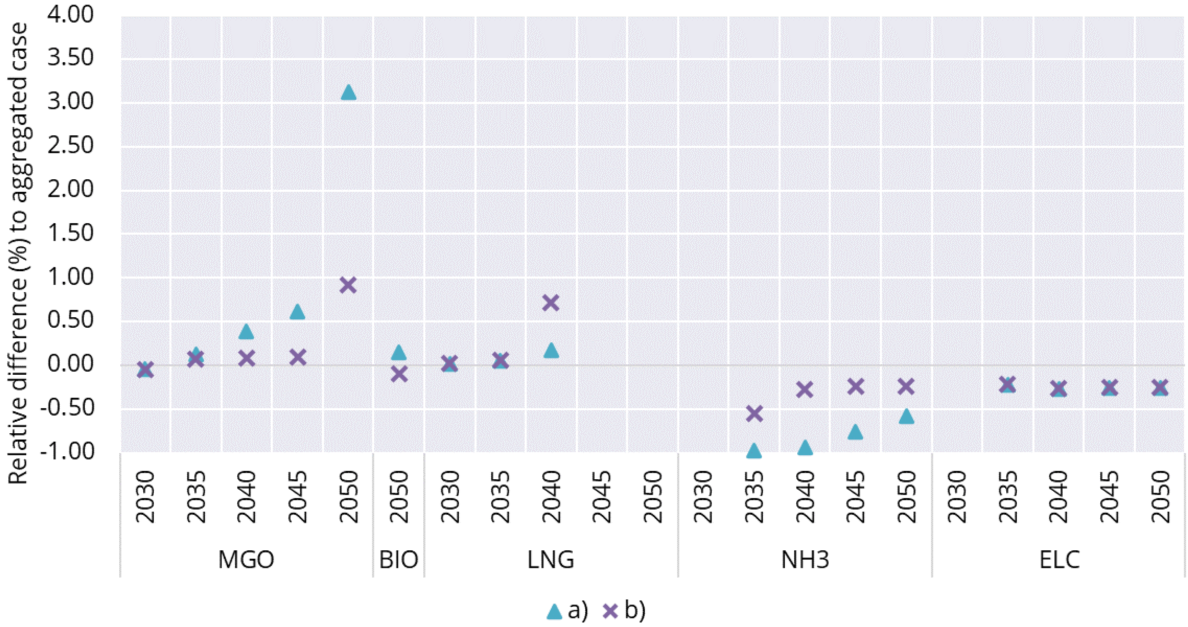


Figure 15. Difference plots for the TECHnological scenario. The bars in the Fuel consumption plot represent the aggregated case; the triangle and cross marks in the plots represent Case A and B, respectively.

