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Needs

Dynamic Techno - Economical Scenario Simulation Model for Sustainable Waterborne Activities and Transport

D2.3 Scenarios for the maritime region

Document information	
Short description	Building upon D2.1 and D2.2 and exploiting relevant information from other key sources, this deliverable describes a set of realistic sustainable fuel development scenarios that were developed and analyzed for the Greek maritime region. Proper energy transition pathways are thus identified, providing valuable insights and recommendations to both policy-makers as well as industrial stakeholders.
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Lead authors	Sdoukopoulos E., Ziakas A., Perra V-M (CERTH)
Contributors	
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Table of Contents

List of Figures

List of Tables

Executive summary

Based on the results of D2.1 (i.e. network formation, fleet selected and aggregation of operational data) and D2.2 (i.e. promising energy carriers and overview of sustainable energy production capacities at national level), a set of six realistic sustainable fuel development scenarios for the Greek maritime region are devised herein for identifying the most promising energy transition pathway to be followed for meeting the 90% GHG emission reduction target that has been set for 2050. The six scenarios that were analysed are the following:

SC1 - Business-As-Usual (BAU) scenario

SC2 - Forced Hybrid scenario

SC3 - Forced Electric and BioLNG catamarans scenario

SC4 - Forced Electric short routes, H2 long routes, and BioLNG catamarans scenario

SC5 - Forced Electric short routes, BioLNG long routes, BioLNG catamarans scenario

SC6 - Forced Electric short routes, Hybrid long routes, BioLNG catamarans scenario

Given the characteristics of the relevant business environment, a forced logic was followed for formulating those scenarios disabling the model's power system selection logic. As documented in D2.1, three vessel types are considered (i.e. medium-sized RoPax vessels, large RoPax vessels and catamarans) operating over shipping routes with diverse characteristics. For catamarans vessels, considering both their characteristics as well as their typical operational profile, hybridization and BioLNG use were only considered so that the impact imposed on the quality of service provided is kept at acceptable levels (e.g. average speed reduction) since otherwise the resulting effects on demand may be substantial with customers (i.e. passengers) potential swifting to another mode of transport considering the applicable price difference vis-à-vis quality of service. For RoPax vessels and per the relevant recommendation of WATERBORNE TP, a distance threshold was applied and thus different solutions were considered for vessels operating on short (i.e. <200 nm) and long routes (i.e. >200 nm).

All network, fleet, traffic and energy carrier related data are being outlined and all attributes considered in each scenario are being explained (i.e. fuel consumption, GHG emissions, transport capacity, average speed, associated costs, energy demand). Simulation results are depicted and described for each scenario, taking also a highly informative comparative view that enables to draw some valuable conclusions and identify the most promising energy transition pathway. More specifically, based on the simulation results, SC5 proves to perform best with regard to all attributes taken into consideration. It nearly meets the 90% GHG emission reduction target (-89,7%) while compared to SC3 and SC4 where fossil fuel has also been phased out[1], it accounts for the smallest reduction in transport capacity and average speed, whilst requiring the least amount of additional electric energy. Only CAPEX and OPEX are higher than that of SC3, but at levels that are similar to the other scenarios that were taken into consideration.

[1] Not the case for SC1, SC2 and SC6

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The model's maritime application enabled therefore to draw some important conclusions and provide a set of insightful recommendations for both the model itself and the portal, as well as for the aforementioned energy transition pathway, to the benefit of both policy makers as well as the shipping and the port industry.

List of abbreviations

BAU	Business As Usual
CAPEX	Capital Expenditures
CO2	Carbon Dioxide
CO2e	CO2 equivalent emissions (also known as CO2eq)
ECA	Emission Control Area
GHG	Greenhouse gases
H2	Hydrogen
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
LNG	Liquified Natural Gas
LPP	Length between perpendiculars
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MWh	Megawatt hours
NOx	Nitrogen Oxides
OPEX	Operational Expenditures
OPS	Onshore Power Supply
PM	Particulate Matter
RES	Renewable Energy Sources
SO_2	Sulfur Dioxide
SRIA	Strategic Research and Innovation Agenda
TRL	Technology Readiness Level
WTW	Well-to-Wake

1. Introduction

Building upon the results of (a) D2.1 where detailed data were collected for creating the coastal shipping network of Greece into the model, and simulating the technical and operational characteristics of a highly representative share of the overall fleet that provided services over the network in 2021 (i.e. our reference year) (see Region, Fleet DB and Traffic DB components of the overall modelling framework presented in Figure 1), and (b) D2.2 where the regional capacities in terms of sustainable and renewable energy production were mapped vis-à-vis planned investments, the scenarios that were formulated within the model for identifying promising energy transition pathways that can lead towards achieving, by 2050, the 90% GHG emissions reduction target that has been set, are being presented and analysed herein, providing a set of useful recommendations and insights to both policy makers (e.g. for setting-up favouring regulatory frameworks, providing incentives, etc.) as well as industrial stakeholders (e.g. for prioritizing investments, etc.).

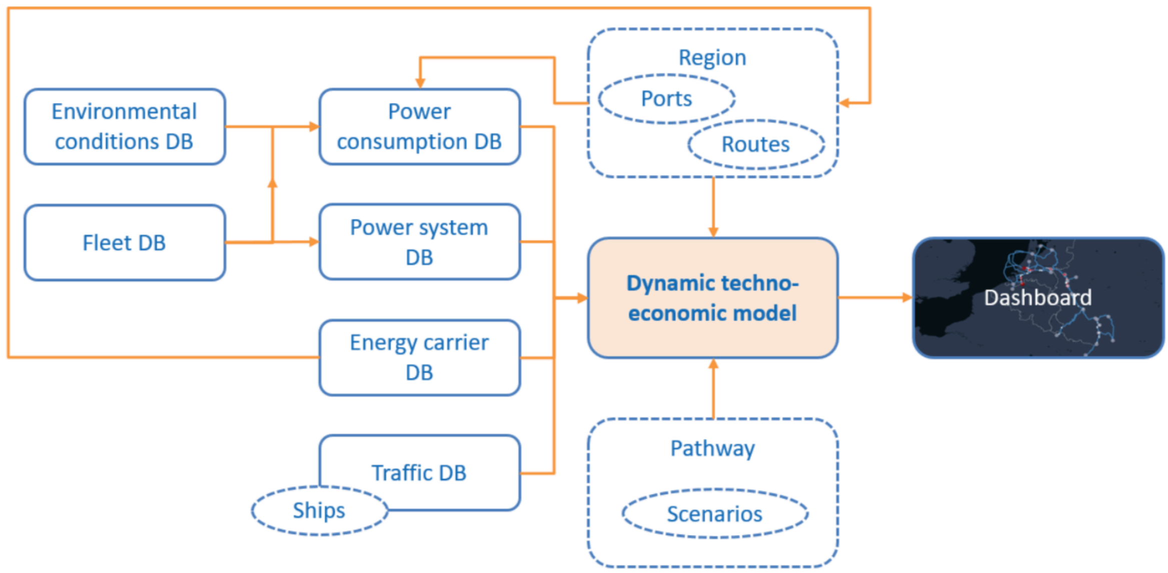

Figure 1: Detailed workflow of the modelling framework (NEEDS, D1.2)

Based on the two aforementioned information sources, the main aim was to formulate and analyse the most realistic scenarios for the region, fleet and operations addressed considering fuel availability status, plans and forecasts, cost implications, etc. Within the scenario formulation process, strategic insights on the decarbonization of waterborne transport, developed within the framework of the STEERER project, were also carefully considered and effectively factored in.

With the model being first applied on the Rhine region[2], its application on the Greek coastal shipping network benefited from the development iterations already conducted and the

[2] Benefiting from the collected data and the background work conducted within the framework and presented in the CCNR studies

competences and knowledge already built. Of course, proper readjustments had to be made so that the model can cater well for the specificities and characteristics of a coastal shipping network and services. More specifically:

- the power system selection logic (see D1.2) had to be disabled since, given the structure and size of the majority of coastal shipping companies, such investment decisions are usually taken at group level considering a variety of influencing factors (e.g. applicable policies, level of service provided to customers, etc.). To this end, a forced logic on selected energy carriers was deemed more appropriate. Furthermore, the 200 nm threshold was applied for differentiating selected energy carriers per the recommendation of WATERBORNE TP as documented in its SRIA for the Partnership on Zero-Emission Waterborne Transport
- changes on the operational profile of selected vessels had to be moderate since prolonging for example journey time over a certain threshold, may negatively affect customer satisfaction and possibly shift part of the demand to air transport (considering the cost difference between those two modes of transport). To this end, sailing speed was inserted as an additional parameter into the model
- given the lack of more relevant data, the innovation level[3] for the Greek region was set to average (see D3.3), and this applied to all scenarios that were formulated

Given the above, besides the business as usual (BAU) scenario that depicts what the situation will be and how it will over time till the selected time horizon (i.e. 2050) if no action is taken, the following five realistic scenarios were formulated and analysed for the Greek maritime region:

SC1 - Business-As-Usual (BAU) scenario

SC2 - Forced Hybrid scenario

SC3 - Forced Electric and BioLNG catamarans scenario

SC4 - Forced Electric short routes, H2 long routes, and BioLNG catamarans scenario

SC5 - Forced Electric short routes, BioLNG long routes, BioLNG catamarans scenario

SC6 - Forced Electric short routes, Hybrid long routes, BioLNG catamarans scenario

Following section 2 where the general assumptions made are being described in more detail, the results of the six scenarios that were taken into consideration are being presented and visualised[4] in section 3. A comparative view of those scenarios is being adopted in section 4, enabling to draw valuable insights and proposed targeted recommendations in section 5, the concluding section of this deliverable.

[3] This influences the prices and availability of the different energy carriers, the capex for refits, the technology readiness level (TRL)

[4] Using the NEEDS portal (https://needs.application.marin.nl/)

2. General assumptions made

Before presenting in detail the scenarios formulated and the corresponding results achieved, it's of real value to summarize first herein the main attributes considered and the general assumptions made, so that the reader can develop a comprehensive understanding of all background knowledge and thus better interpret the scenario results.

2.1 Considered transport network and representative part of the overall fleet

The 151 vessels[5] that provided services over the Greek coastal shipping network in 2021, were grouped into 10 categories and the transport work performed at each one of those categories was calculated, for the reference year, in terms of both passenger and vehicle-miles. Catamaran vessels along with medium-sized and large RoPax vessels were found to have served over 90% of all passenger and vehicle volumes. Those vessels, which amount to 74 in total, were thus selected as a highly representative sample of the overall fleet. A representative shipping route[6] was then selected for each one of the 74 selected vessels (Table 1), with 60 routes being unique (i.e. being served by only one of the selected vessels) and the remaining 14 vessels providing services over 11 routes (Table 2).

Table 1: List of representative routes of the selected 74 vessels

Vessel name	Representative shipping route (port UNLOCODES)	Number of transport journeys completed over each route in 2021
ACHAEOS	GRPIRGRAEGGRAGG	333
ACHILLEAS	GRSKUGRKIM	367
ADAMANTIOS KORAIS	GRAXDGRSAM	258
AGIA THEODORA	GRIGOGRCFU	635
AGIOS SPIRIDON	GRCFUGRIGO	411
ANDREAS KALVOS	GRPKEGRKYL	341
APOLLON HELLAS	GRAEGGRPIR	359
AQUA BLUE	GRLAVGRAGOGRMYRGRKVA	100
AQUA JEWEL	GRKISGRPOAGRDIKGRGYT	59
ARIADNE	GRRHOGRKGSGRVTHGRPIR	24
ARTEMIS	GRJSYGRPASGRSERGRKREGRKMSGRADL	93
BLUE GALAXY	GRCHQGRPIR	142
BLUE HORIZON	GRPIRGRHER	111
BLUE STAR 2	GRRHOGRKGSGRKMIGRPKKGRPMSGRJSYGRPIR	82
BLUE STAR CHIOS	GRSKGGRMYRGRMJTGRJKHGRVTHGRKARGRFOUGREYDGRJMK GRJSYGRPIR	14
BLUE STAR DELOS	GRJTRGRJNXGRPASGRPIR	156

[5] Total number was 153 vessels, but for 2 vessels no relevant data were found to be available