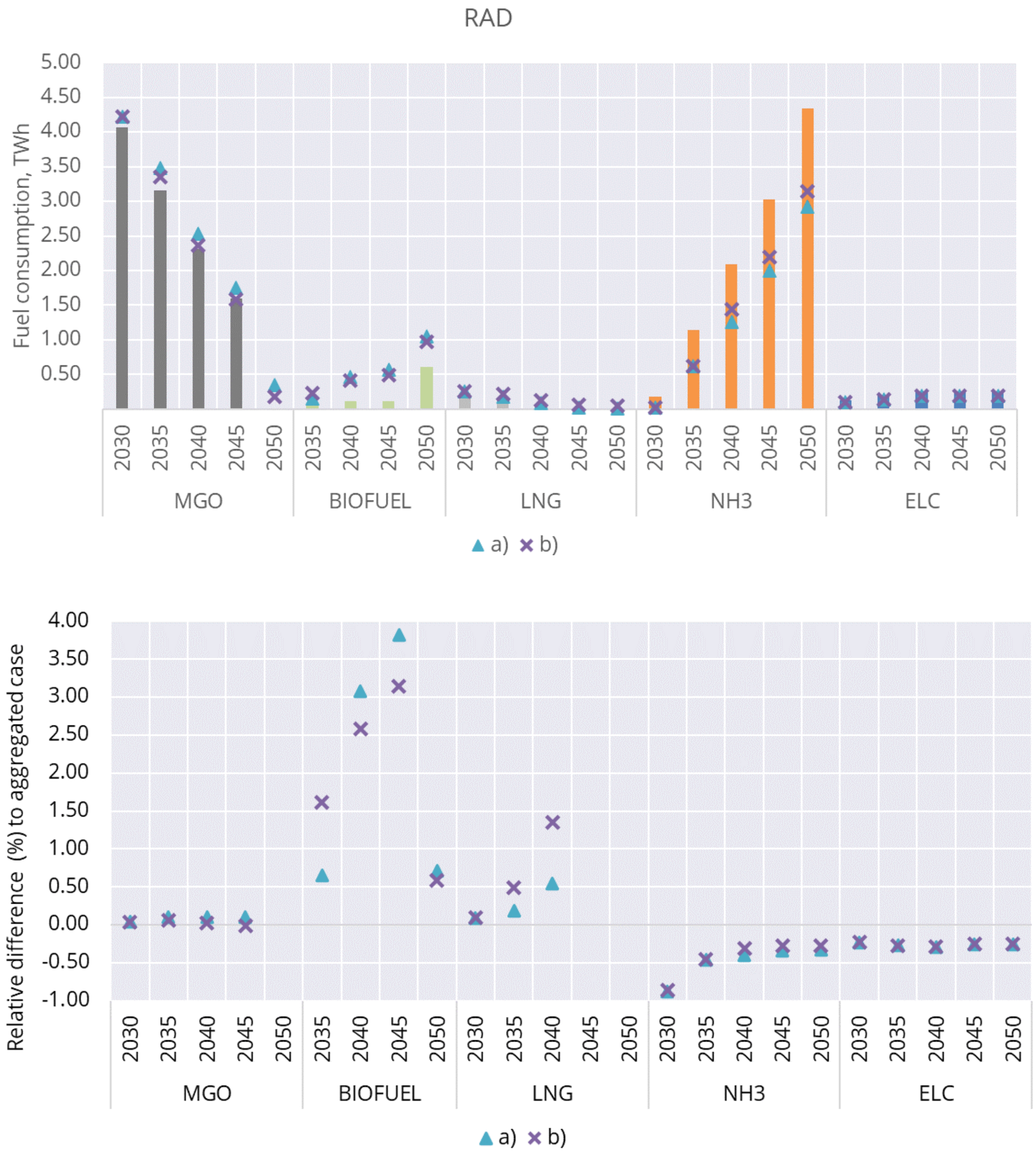


Figure 16. Difference plots for the RADical scenario. The bars in the Fuel consumption plot represent the aggregated case; the triangle and cross marks in the plots represent Case A and B, respectively.