[6] Route over which the selected vessel performed most of its journeys in 2021

BLUE STAR MYCONOS	GRKARGREYDGRJMKGRJSYGRPIR	29
BLUE STAR NAXOS	GRJTYGRAIGGRDONGRJNXGRPASGRPIR	151
BLUE STAR PAROS	GRJMKGRTINGRJSYGRPIR	248
BLUE STAR PATMOS	GRJTRGRIOSGRJNXGRPASGRPIR	57
CALDERA VISTA	GRJSYGRPASGRJNXGRFOLGRSIIGRIOSGRTRSGRJTRGRANA	26
CHAMPION JET 1	GRSKGGRJSIGRSKOGRALOGRKYM	28
CHAMPION JET 2	GRADLGRKREGRSERGRPIR	199
DIAGORAS	GRMJTGRJKHGRPIR	41
DIONISIOS SOLOMOS	GRJTRGRIOSGRSIIGRFOLGRKMSGRADLGRKREGRSERGRKYTGRPIR	98
DODEKANISOS EXPRESS	GRRHOGRKAS	58
DODEKANISOS PRIDE	GRRHOGRSYMGRKGSGRKMIGRPKKGRLIPGRAGN	45
EKATERINI P	GRRAFGRTINGRJMKGRJNXGRKOF	67
ELYROS	GRPIRGRCHQ	151
EXPRESS SKIATHOS	GRALOGRSKOGRGLOGRJSIGRVOL	265
FAST FERRIES ANDROS	GRJMKGRTINGRANDGRRAF	206
FESTOS PALACE	GRPIRGRHERGRSUD	87
FIOR DI LEVANTE	GRKYLGRPKE	394
FLYING CAT 5	GRPIRGRPTRGRHYDGRERMGRSPEGRPHE	95
FLYING CAT 6	GRPIRGRPTRGRHYDGRERMGRSPEGRPHE	179
FLYINGCAT 3	GRRAFGRTINGRJMKGRJNX	50
FLYINGCAT 4	GRPIRGRPTRGRHYDGRSPE	84
HERMES	GRCFUGRIGO	557
HIGHSPEED 4	GRKTPGRKOFGRJNXGRPASGRPIR	62
IONIS	GRLAVGRKEA	278
KEFALONIA	GRKYLGRPKE	241
KERKYRA EXPRESS	GRCFUGRIGO	185
KNOSSOS PALACE	GRPIRGRHERGRSUD	102
KRITI I	GRHERGRPIR	173
KYDON PALACE	GRSUDGRPIR	117
MACEDON	GRKEAGRLAV	348
MARE DI LEVANTE	GRZTHGRKYL	1.028
MARMARI EXPRESS	GRLAVGRKEA	340
NAXOS JET	GRJTRGRHER	34
NISSOS RODOS	GRHERGRPIR	66
NISSOS SAMOS	GRMJTGRJKHGRINOGRPAAGRPIR	70
OLYMPUS	GRJTRGRADLGRKREGRPIR	26
PANAGIA SKIADENI	GR088GRRHO	13
PANORAMA	GRMRMGRRAF	117
PHIVOS	GRAEGGRPIR	391
PORFYROUSA	GRDIKGRNEA	245
POSIDON HELLAS	GRAEGGRPIR	225
POWER JET	GRHERGRJTRGRIOSGRJNXGRJMKGRPASGRJNXGRJTRGRHER	43
PREVELIS	GRPIRGRADLGRJTRGRANAGRHERGRJSHGRKSJGRAOKGRDIAGRHAL GRRHO	41
PROTEUS	GRVOLGRJSIGRGLOGRKYM	81
SANTORINI PALACE	GRHERGRJTRGRJNXGRPASGRJMKGRJSYGRPIR	28
SEA JET 2	GRADLGRKREGRPASGRJMKGRJNXGRKOFGRKTPGRJTRGRFOL GRADLGRKREGRSERGRPIR	97
SIFNOS JET	GRPASGRJMK	23
SPEED CAT 1	GRPIRGRPTRGRHYDGRSPE	185
SPORADES STAR	GRKVAGRMYRGRAGOGRLAV	16

STAVROS	GRRHOGRKAS	141
SUPER FERRY	GRJMKGRTINGRANDGRRAF	249
SUPEREXPRESS	GRRAFGRTINGRJMKGRJNXGRPASGRIOSGRJTR	107
SUPERJET	GRADLGRKREGRPASGRJLKGRJNXGRKOFGRKTPGRJTRGRFOLGRADL GRKREGRSERGRPIR	115
SUPERSTAR	GRPASGRJNXGRJMKGRTINGRANDGRRAF	107
SYMI	GRAKOGRGLYGRJSIGRGLOGRKYMGRANLGRALO	10
THEOLOGOS P	GRJMKGRTINGRANDGRRAF	238
THUNDER	GRJNXGRJMKGRJSYGRPIR	73
WORLDCHAMPION JET	GRJTRGRIOSGRJNXGRJMKGRJSYGRPIR	107

Source: NEEDS, D2.1

Table 2: List of representative shipping routes served by more than one of the selected vessels

	Representative shipping route (port UNLOCODES)	**Selected vessels providing services over the route**
1	GRCFUGRIGO	AGIOS SPIRIDON, HERMES, KERKYRA EXPRESS
2	GRAEGGRPIR	APOLLON HELLAS, PHIVOS, POSIDON HELLAS
3	GRHOGGRKAS	DODEKANISOS EXPRESS, STAVROS
4	GRJMKGRTINGRANDGRRAF	FAST FERRIES ANDROS, SUPER FERRY, THEOLOGOS P.
5	GRPIRGRHERGRSUD	FESTOS PALACE, KNOSSOS PALACE
6	GRKYLGRPKE	FIOR DI LEVANTE, KEFALONIA
7	GRPIRGRPTRGRHYDGRERMGRSPEGRPHE	FLYING CAT 5, FLYING CAT 6
8	GRPIRGRPTRGRHYDGRSPE	FLYINGCAT 4, SPEED CAT 1
9	GRLAVGRKEA	IONIS, MARMARI EXPRESS
10	GRHERGRPIR	KRITI I, NISSOS RODOS
11	GRADLGRKREGRPASGRJMKGRJNXGRKOF GRJTPGRJTRGRFOLGRADLGRKREGRSERGRPIR	SEA JET 2, SUPERJET

Source: NEEDS, D2.1

Considering though the huge, unmanageable effort that would be needed for modelling all 74 vessels and for cutting down the time and resources needed, the selected vessels were structured into 21 groups, with each group sharing a representative set of technical characteristics (i.e. LPP, breadth, draft, speed, power and capacity in terms of both passengers and cars). Those 21 vessel types modelled, operated[7] over the shipping routes of the originally selected vessels belonging to each group.

2.2 Considered energy carriers and technologies

As documented in D2.2 and presented in Figure 2 below, opting for different energy carriers is the only way to achieve a 90% reduction in GHG emissions from shipping. Available solutions are multiple, with each one accounting for a different market share or being at a different stage of technological maturity and uptake, with their future outlook also varying considerably. In its Sustainable Power Database[8] (that is publicly available), MARIN offers a detailed overview of all available solutions, providing a range of characteristics and attributes.

[7] Considering the operational data that were available (see D2.1)
[8] https://sustainablepower.application.marin.nl

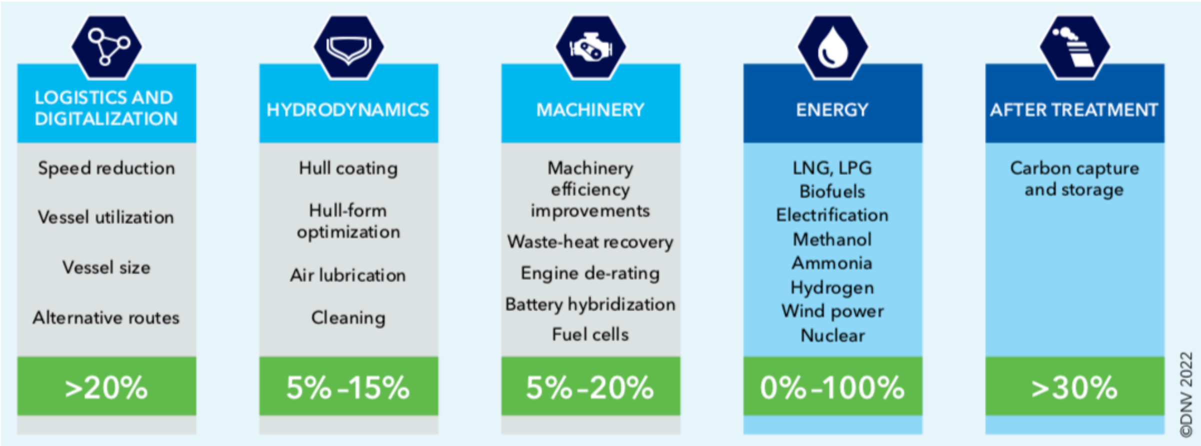

Figure 2: GHG emissions reduction potential of technologies that can contribute to shipping decarbonization

Taking into consideration the technical and operational characteristics of the Greek coastal shipping network (fleet and ports) as well as the energy capacities at regional level (current and planned) as they have been documented in D2.2, eight (8) energy options were selected and integrated into the five (5) sustainable fuel development scenarios that were formulated for the Greek maritime region (Table 3).

Table 3: Energy options selected and integrated in the sustainable fuel development scenarios formulated for the Greek maritime region

Energy group	Energy option
Diesel options	Fossil diesel
	Hydrotreated Vegetable Oil (HVO)
	Biodiesel
Types of liquified methane	BioLNG
Forms of electricity	Grid electricity swapping
	Renewable electricity swapping
Forms of hydrogen	Renewable hydrogen swapping
	CCS hydrogen swapping

Source: Own elaboration

Diesel (drop-in) options

Fossil diesel

Over 95% of the world fleet are still powered by ICEs that run on various petroleum products such as heavy fuel oil (HFO), marine gas oil (MGO) and marine diesel oil (MDO). Such is the case also in the Greek coastal shipping network, where the entire fleet runs on MDO[9].

[9] Blend of gasoil and HFO, resulting from a catalytic cracking and visbreaking refinery

Although it is a relatively cleaner option than HFO (i.e. lower sulphur content), the generated environmental impact is still important. More specifically, MDO combustion releases pollutants of SO_2, NO_x and PM, which lower air quality and can have severe adverse effects on human health[10] and ecosystems. Furthermore, like other fossil fuels, MDO is a source of GHG emissions, primarily CO_2.

Being more refined than HFO, both MGO and MDO account for a higher price. Their price difference with HFO depends on a variety of factors such as regional supply and demand dynamics, geopolitical tensions, etc. Despite being more expensive, MDO offers a range of benefits:

- its sulphur content makes it compliant with the existing IMO regulations (i.e. MARPOL Annex VI – ECAs) and thus there is currently no need to invest in exhaust gas cleaning systems (i.e. scrubbers) and other emission reduction technologies;
- it burns more cleanly and efficiently in ship engines, resulting in reduced carbon deposits in engine components and thus leading to lower maintenance costs and extended engine life;
- it is typically more stable (than HFO) and less prone to microbial contamination, contributing in that way to more reliable engine performance and thus reducing the risk of fuel-related issues during voyage and at berth (e.g. power blackouts);
- it is compatible with a wide range of diesel engines and marine propulsion systems, allowing ships to switch between MDO and other distillate fuels as needed, providing operational flexibility
- MDO is widely available in several ports and regions in Europe and around the world, making it a highly convenient fuel choice

Hydrotreated Vegetable Oil (HVO)

HVO is a renewable diesel fuel derived from various renewable feedstocks such as vegetable oils, animal fats, used cooking oil, crop oils and other bio-based materials. It is produced through a hydrotreating process that removes impurities and refines the feedstock into a high-quality diesel fuel. Regions with access to such feedstocks can thus support local production and reduce reliance on fossil fuels.

HVO is a drop-in replacement for conventional diesel fuels like HFO or MDO, meaning that it can be used as the main engine fuel in vessels equipped with diesel engines[11]. No engine or fuel system modifications are required, and the same goes also for the relevant infrastructure (e.g. storage tanks, refueling equipment). Furthermore, due to the high cetane numbers that it has, HVO can increase engine performance and smoothen its operation, reducing in that way noise levels as well as maintenance requirements.

[10] This is particularly the case in Greece, where the majority of ports are located in close proximity to urban areas

[11] It can also be blended with fossil diesel in various proportions, creating in that way biodiesel blends. This flexibility allows ship operators to tailor their fuel choices based on environmental goals to be reached and fuel availability levels

Due to its low sulphur content, HVO accounts for a low-emission fuel, reducing significantly GHG and PM emissions compared to traditional fossil-based diesel fuels. This makes it an attractive option for coastal shipping operators looking to reduce their environmental impact and comply with emission regulations that apply at different coastal regions. It can thus contribute into improving air quality in port cities and coastal communities. Depending on the feedstock source and production processes, it can even achieve carbon neutrality (e.g. if produced from waste or residues).

The price of HVO is higher than that of fossil-based diesel fuels, with the price difference fluctuating however over time. It largely depends on the cost of the renewable feedstocks used in its production. If those are readily available and competitively priced, the cost of HVO can be quite competitive with fossil-based diesel fuels. Of course, large-scale HVO production facilities can achieve significant economies of scale and thus drive down production costs per unit of fuel.

Its availability varies per region and country (considering feedstock availability). It is more widely available in European countries than in other parts of the world, particularly in Scandinavia and Western Europe, with plans to initiate / expand production and enhance HVO distribution in other parts of the continent already existing[12].

Biodiesel

Biodiesel is a renewable and environmentally friendly alternative to conventional fossil-based diesel fuels. It is typically produced from renewable feedstocks, primarily vegetable oils, animal fats or algae. It can also serve as a drop-in replacement for traditional fuels such as HFO or MDO, without any engine and infrastructure modifications being required. Biodiesel is often blended with conventional diesel[13], with many modern diesel engines being compatible with such blends (e.g. B5 – 5% biodiesel or B20 – 20% biodiesel)[14].

Compared to fossil-based diesel fuels, biodiesel offers several environmental benefits, including a reduction in GHG emissions, as it is derived from organic materials that absorb CO_2 during growth[15]. It also emits fewer harmful pollutants such as SO_2 and PM, contributing towards better air quality in coastal regions. Use of biodiesel can thus help coastal shipping operators comply with existing environmental regulations (e.g. ECAs).

The availability of biodiesel can vary by region since it relies on the availability of the renewable feedstock chosen[16], a choice that also has an impact on costs. In some EU regions,

[12] Case study in Northern Greece (https://www.biofit-h2020.eu/hellenic-petroleum-greece-fossil-refineries/) looking at an annual production of 22.000 tonnes of HVO
[13] Addressing also issues that biodiesel has operating at cold weather – it can get gel at low temperatures
[14] Some older diesel engines may require modifications or retrofits in order to effectively handle higher biodiesel blends. It is essential to ensure that engines are compatible and well-maintained when using biodiesel
[15] It thus also has a lower carbon footprint
[16] Regions with access to feedstock sources like soybean oil, canola oil or palm oil may have a stronger supply of biodiesel

mainly in Northern Europe, biodiesel is readily available at ports and terminals, whereas in others, relevant plans are already in place. However, distribution infrastructure is not so extensive as that of traditional diesel fuels, which poses a challenge.

Types of liquified methane

BioLNG

Bio-LNG is a renewable and sustainable alternative to traditional (i.e. fossil) LNG, with the latter accounting now for the highest rate of adoption among all other alternative marine fuels. BioLNG is being produced from organic materials such as organic waste, agricultural residues or dedicated energy crops through a process known as anaerobic digestion or gasification.

BioLNG can be used as direct substitute in traditional LNG-powered vessels. It accounts for a higher energy density, and can thus provide coastal shipping vessels with the necessary power for covering long-range shipping routes. BioLNG engines[17] tend to produce less noise and vibration, compared to traditional diesel engines, improving in that way overall passenger and crew comfort.

BioLNG is being acknowledged as a low-carbon or even carbon-neutral fuel, since it is produced from organic feedstock that capture CO_2 during their growth. Its use results in significant reductions in GHG emissions, compared to HFO or MDO. It also produces low levels of SO2, NOx and PM, leading to improved air quality in coastal areas.

Ports and terminals with LNG bunkering facilities[18] can potentially offer BioLNG alongside traditional LNG, making it easily accessible to coastal shipping companies. Relevant infrastructure can be easily adapted for BioLNG storage and dispersing. However, BioLNG availability will depend on local access to feedstock, making it suitable for use in certain regions or shipping routes.

Forms of electricity

Electrification of vessels involves the use of electricity as a primary source of power for propulsion and onboard systems use, reducing (in the case of hybrid systems) or eliminating (in the case of fully electric solutions) dependence on traditional fossil-based fuels. Both hybrid and fully electric coastal shipping vessels are already operational in different regions around Europe[19], while in several cases, OPS facilities are available at various European ports with which vessels can connect and use electricity from onshore for powering their systems, allowing them to completely shut down their auxiliary engines during their port stay.

[17] Same for LNG engines
[18] See D2.2 for status of Greek ports
[19] Since as stated before, due to the fact that they operate between fixed points, coastal shipping vessels are excellent candidates for electrification

The environmental benefits derived from such solutions are substantial. However, a number of operational challenges have to be addressed. These are mainly (for fully electric vessels) (a) the vessels' operational range, (b) charging time at ports, and (c) reduced capacity due to the space required for batteries. For expediting the charging process and thus overcoming a major bottleneck that this business case presents, swapping empty with fully charged batteries[20] accounts for a more appropriate approach. The latter was thus adopted differentiating the energy source, i.e. coming from the grid or from renewable energy sources.

Grid electricity swapping

Instead of providing electricity from the grid directly to the vessel (i.e. grid electricity charging), this electricity is being used for charging batteries that are stored onshore waiting to be loaded on incoming vessels. Such electricity is being generated from a mix of sources. In Greece, fossil fuels (i.e. lignite) still hold a major share, although this has started to decrease from year to year with RES (i.e. solar, wind, hydropower) and LNG mainly up-taking this lost share.

As mentioned above, such a solution can substantially or completely eliminate the emission of pollutants at the port area and during voyage (tank-to-wake level). This however will not be the case at the well-to-tank level, since a mix of grey and green electricity is often used in practice.

Of course, such a solution is coupled with some key challenges: (a) the electricity grid needs to present sufficient capacity for adhering to new connections to be established at the port area for recharging the batteries, (b) port authorities and terminal operators need to allocate space and develop the necessary infrastructure for accommodating such an operation, and (c) a proper business model needs to be set for covering the capital expenditure of the batteries (e.g. an energy-as-a-service concept may be a good fit for this case).

Renewable electricity swapping

Renewable electricity swapping differs from the previous solution only in the sense that instead of using electricity from the grid for charging the batteries, electricity generated from renewable energy sources is being used to this end. Therefore, at the well-to-wake level, emissions are totally eliminated.

Forms of hydrogen

Renewable H2 swapping

This solution refers to using electricity produced by a fuel cell for powering a vessel. The hydrogen used in the fuel cell is made available through a swappable storage container following a similar process to that of a swappable container filled with batteries. In this case, hydrogen is being produced through electrolysis using renewable electricity ('green hydrogen').

[20] Possibly stacked in a container that can be used as electricity power source

Of course, due to the nature of hydrogen, additional safety measures need to be taken, while green hydrogen availability and applicable cost levels should also be taken into careful consideration. Availability is expected to be limited and cost levels are expected to be at a high end in the next few years, but both will gradually improve (i.e. greater availability, reduced costs exploiting economies of scale in production) till the targeted time horizon.

CCS H2 swapping

The process remains the same as in the case of renewable H2 swapping, with the only difference that in this case hydrogen is being produced from natural gas ('blue hydrogen') with carbon emissions being captured[21] and stored using CCS technologies. Such infrastructure requires though significant capital investment, and thus production levels and availability should be taken into careful consideration.

2.3 Other attributes

Due to lack of additional (regional) data related to the selected energy carriers and technologies, default data already included in the model's databases[22] were utilized. More specifically, the innovation level was to average for all six (6) scenarios, which influences prices and availability of the selected energy carriers, capex for refits, TRL and social acceptance of the different solutions. Furthermore, as mentioned above, given the characteristics of the respective business environment and the way investment decisions are taken, it was considered more realistic for this case application, to disable the power system selection logic.

[21] Before they are released to the atmosphere
[22] Some extracted from the IWT application (see D3.3)

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3. Scenario results

Results for each of the six (6) scenarios developed for the Greek maritime region can be easily downloaded and visualised via the NEEDS online dashboard. More specifically, after selecting the Greek region from the drop-down list, all scenarios developed are loaded and can be selected. For each of these scenarios, the following information is displayed via charts, and can be downloaded in csv file format, covering the selected time period (i.e. 2020-2050):

- Monthly fuel consumption [MWh]
- Monthly GHG emission [kTon CO2eq]
- Monthly fuel price [€ per kWh]
- Monthly transport capacity [relative to simulation start]
- % of sailing ships [relative to simulation start]
- % of monthly bunker events [relative to simulation start]
- Monthly + cumulative capital expenditure [M€]
- Monthly + cumulative operational expenditure [M€]
- Monthly average speed [kn]
- Total monthly electric energy demand [GWh]

Those charts, and downloadable data, present information for the whole fleet that has been taken into consideration (i.e. all groups), but there is possibility to also select (from a drop-down list) one of the vessel groups considered and display / download the aforementioned information for the selected group.

Besides the charts tab where the data download function is also included, three other tabs are also available:

- *General information* tab, where simulation settings and information on applicable energy carriers and fleet are displayed;
- *Bunkering information* tab, where the monthly bunkered fuel (MWh) is being displayed per port and visualised on the map of the region (via pie charts) over time;
- *Route information tab*, where over the selected shipping routes, the number of ships, CO2eq GWP100 emissions and transport capacity is being displayed via colour scaling over time.

Within the following sub-sections, the results of each of the six (6) scenarios are presented for the *whole representative fleet*, while a highly informative and insightful comparative view is being adopted within the following section.

3.1 SC1 - Business As Usual (BAU) scenario

The following settings were used for the simulation of this scenario:

- The simulation has run from January 1st 2020 to January 1st 2050;

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- Ships have not automatically been added and deleted to the fleet to keep the transport capacity as constant as possible;
- The ships have retained their power system throughout the simulation, unless enforced from the outside;
- The innovation level was set to average. This influences the prices and availability of energy carriers, the CAPEX for refits, the TRL and social acceptance of technology solutions;
- The energy carriers available in the simulation were: **Fossil diesel** and **HVO**.

Quantitative results at key time intervals (i.e. 2025 and 2035) and at the end of the simulation run (i.e. 2049) are being presented below in Table 4[23], while their evolution (per month) over the targeted time framework is being depicted in Figure 3 as generated by the NEEDS portal. Seasonality, a key characteristic of the Greek coastal shipping network, is obvious in all relevant charts.

Table 4: Results of SC1

Year	**2020**	**2025**	**2035**	**2049**
Fuel consumption	155.527,631	154.646,925	149.952,839	148.746,966
Fossil diesel [MWh]	152.946,276	152.728,104	147.748,182	145.725,251
Share (%)	*98,34%*	*98,76%*	*98,53%*	*97,97%*
HVO [MWh]	2.581,355	1.918,821	2.204,657	3.021,715
Share (%)	*1,66%*	*1,24%*	*1,47%*	*2,03%*
GHG emissions [kTon CO2eq]	77,926	77,591	76,198	74,556
% change	*Reference*	*-0,43%*	*-2,22%*	*-4,32%*
Transport capacity [Ton-miles]	90.445.755,57	90.111.638,36	86.394.844,96	86.015.164,45
% change	*Reference*	*-0,37%*	*-4,48%*	*-4,90%*
Total CAPEX (2020-2050)	€ 0			
Total OPEX (2020-2050)	€ 3.791.909.219,30			
Average speed [kn]	18,41	18,41	18,35	18,37
% change	*Reference*	*0,00%*	*-0,33%*	*-0,22%*
Total electricity energy demand [GWh]	0,00	0,00	0,00	0,00

It is clearly depicted that in this 'do-nothing' scenario, fossil diesel continues to dominate the market, with HVO holding a marginal share (2%). A slight reduction (4,3%) in GHG emissions is observed in 2050, which can be attributed to a similar reduction in transport capacity driven by an increase in the price of fossil diesel. The latter also slightly affects average speed, with total OPEX estimated to 3,7 billion €.

[23] Annual averages are calculated, with the exception of GHG emissions that are calculated per peak period over the year (i.e. August)

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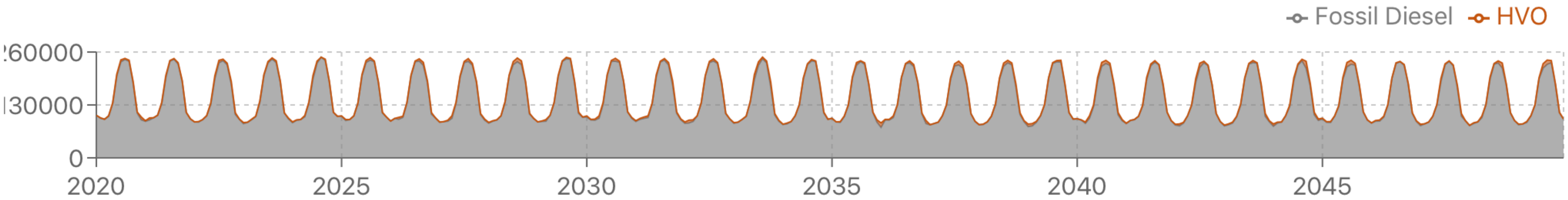
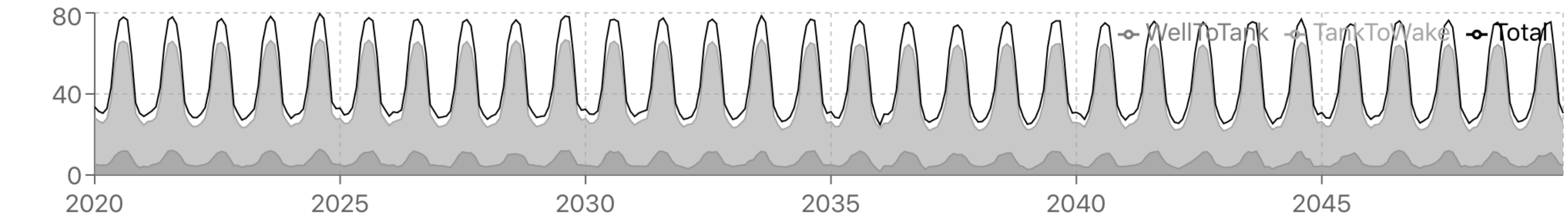
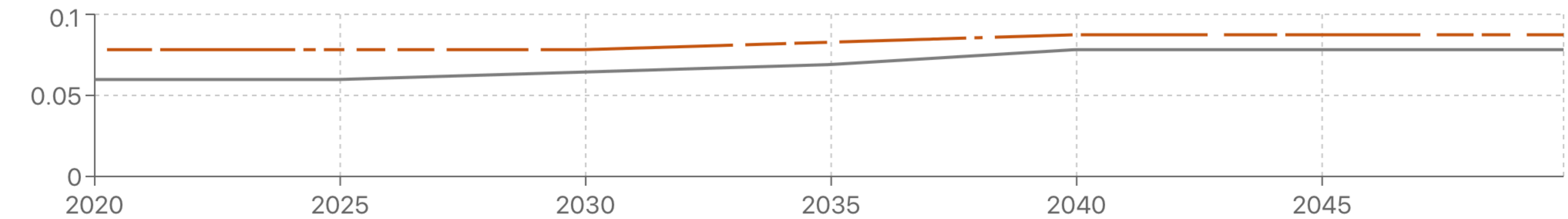
Monthly Fuel Consumption [MWh]



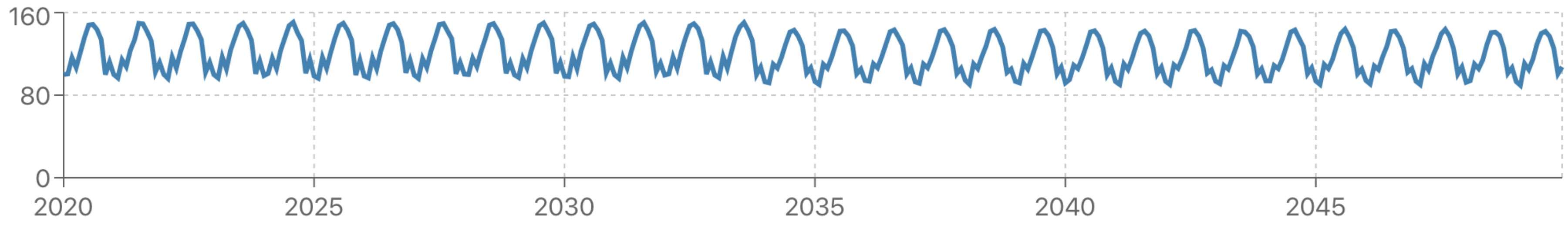
Monthly GHG emission [kTon CO2eq]