Comparison of maritime freight energy consumption by region in 2050

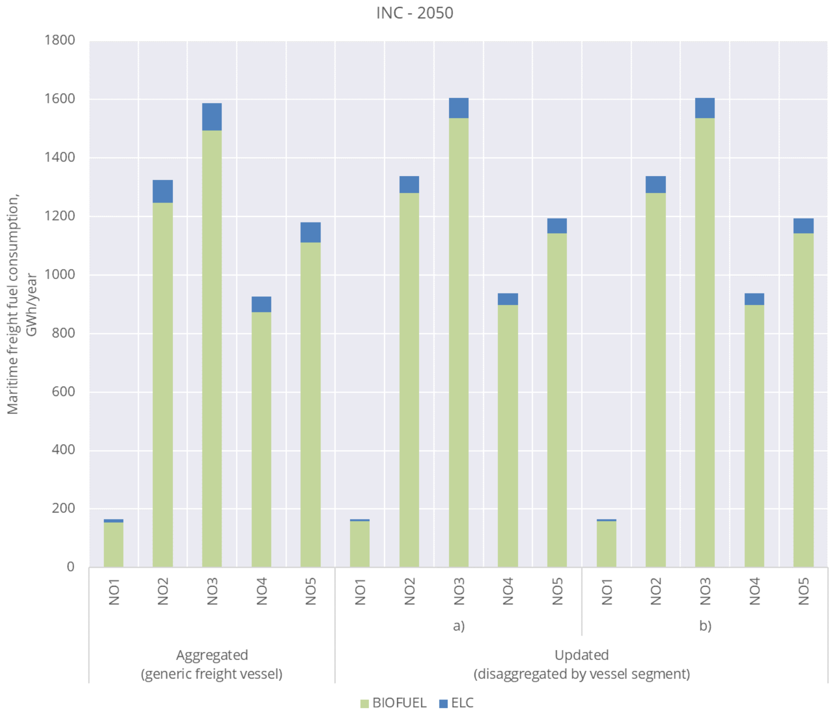


Figure 17. Fuel consumption shares by 2050 across the five bidding areas in the INCremental scenario for the aggregated case and the detailed representations in case a) and b).

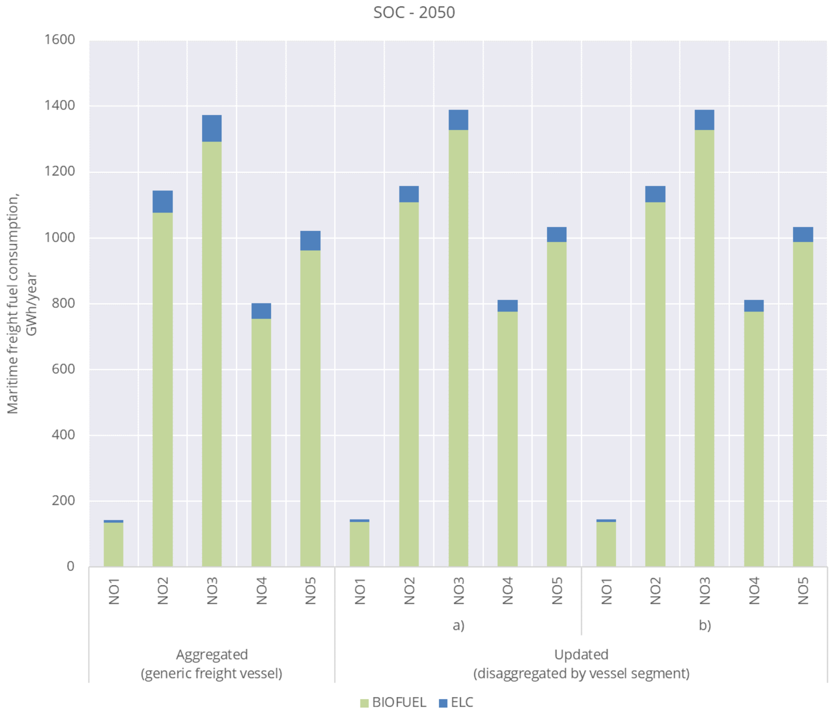


Figure 18. Fuel consumption shares by 2050 across the five bidding areas in the SOCial scenario for the aggregated case and the detailed representations in case a) and b).