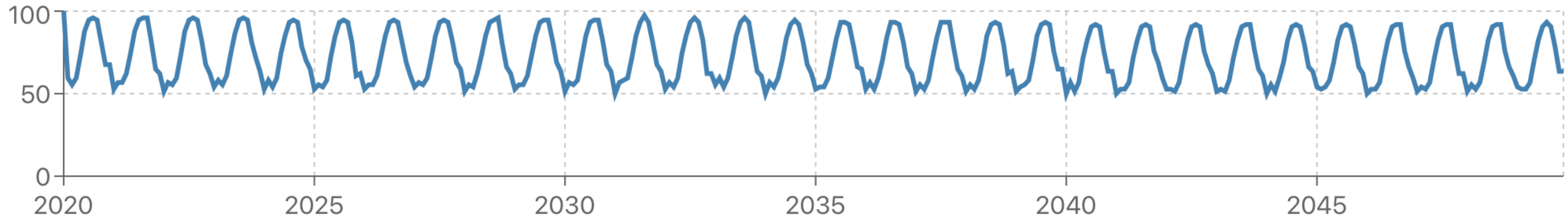
Monthly Fuel Price [Euro per kWh]



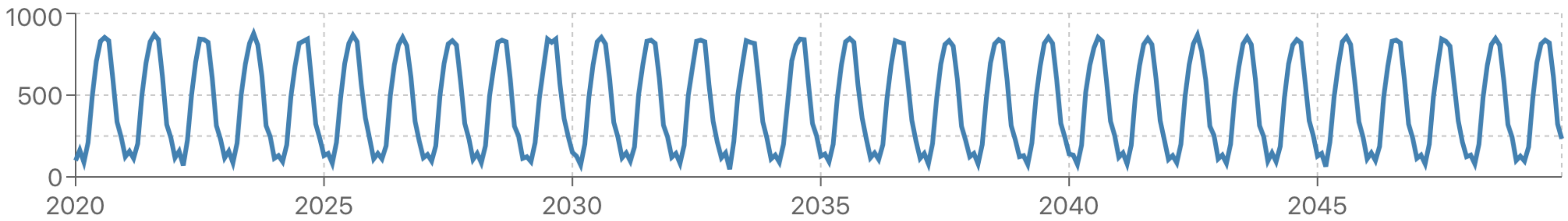
Monthly Transport Capacity [Relative to simulation start]



% of Sailing Ships [Relative to simulation start]



% of monthly bunker events [Relative to simulation start]



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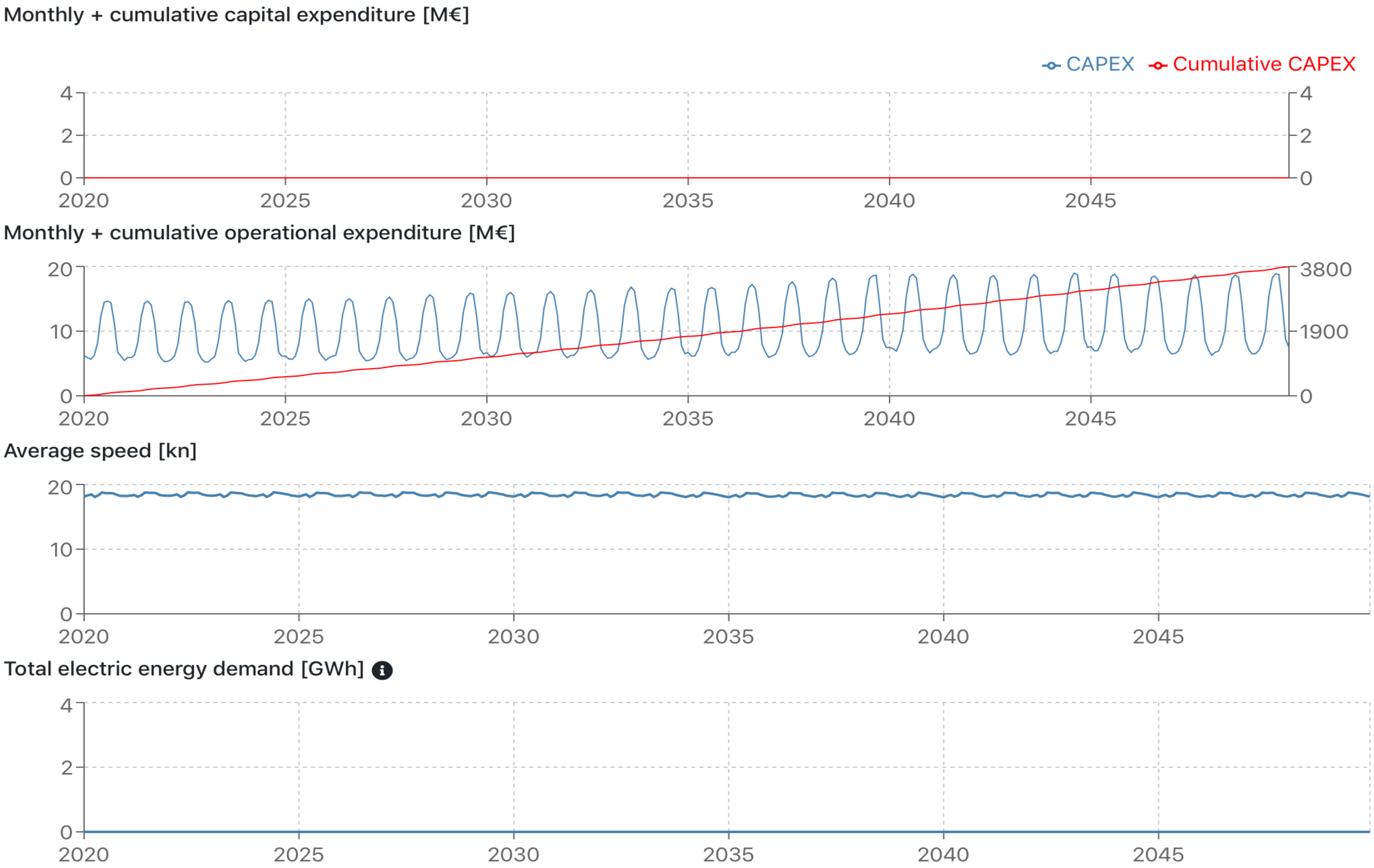

Figure 3: Development of key attributes over time for SC1

3.2 SC2 - Forced Hybrid scenario

The following settings were used for the simulation of this scenario:

- The simulation has run from January 1st 2020 to January 1st 2050;
- Ships have not automatically been added and deleted to the fleet to keep the transport capacity as constant as possible;
- The ships have retained their power system throughout the simulation, unless enforced from the outside;
- The innovation level was set to average. This influences the prices and availability of energy carriers, the CAPEX for refits, the TRL and social acceptance of technology solutions;
- The energy carriers available in the simulation were: **Fossil diesel**, **Biodiesel** and **Grid electricity swapping**

Quantitative results at key time intervals (i.e. 2025 and 2035) and at the end of the simulation run (i.e. 2049) are being presented below in Table 5[24], while their evolution (per month) over the targeted time framework is being depicted in Figure 4 as generated by the NEEDS portal.

Table 5: Results of SC2

Year	2020	2025	2035	2049
Fuel consumption	155.753,025	154.229,794	135.088,923	99.341,834
Fossil diesel [MWh]	152.315,555	151.913,952	127.209,818	88.780,810
Share (%)	*97,79%*	*98,50%*	*94,17%*	*89,37%*
Biodiesel [MWh]	3.437,470	2.300,095	2.473,840	1.331,632
Share (%)	*2,21%*	*1,49%*	*1,83%*	*1,34%*
Grid electricity swapping [MWh]	0	15,747	5.405,265	9.229,392
Share (%)	*0,00%*	*0,01%*	*4,00%*	*9,29%*
GHG emissions [kTon CO2eq]	78,222	77,313	62,571	41,299
% change	*Reference*	*-1,16%*	*-20,01%*	*-47,20%*
Transport capacity [Ton-miles]	90.496.716,12	89.346.778,25	86.581.351,13	83.566.112,78
% change	*Reference*	*-1,27%*	*-4,33%*	*-7,66%*
Total CAPEX (2020-2050)	€ 494.284.538,05			
Total OPEX (2020-2050)	€ 3.352.581.849,92			
Average speed [kn]	18,42	18,42	18,17	17,89
% change	*Reference*	*0,00%*	*-1,36%*	*-2,88%*
Total electricity energy demand [GWh]	0,00	0,01	5,41	9,23

[24] Annual averages are calculated, with the exception of GHG emissions that are calculated per peak period over the year (i.e. August)

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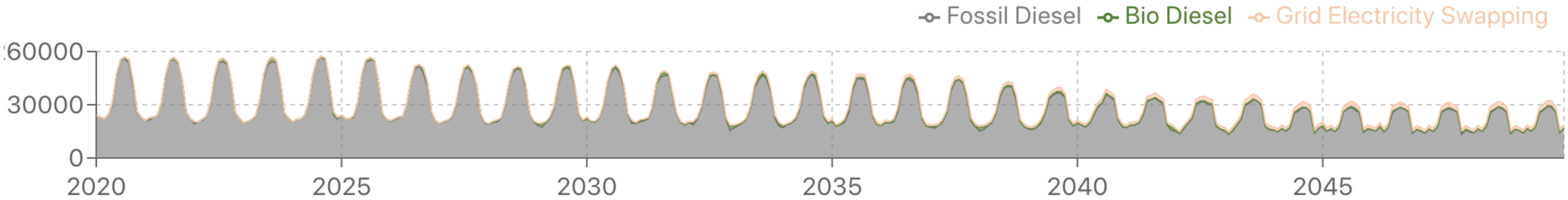
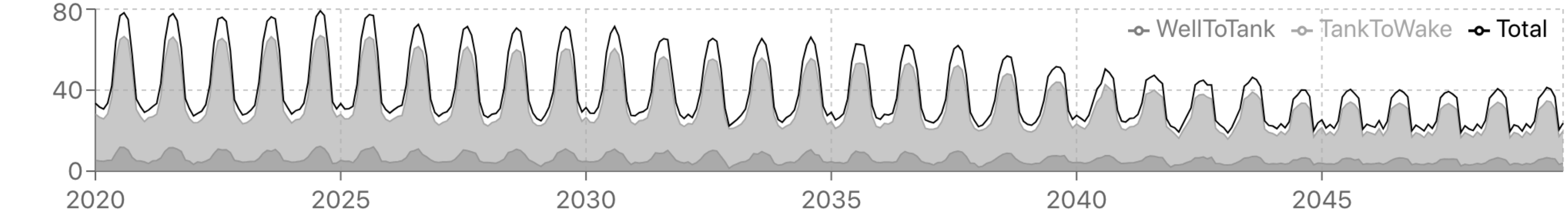
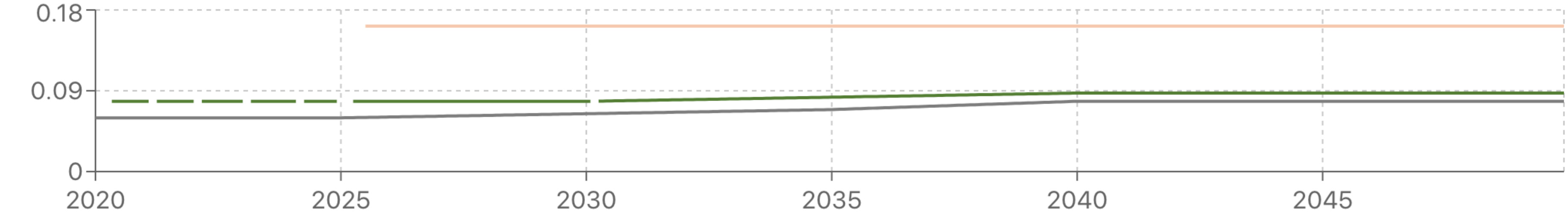
Monthly Fuel Consumption [MWh]



Monthly GHG emission [kTon CO2eq]



Monthly Fuel Price [Euro per kWh]



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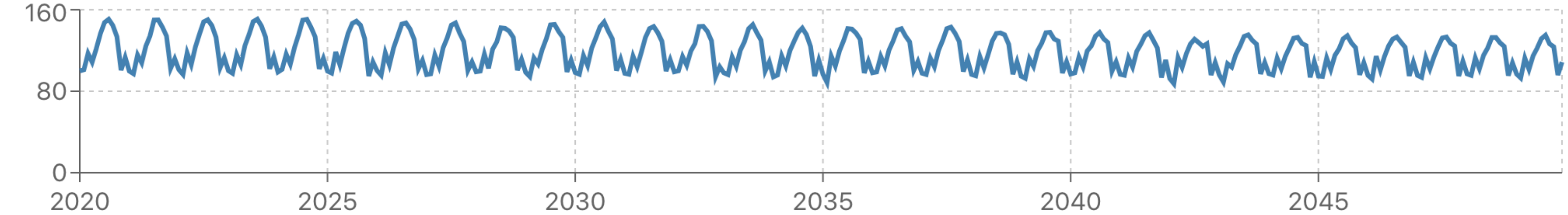
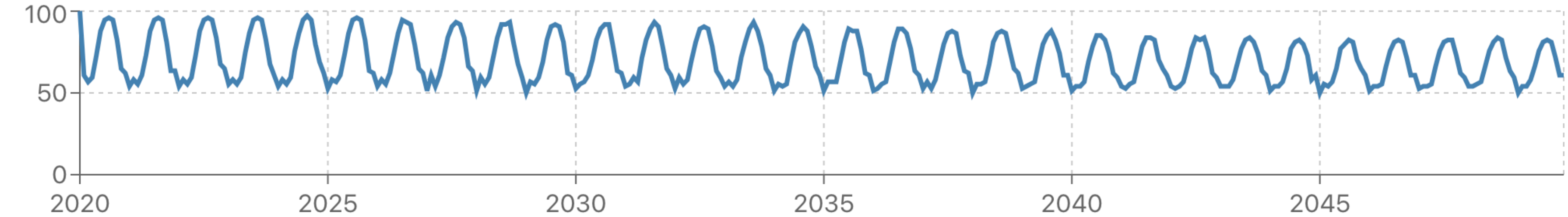
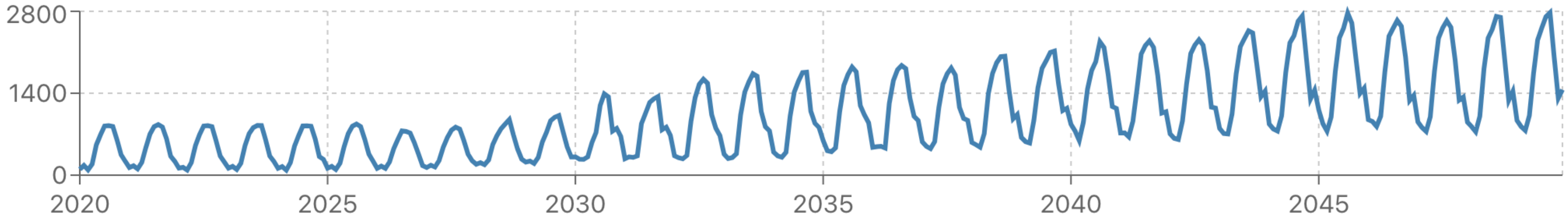
Monthly Transport Capacity [Relative to simulation start]



% of Sailing Ships [Relative to simulation start]



% of monthly bunker events [Relative to simulation start]



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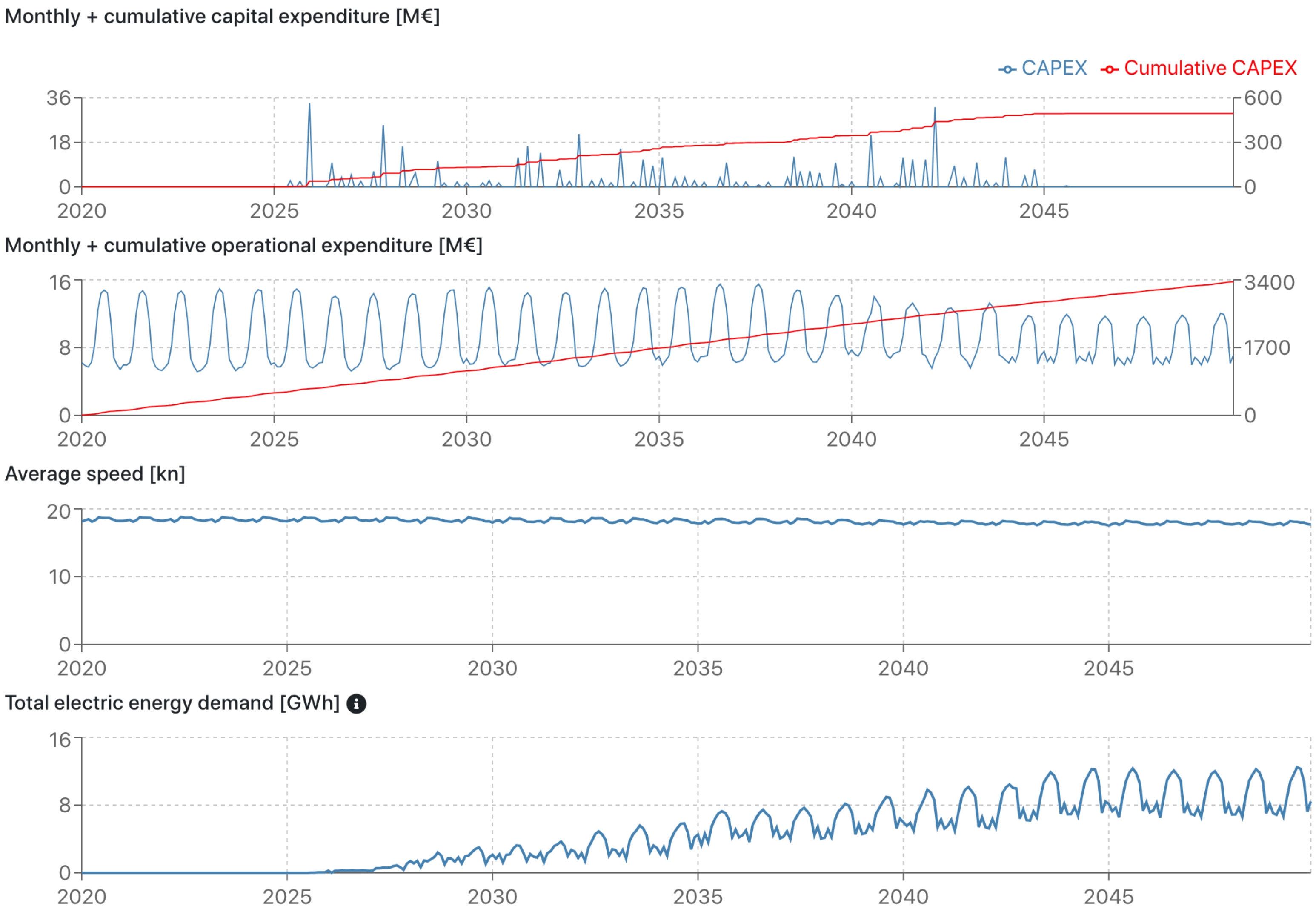

Figure 4: Development of key attributes over time for SC2

In this forced scenario, a swift towards hybridization is being evaluated. Given the time needed for the business case to mature, grid electricity swapping is introduced in July 2025, with fossil diesel dominating the market till then. Despite a considerable increase in the share of grid electricity swapping till our target year (9,3%), fossil diesel still accounts for the preferred fuel option, driven mainly by the large price difference of those two energy carriers. Although the aforementioned share of grid electricity swapping lies at low levels, considerable proves to be the reduction in total fuel consumption (-36,2%) as well as in GHG emissions generated (-47,2%), failing to reach however the 90% GHG emission reduction target that has been set. Transport capacity and average speed are reduced to acceptable levels (-7,7% and 2,9% respectively), while the relevant investment required amounts to approximately 494 million €. Compared to SC1, total OPEX is lower (-11,6%) with 9,23 GWh of electricity being however needed for covering this energy transition. Given planned investments, it is believed that such a requirement for additional energy may be well served.

3.3 SC3 - Forced Electric and BioLNG catamarans scenario

The following settings were used for the simulation of this scenario:

- The simulation has run from January 1st 2020 to January 1st 2050;
- Ships have not automatically been added and deleted to the fleet to keep the transport capacity as constant as possible;
- The ships have retained their power system throughout the simulation, unless enforced from the outside;
- The innovation level was set to average. This influences the prices and availability of energy carriers, the CAPEX for refits, the TRL and social acceptance of technology solutions;
- The energy carriers available in the simulation were: **Fossil diesel**, **Biodiesel**, **Grid electricity swapping**, **Renewable electricity swapping** and **BioLNG**

Quantitative results at key time intervals (i.e. 2025 and 2035) and at the end of the simulation run (i.e. 2049) are being presented below in Table 6, while their evolution (per month) over the targeted time framework is being depicted in Figure 5 as generated by the NEEDS portal.

Table 6: Results of SC3

Year	2020	2025	2035	2049
Fuel consumption	155.615,568	141.375,709	65.528,311	49.479,769
Fossil diesel [MWh]	150.793,568	131.894,304	22.139,266	0
Share (%)	*96,90%*	*93,29%*	*33,79%*	*0,00%*
Biodiesel [MWh]	4.821,832	4.557,196	962,488	0
Share (%)	*3,10%*	*3,22%*	*1,47%*	*0,00%*
Grid electricity swapping [MWh]	0	826,731	20.889,693	27.677,883
Share (%)	*0,00%*	*0,58%*	*31,88%*	*55,94%*
Renewable electricity swapping [MWh]	0	15,558	371,603	592,861
Share (%)	*0,00%*	*0,01%*	*0,57%*	*1,20%*

BioLNG [MWh]	0	4.081,920	21.165,261	21.209,025
Share (%)	*0,00%*	*2,89%*	*32,30%*	*42,86%*
GHG emissions [kTon CO2eq]	77,567	64,200	12,652	4,896
% change	*Reference*	*-17,23%*	*-83,69%*	*-93,69%*
Transport capacity [Ton-miles]	90.441.473,955	88.069.486,858	48.000.954,796	40.386.629,703
% change	*Reference*	*-2,62%*	*-46,93%*	*-55,35%*
Total CAPEX (2020-2050)	€ 217.989.986,00			
Total OPEX (2020-2050)	€ 2.811.284.614.43			
Average speed [kn]	18,43	18,28	16,93	16,28
% change	*Reference*	*-0,81%*	*-8,14%*	*-11,67%*
Total electricity energy demand [GWh]	0,00	0,84	21,26	28,27

In this forced scenario, a swift towards electrification for RoPax vessels is evaluated, with catamarans vessels opting for BioLNG[25] so that their operational profile (e.g. average speed) is not negatively impacted heavily, since otherwise demand may be reduced considerably, possibly swifting to air transport[26]. Electricity from the grid is being considered primarily for battery charging, while marginal is the share of electricity coming from renewable energy sources. The up-take of marine fuels completely changes over time, with fossil diesel that was dominant in 2020 being completely phased out in July 2039. Fuel consumption is thus heavily reduced over the examined time period (-68,2%), and so are GHG emissions, surpassing the 90% GHG emissions reduction target that has been set (-93,7%). Transport capacity however is cut by half due to the rise of bunkering (i.e. battery swapping) events and the reduction in average speed (-11,7%). Plans for filling-up this lost capacity should therefore be carefully devised[27]. Given that a swapping solution was selected for the electrification of RoPax vessels and considering the investment needed for converting conventional engines to be more flexible in fuel type including BioLNG, CAPEX is relatively low. So is OPEX, considering the development of fuel prices and the operational characteristics of the selected energy carriers. The total electricity demand for materializing such an energy transition is however high (28,27 GWh), pointing out the need for heavy investments on sustainable energy production facilities.

[25] Same for all 3 scenarios that follow
[26] Depends on the price difference per service characteristics
[27] New vessel deployment for example

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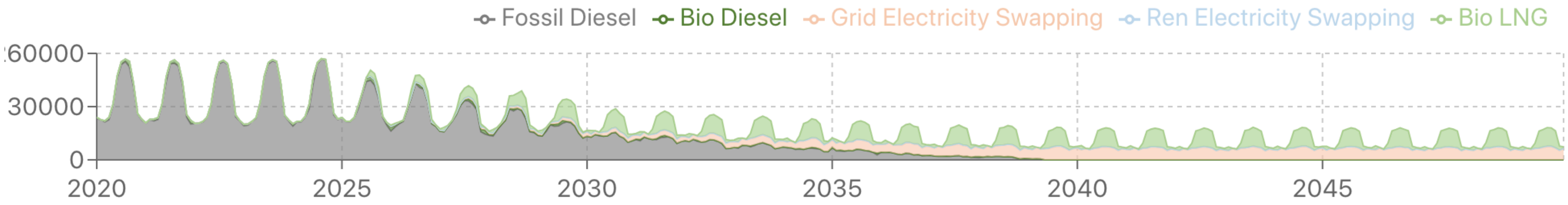
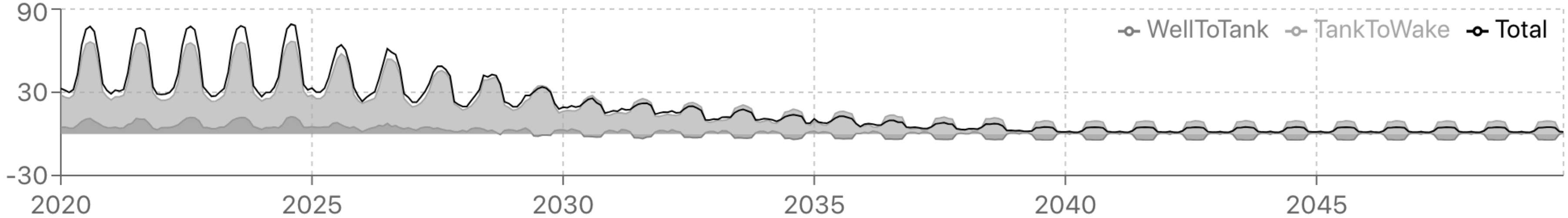
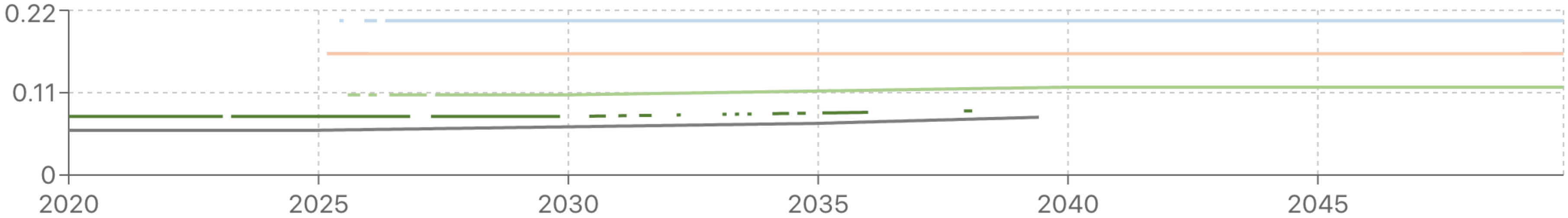
Monthly Fuel Consumption [MWh]



Monthly GHG emission [kTon CO2eq]



Monthly Fuel Price [Euro per kWh]