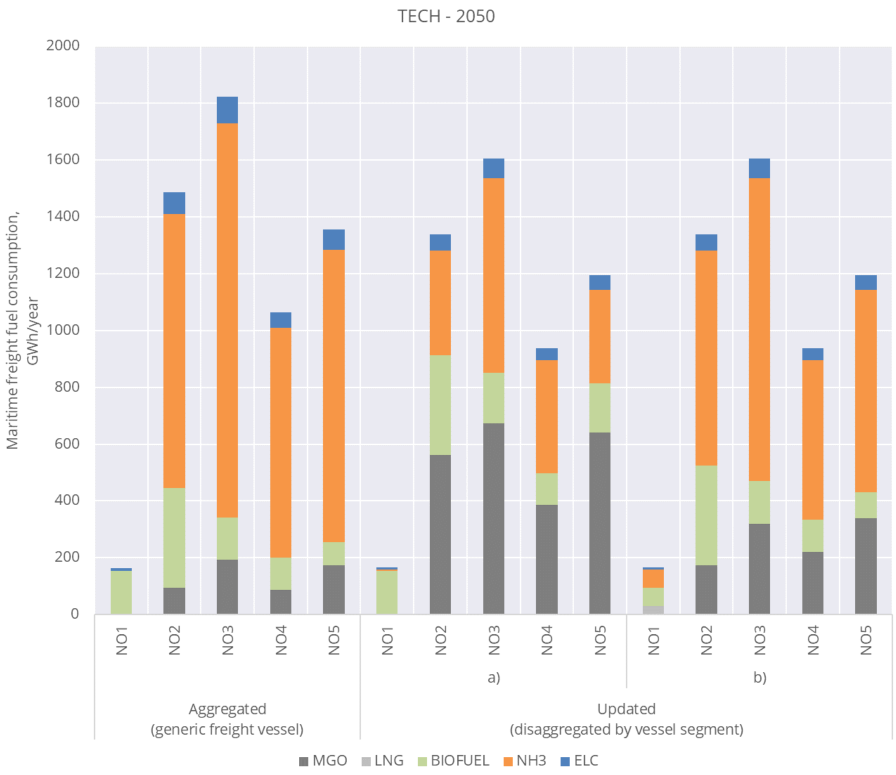


Figure 19. Fuel consumption shares by 2050 across the five bidding areas in the TECHnological scenario for the aggregated case and the detailed representations in case a) and b).

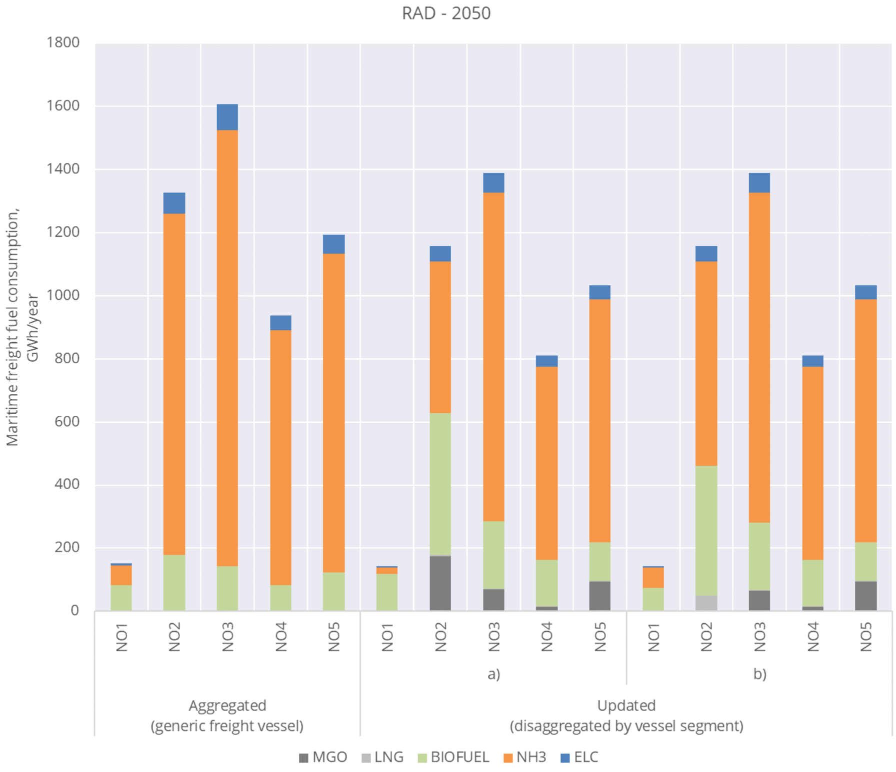


Figure 20. Fuel consumption shares by 2050 across the five bidding areas in the RADical scenario for the aggregated case and the detailed representations in case a) and b).