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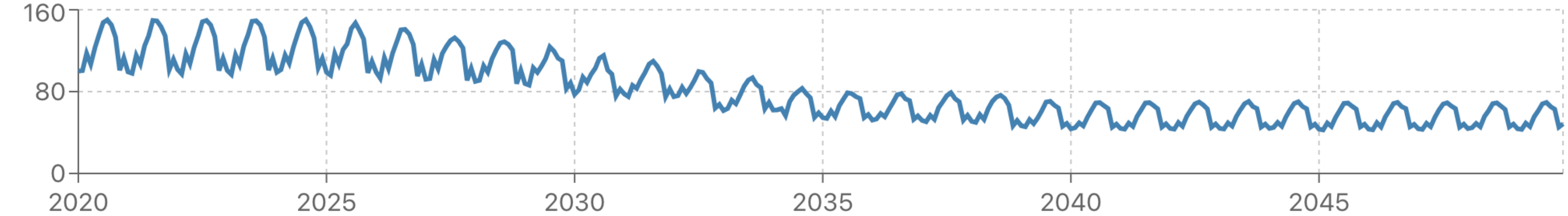
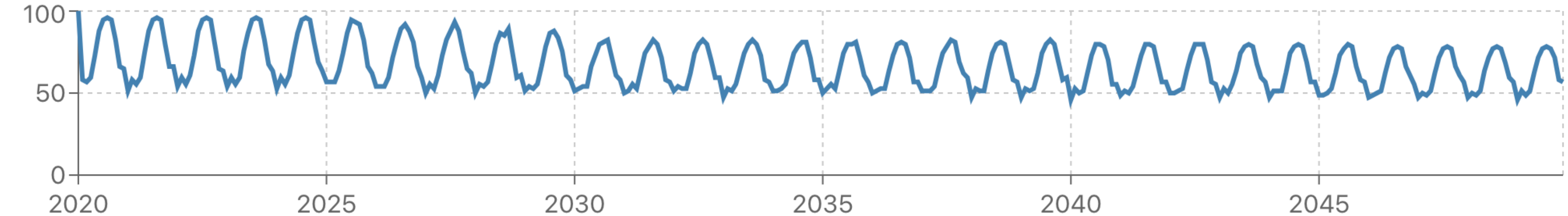
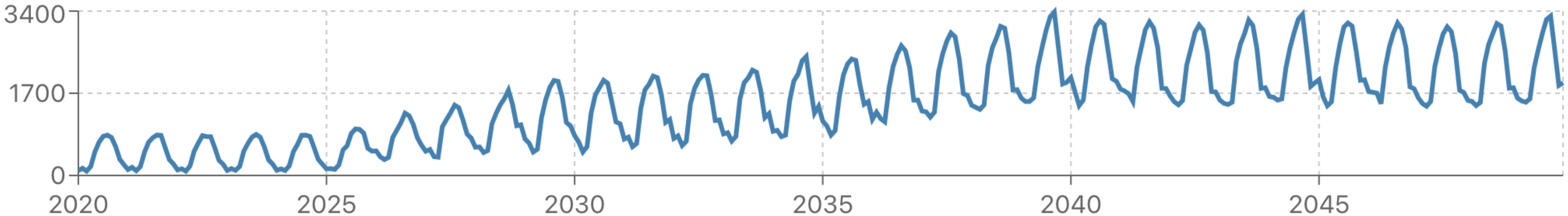
Monthly Transport Capacity [Relative to simulation start]



% of Sailing Ships [Relative to simulation start]



% of monthly bunker events [Relative to simulation start]



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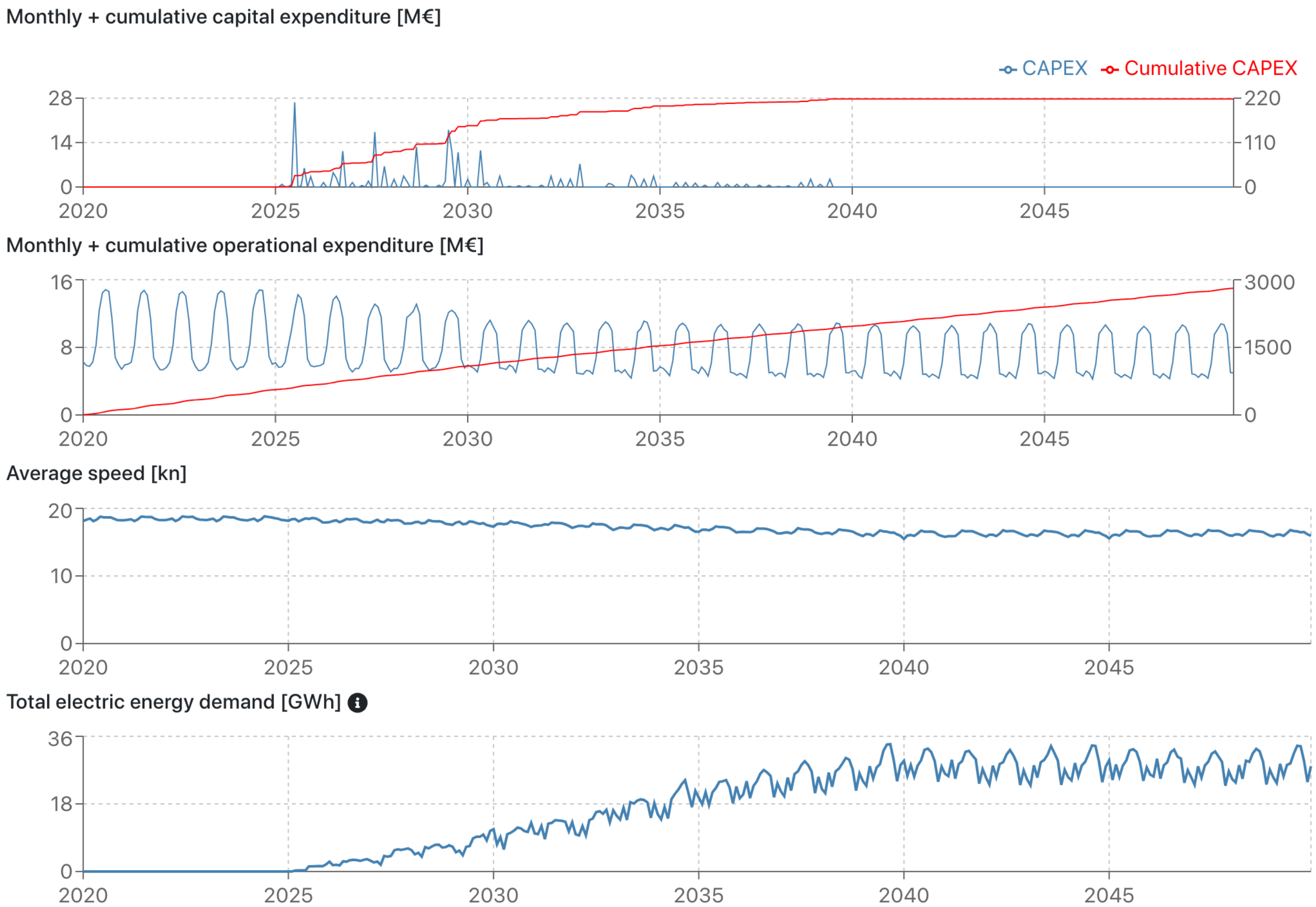

Figure 5: Development of key attributes for SC3

3.4 SC4 - Forced Electric short routes, H2 long routes and BioLNG catamaran scenario

The following settings were used for the simulation of this scenario:

- The simulation has run from January 1st 2020 to January 1st 2050;
- Ships have not automatically been added and deleted to the fleet to keep the transport capacity as constant as possible;
- The ships have retained their power system throughout the simulation, unless enforced from the outside;
- The innovation level was set to average. This influences the prices and availability of energy carriers, the CAPEX for refits, the TRL and social acceptance of technology solutions;
- The energy carriers available in the simulation were: **Fossil diesel**, **Biodiesel**, **BioLNG**, **Grid electricity swapping**, **Renewable electricity swapping**, **Renewable H2 swapping** and **CCS H2 swapping**

Quantitative results at key time intervals (i.e. 2025 and 2035) and at the end of the simulation run (i.e. 2049) are being presented below in Table 7, while their evolution (per month) over the targeted time framework is being depicted in Figure 6 as generated by the NEEDS portal.

Table 7: Results of SC4

Year	2020	2025	2035	2049
Fuel consumption	155.802,169	154.892,491	124.621,736	81.966,602
Fossil diesel [MWh]	151.013,284	150.812,823	82.828,871	0
Share (%)	*96,93%*	*97,37%*	*66,46%*	*0,00%*
Biodiesel [MWh]	4.788,885	2.839,997	1.936,313	0
Share (%)	*3,07%*	*1,83%*	*1,55%*	*0,00%*
BioLNG [MWh]	0	535,374	4.477,335	21.123,681
Share (%)	*0,00%*	*0,35%*	*3,59%*	*25,77%*
Grid electricity swapping [MWh]	0	27,347	7.418,996	12.462,809
Share (%)	*0,00%*	*0,02%*	*5,95%*	*15,20%*
Ren electricity swapping [MWh]	0	2,385	160,451	240,722
Share (%)	*0,00%*	*0,00%*	*0,13%*	*0,29%*
Ren H2 swapping [MWh]	0	0	27.799,770	48.139,390
Share (%)	*0,00%*	*0,00%*	*22,31%*	*58,73%*
CCS H2 swapping [MWh]	0	674,565	0	0
Share (%)	*0,00%*	*0,44%*	*0,00%*	*0,00%*
GHG emissions [kTon CO2eq]	77,197	78,908	47,942	4,207
% change	*Reference*	*+2,22%*	*-37,90%*	*-94,55%*
Transport capacity [Ton-miles]	90.487.069,996	88.835.222,317	64.295.551,293	45.680.396,55
% change	*Reference*	*-1,83%*	*-28,95%*	*-49,52%*
Total CAPEX (2020-2050)	€ 1.928.630.306,00			
Total OPEX (2020-2050)	€ 3.492.023.640,85			
Average speed [kn]	18,42	18,42	17.63	16.97
% change	*Reference*	*0,00%*	*-4,29%*	*-7,87%*

Total electricity energy demand [GWh]	0,00	0,03	52,42	90,35

As was the case in the previous scenario, BioLNG is also the preferred fuel choice in this scenario for catamarans. For RoPax vessels though, an important distinction was made following the recommendation of WATERBORNE TP as documented in its 'Strategic Research and Innovation Agenda for the Partnership on Zero-Emission Waterborne Transport'. More specifically, a distance threshold was applied (i.e. 200 nm). To this end, for RoPax vessels proving services over shipping routes up to 200 nm, electrification was selected as the preferred choice, whereas for RoPax vessels that provide services over longer routes, the use of hydrogen was examined[28]. Swapping solutions were considered in both cases for expediting bunkering time and thus forming a realistic business case. Electricity from both the grid and renewable energy sources was taken into account for the electrification of RoPax vessels operating on shorter routes, while both green and blue hydrogen were considered for the powering of RoPax vessels operating on longer routes.

With such a setting, results indicate that fuel consumption will be cut in half by 2050 (-47,4%), with fossil diesel being phased out in September 2044. Given the time needed for hydrogen use to mature as a business case tackling all technological, safety and regulatory issues, green hydrogen starts dominating the domestic market from 2040 and onwards, with grid electricity swapping also holding an important share since given the network's structure, several shipping routes are short ones i.e. below the threshold that was set. In season peaks (i.e. summer months), consumption of BioLNG increases considerably, since it is then that catamarans are deployed serving demand increases[29]. In line with the above, heavy is also the reduction of GHG emissions, surpassing the 90% reduction target that has been set for 2050. Similarly to SC3, transport capacity is cut in half[30] and thus plans for filling-up this lost capacity should be devised. Given all issues that have to be tackled and the infrastructure that needs to be in place for safely using hydrogen, CAPEX is very high (1,9 billion €), while OPEX lies within the same level as that in SC1 and SC2. Average speed is reduced to acceptable levels (i.e. -7,9%). Particular attention should be placed though on the electricity energy required, which amounts to 90,35 GWh by 2050. Given existing and planned energy productivity, it is highly unlikely that such a requirement can be successfully met unless the untapped potential that the country offers in terms of offshore projects is effectively exploited (i.e. after resolving all regulatory hurdles).

[28] Considering pilot production activities (for green hydrogen) that have been planned in Greece, with the construction of the relevant infrastructure being ongoing

[29] The majority of them does not usually provide services over the winter period

[30] Again due to the increase of bunkering events and the reduction of average speed

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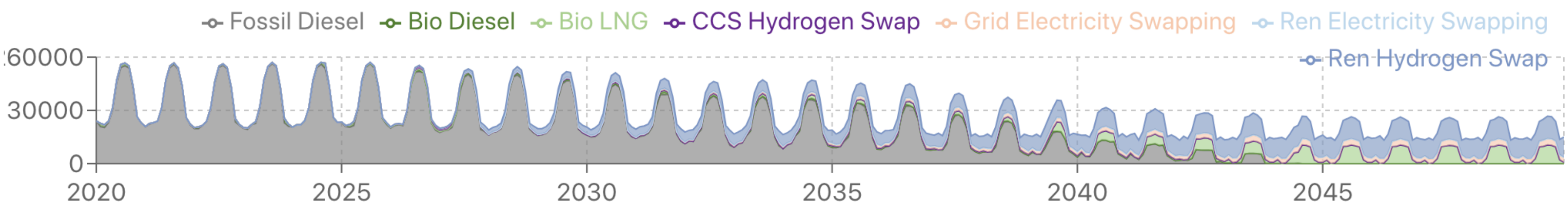
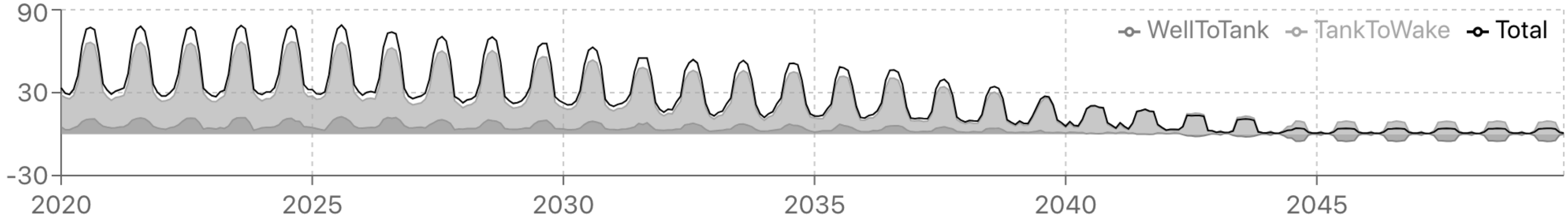
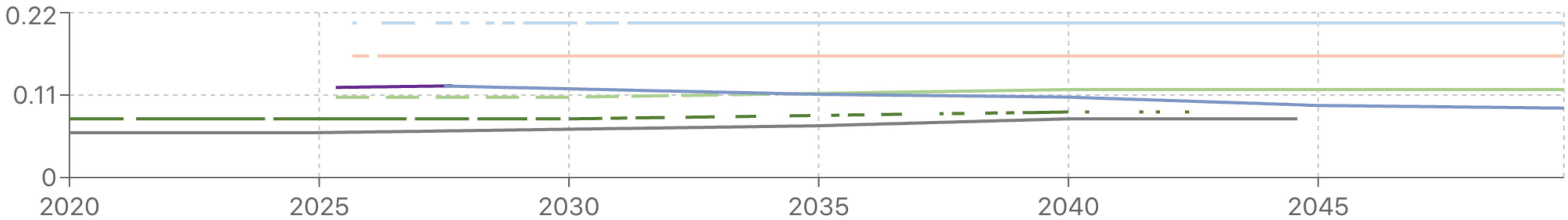
Monthly Fuel Consumption [MWh]