Shares of freight energy consumption by region and segment in 2050

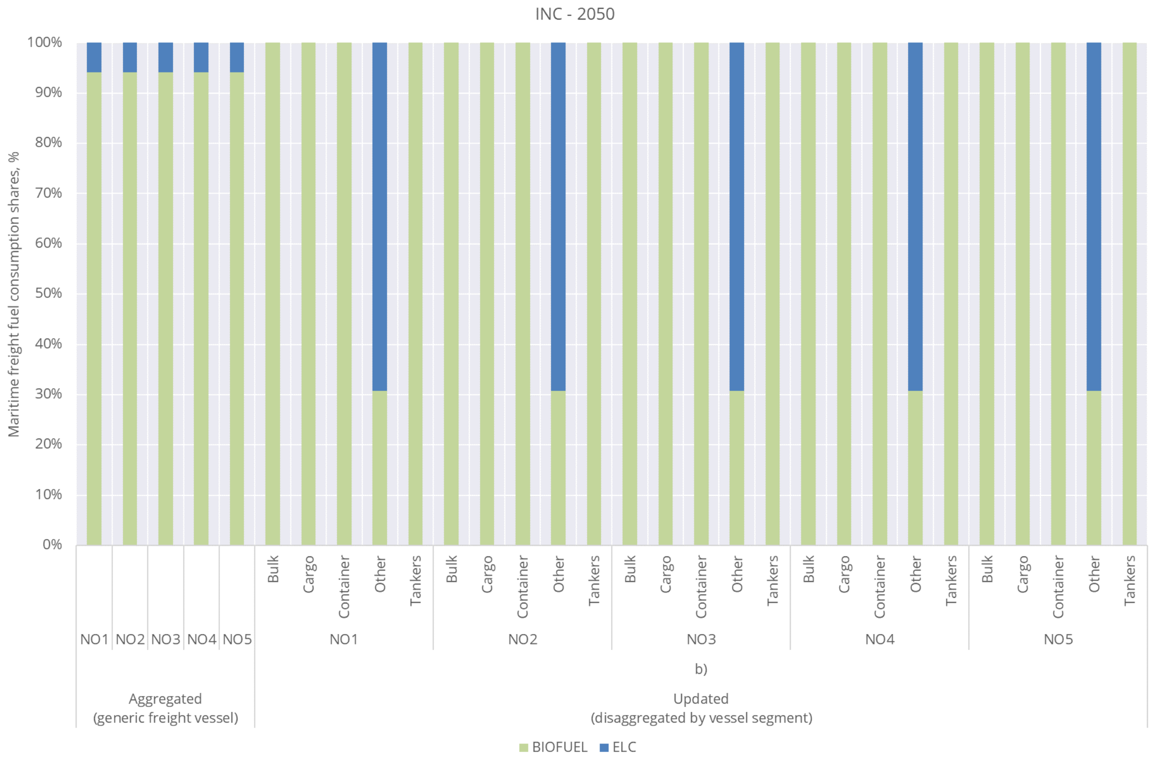


Figure 21. Fuel consumption shares across segments for the INCremental scenario by 2050 for the aggregated case and case b), in all five bidding areas modelled.