Monthly GHG emission [kTon CO2eq]



Monthly Fuel Price [Euro per kWh]



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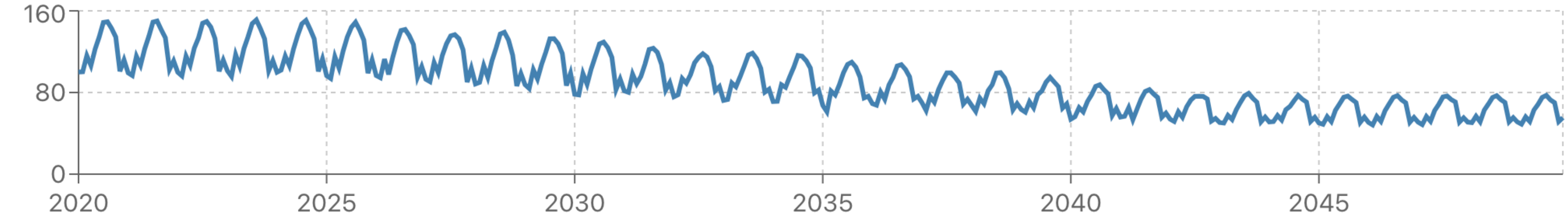
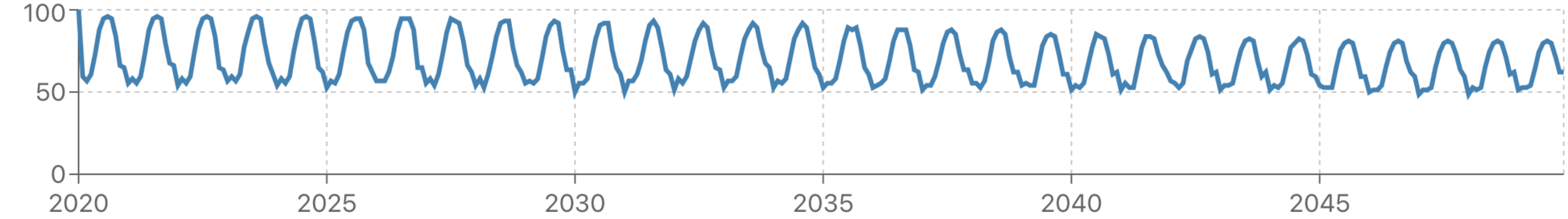
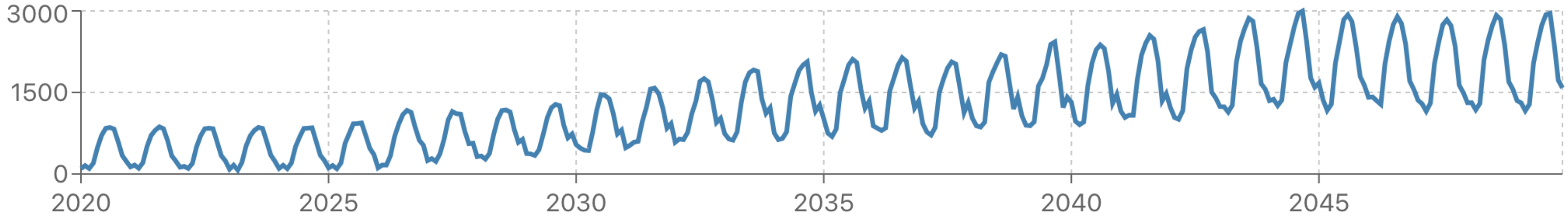
Monthly Transport Capacity [Relative to simulation start]



% of Sailing Ships [Relative to simulation start]



% of monthly bunker events [Relative to simulation start]



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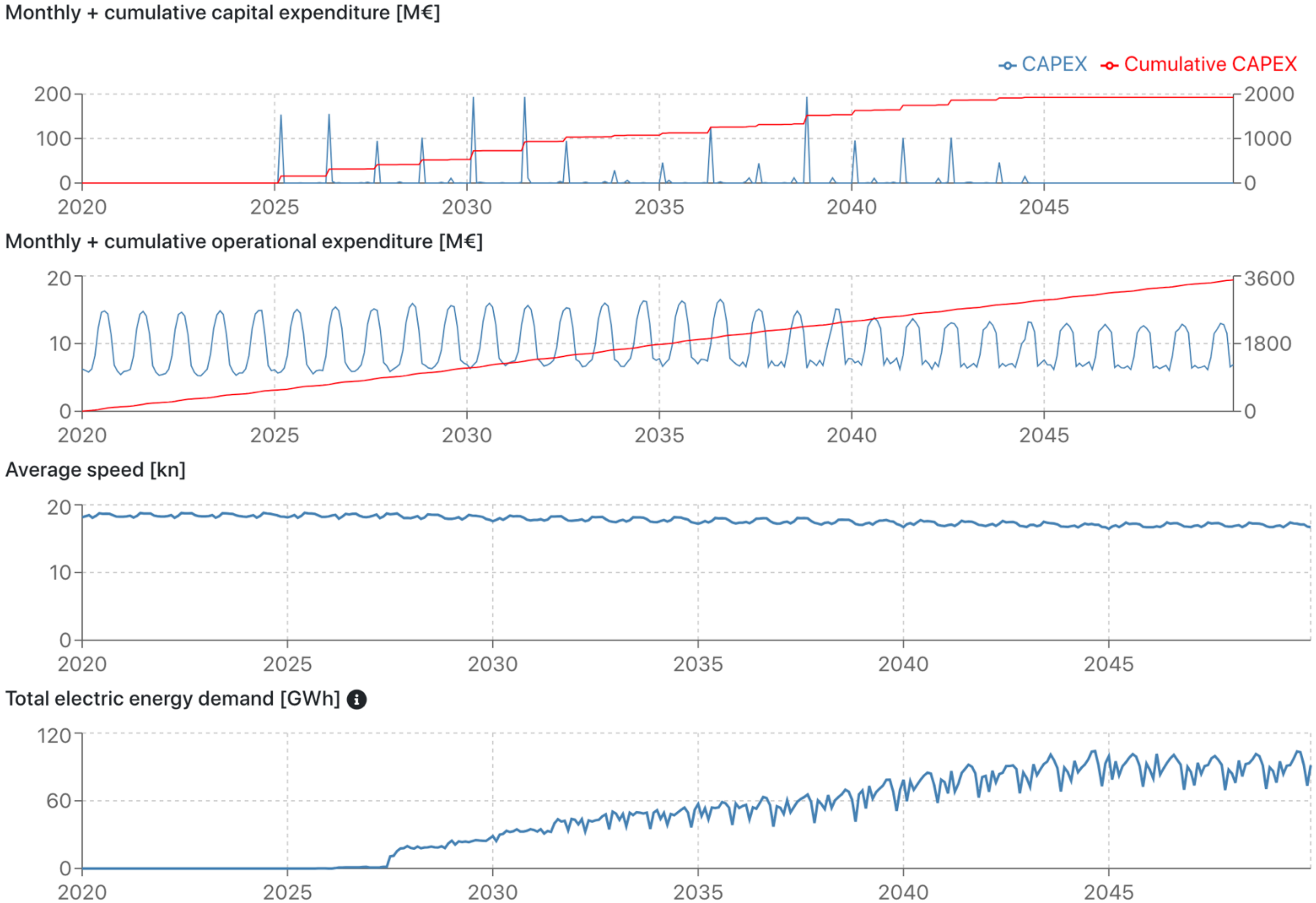

Figure 6: Development of key attributes over time for SC4

3.5 SC5 - Forced Electric short routes, BioLNG long routes, and BioLNG catamaran scenario

The following settings were used for the simulation of this scenario:

- The simulation has run from January 1st 2020 to January 1st 2050;
- Ships have <u>not</u> automatically been added and deleted to the fleet to keep the transport capacity as constant as possible;
- The ships have retained their power system throughout the simulation, unless enforced from the outside;
- The innovation level was set to <u>average</u>. This influences the prices and availability of energy carriers, the CAPEX for refits, the TRL and social acceptance of technology solutions;
- The energy carriers available in the simulation were: **Fossil diesel**, **Biodiesel**, **BioLNG**, **Grid electricity swapping** and **Renewable electricity swapping.**

Quantitative results at key time intervals (i.e. 2025 and 2035) and at the end of the simulation run (i.e. 2049) are being presented below in Table 8, while their evolution (per month) over the targeted time framework is being depicted in Figure 7 as generated by the NEEDS portal.

Table 8: Results of SC5

Year	2020	2025	2035	2049
Fuel consumption	155.378,520	150.049,903	108.525,268	75.778,646
Fossil diesel [MWh]	151.281,331	143.536,738	70.524,311	0,254
Share (%)	*97,36%*	*95,66%*	*64,98%*	*0,00%*
Biodiesel [MWh]	4.097,189	2.992,418	703,245	0
Share (%)	*2,64%*	*1,99%*	*0,65%*	*0,00%*
BioLNG [MWh]	0	3.214,010	28.451,164	64.121,133
Share (%)	*0,00%*	*2,14%*	*26,22%*	*84,62%*
Grid electricity swapping [MWh]	0	295,815	8.737,891	11.380,446
Share (%)	*0,00%*	*0,20%*	*8,05%*	*15,02%*
Ren electricity swapping [MWh]	0	10,922	108,657	276,813
Share (%)	*0,00%*	*0,01%*	*0,10%*	*0,37%*
GHG emissions [kTon CO2eq]	77,264	73,873	39,128	7,961
% change	*Reference*	*-4,39%*	*-49,36%*	*-89,70%*
Transport capacity [Ton-miles]	90.387.619,825	88.516.571,393	77.716.099,166	73.624.413,382
% change	*Reference*	*-2,07%*	*-14,02%*	*-18,55%*
Total CAPEX (2020-2050)	€ 397.140.310,00			
Total OPEX (2020-2050)	€ 3.436.313.135,86			
Average speed [kn]	18,42	18,38	17.68	17.12
% change	*Reference*	*-0,22%*	*-4,02%*	*-7,06%*
Total electricity energy demand [GWh]	0,00	0,31	8,85	11,66

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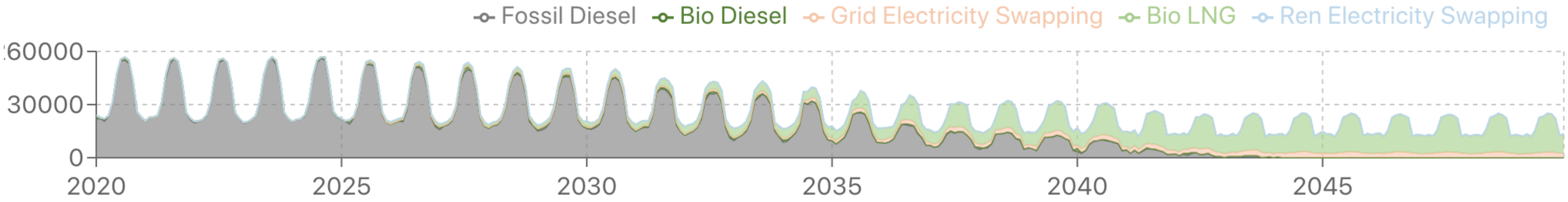
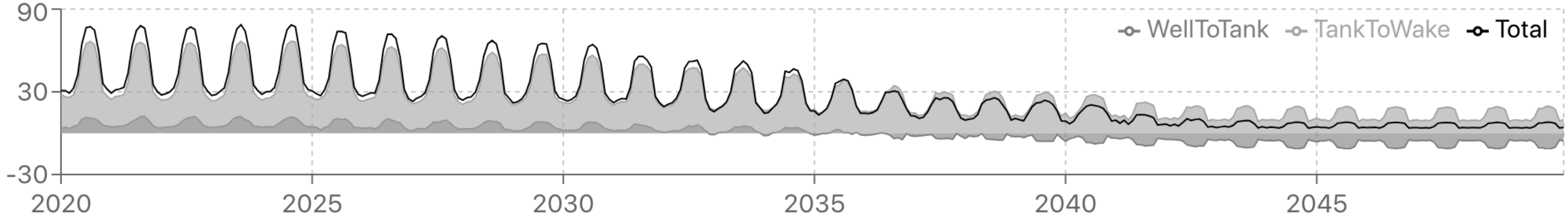
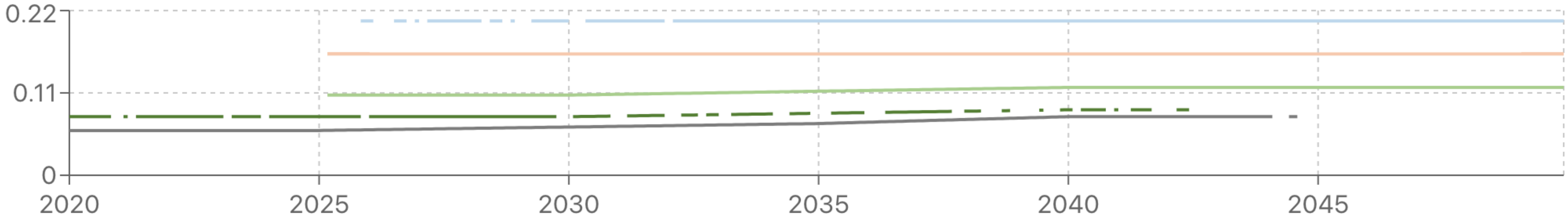
Monthly Fuel Consumption [MWh]