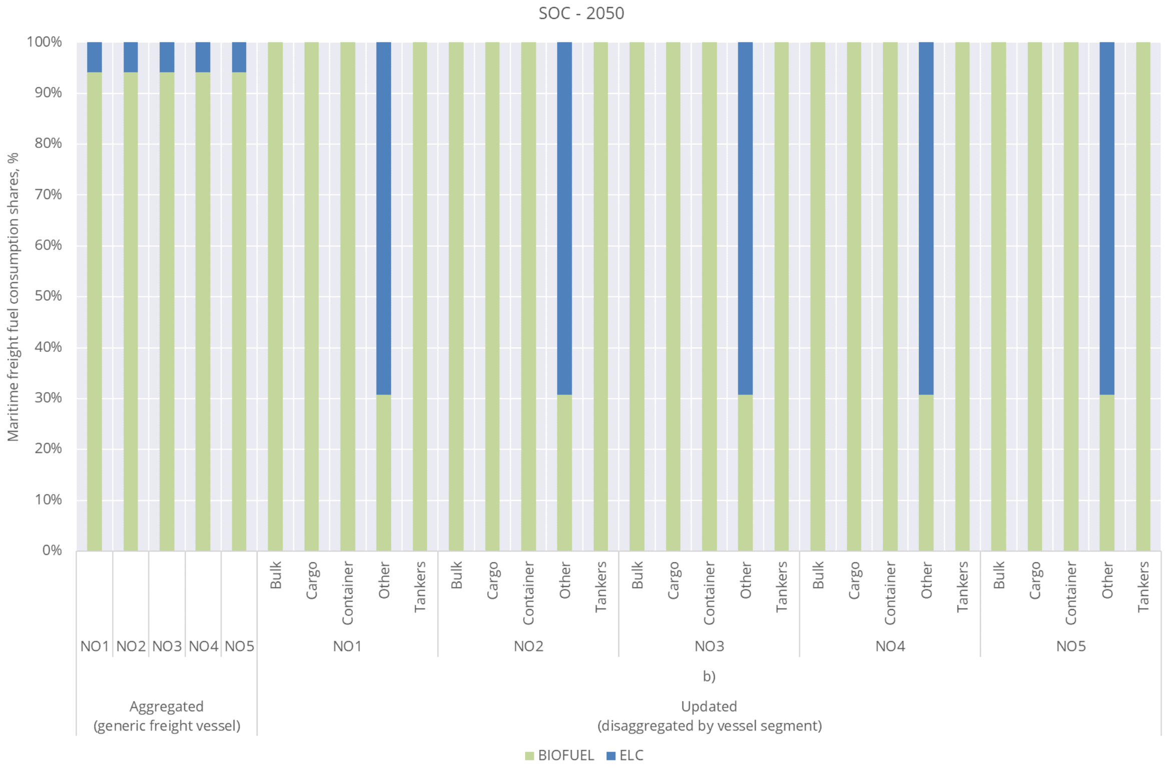


Figure 22. Fuel consumption shares across segments for the SOCial scenario by 2050 for the aggregated case and case b), in all five bidding areas modelled.

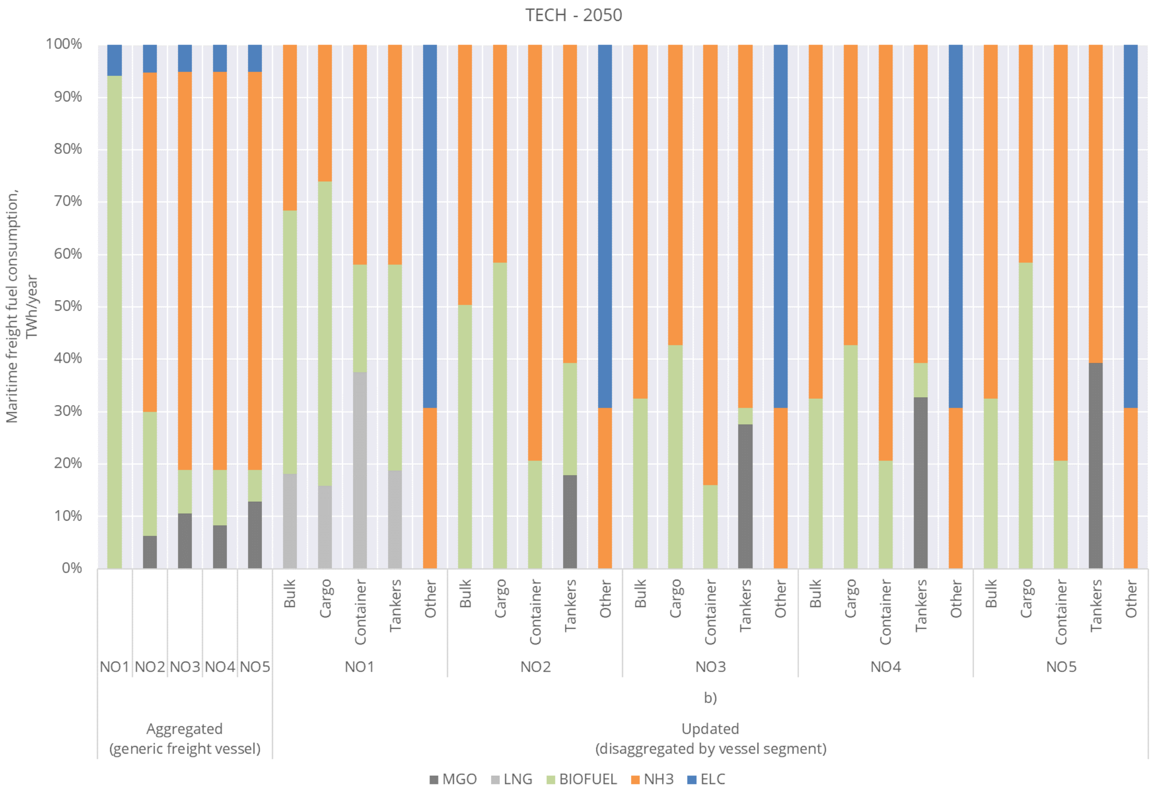


Figure 23. Fuel consumption shares across segments for the TECHnological scenario by 2050 for the aggregated case and case b), in all five bidding areas modelled.

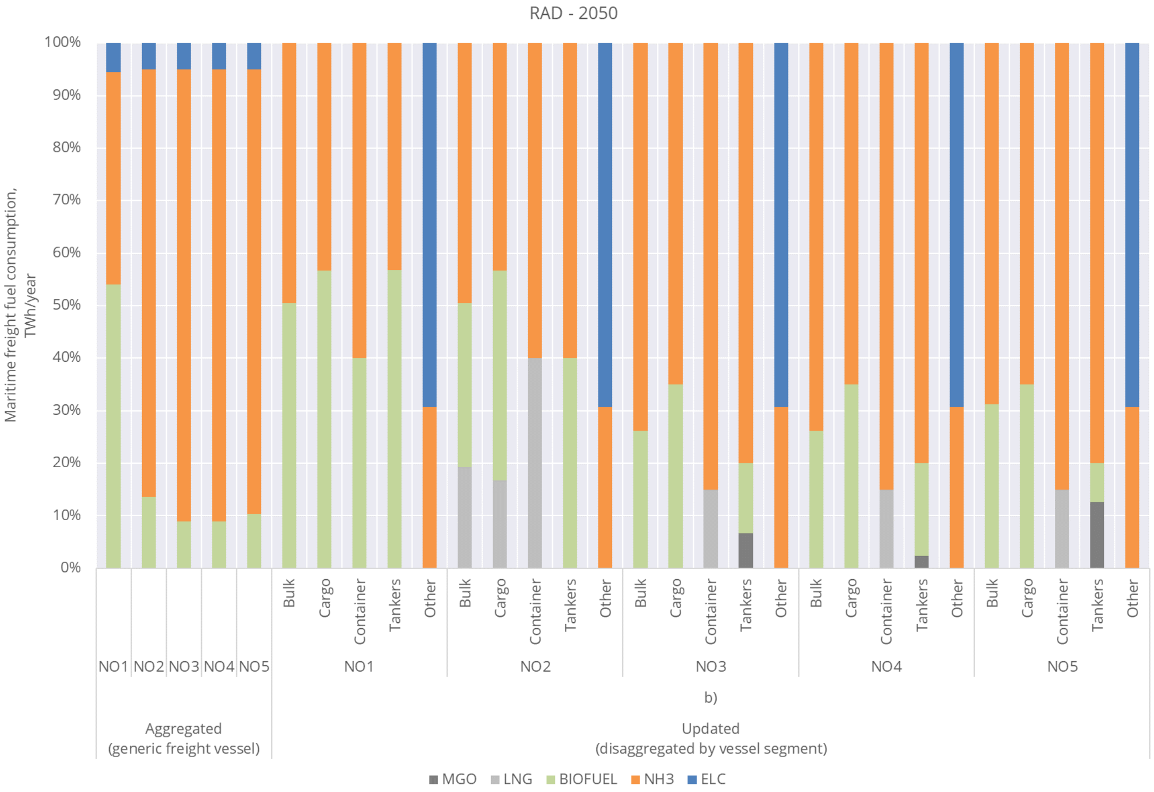


Figure 24. Fuel consumption shares across segments for the RADical scenario by 2050 for the aggregated case and case b), in all five bidding areas modelled.

www.ntnu.no/ntrans

NTRANS

We study the role of the energy system in the transition to the zero-emission society.