Monthly GHG emission [kTon CO2eq]



Monthly Fuel Price [Euro per kWh]



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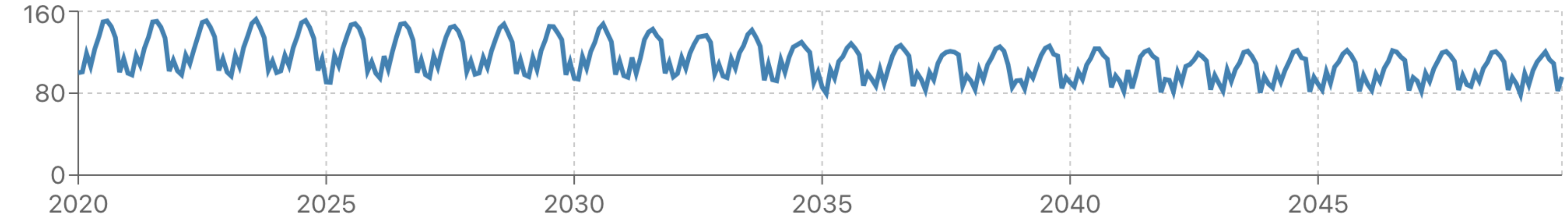
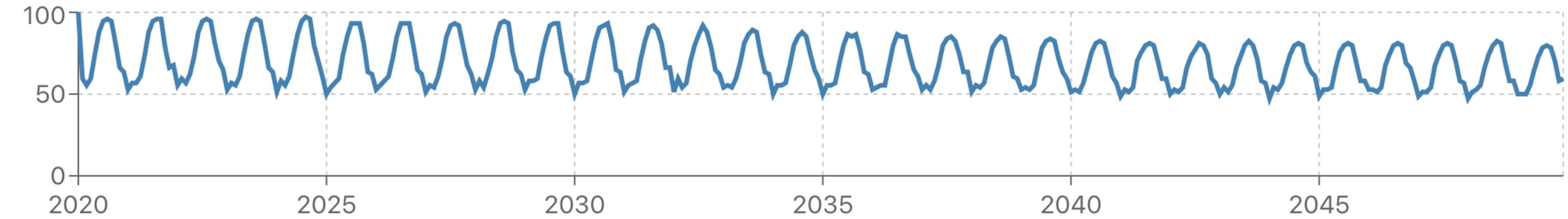
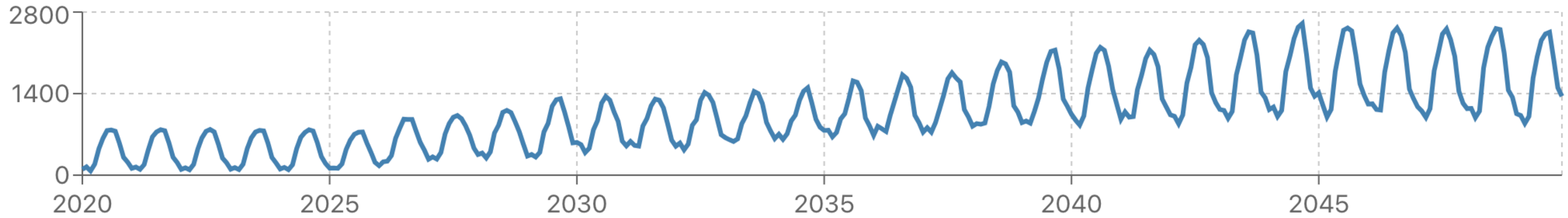
Monthly Transport Capacity [Relative to simulation start]



% of Sailing Ships [Relative to simulation start]



% of monthly bunker events [Relative to simulation start]



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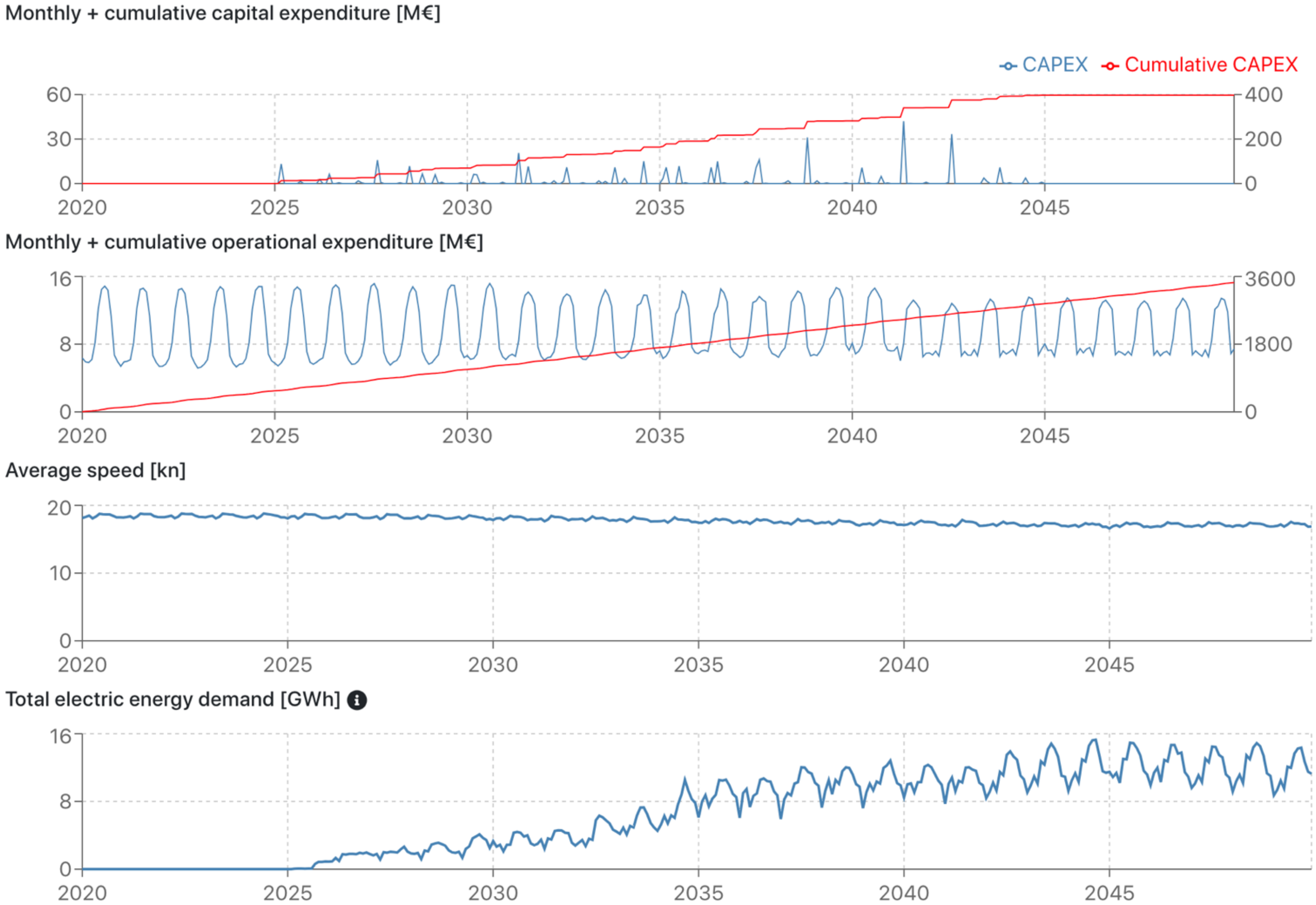

Figure 7: Development of key attributes over time for SC5

This scenario resembles SC4 with the only difference that, besides catamarans, BioLNG is also selected for powering RoPax vessels operating over long (i.e. >200 nm) shipping routes. Fuel consumption is also cut by half herein (-51,23%)[31], and GHG emissions are also heavily reduced, not surpassing though, by a very small fraction, the 90% reduction target that has been set for 2050 (-89,7%). Compared to SC3 however, this scenario performs very well in terms of transport capacity reduction (-18,55%), average speed reduction (-7,1%) and electricity energy demand (11,7 GWh), while CAPEX and OPEX lie quite within the same levels as that of SC1 (for OPEX) and SC2.

Considering that GHG emissions reduction is very close to the target that has been set, and the results of all other attributes are at the low end compared to the previous scenarios, SC5 accounts for a highly promising energy transition pathway.

3.6 SC6 - Forced Electric short routes, Hybrid long routes, and BioLNG catamaran scenario

The following settings were used for the simulation of this scenario:

- The simulation has run from January 1st 2020 to January 1st 2050;
- Ships have not automatically been added and deleted to the fleet to keep the transport capacity as constant as possible;
- The ships have retained their power system throughout the simulation, unless enforced from the outside;
- The innovation level was set to average. This influences the prices and availability of energy carriers, the CAPEX for refits, the TRL and social acceptance of technology solutions;
- The energy carriers available in the simulation were: **Fossil diesel**, **Biodiesel**, **BioLNG**, **Grid electricity swapping** and **Renewable electricity swapping**

Quantitative results at key time intervals (i.e. 2025 and 2035) and at the end of the simulation run (i.e. 2049) are being presented below in Table 9, while their evolution (per month) over the targeted time framework is being depicted in Figure 8 as generated by the NEEDS portal.

Table 9: Results of SC6

Year	2020	2025	2035	2049
Fuel consumption	155.652,551	151.520,860	118.883,415	79.486,335
Fossil diesel [MWh]	151.594,398	147.153,513	105.041,465	40.747,523
Share (%)	*97,39%*	*97,12%*	*88,36%*	*51,26%*
Biodiesel [MWh]	4.058,153	2.971,250	2.206,853	487,347
Share (%)	*2,61%*	*1,96%*	*1,86%*	*0,61%*
BioLNG [MWh]	0	535,385	3.075,360	21.164,795
Share (%)	*0,00%*	*0,35%*	*2,59%*	*26,63%*
Grid electricity swapping [MWh]	0	850,559	8.420,617	16.798,045

[31] Fossil diesel is also phased out six months earlier than in SC4.

Share (%)	*0,00%*	*0,56%*	*7,08%*	*21,13%*
Ren electricity swapping [MWh]	0	10,153	139,120	288,625
Share (%)	*0,00%*	*0,01%*	*0,12%*	*0,36%*
GHG emissions [kTon CO2eq]	76,451	76,721	49,731	19,024
% change	*Reference*	*+0,35%*	*-34,95%*	*-75,12%*
Transport capacity [Ton-miles]	90.454.311,055	88.185.108,125	82.561.606,183	73.041.664,482
% change	*Reference*	*-2,51%*	*-8,73%*	*-19,25%*
Total CAPEX (2020-2050)	€ 379.015.938,80			
Total OPEX (2020-2050)	€ 3.308.079.102,15			
Average speed [kn]	18,42	18,33	17.67	17.00
% change	*Reference*	*-0,49%*	*-4,07%*	*-7,71%*
Total electricity energy demand [GWh]	0,00	0,86	8,56	17,09

This scenario is another version of the previous two, since only the energy carrier of the RoPAx vessels operating on long routes (i.e. >200 nm) changes. Hybridization was examined in this case. Fuel consumption reduction lies within the same levels as in the previous two scenarios (-48,9%), but much more limited was the reduction of GHG emissions in this case (-75,1%), failing to meet the 90% reduction target. All other attributes are very similar to that of SC5 with the exception of electricity energy demand which amounts to 17,1 GWh (i.e. +46,1% compared to SC5).

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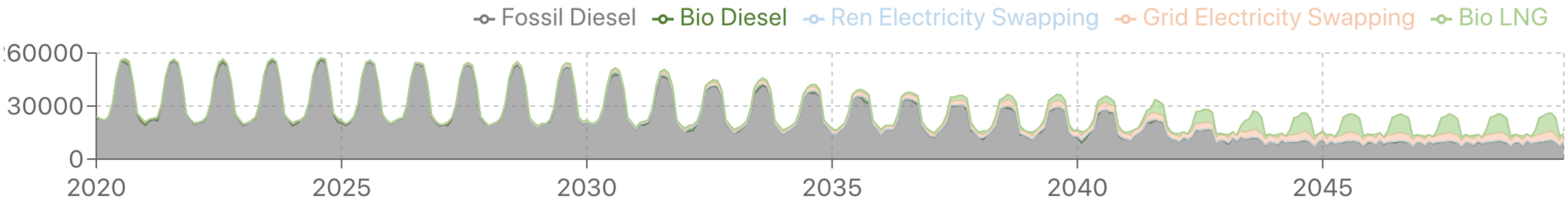
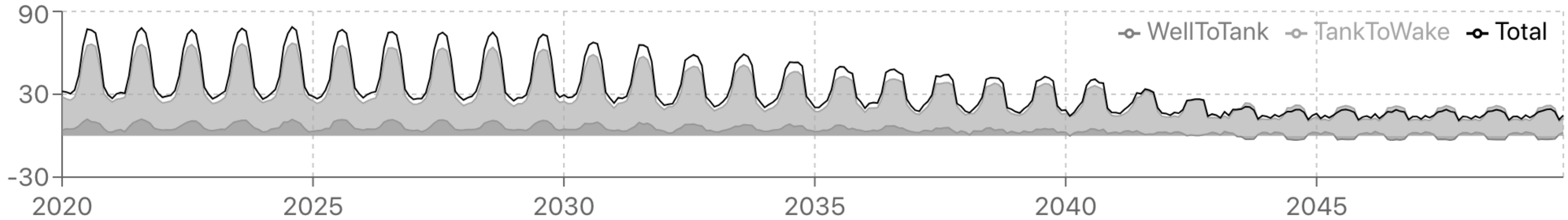
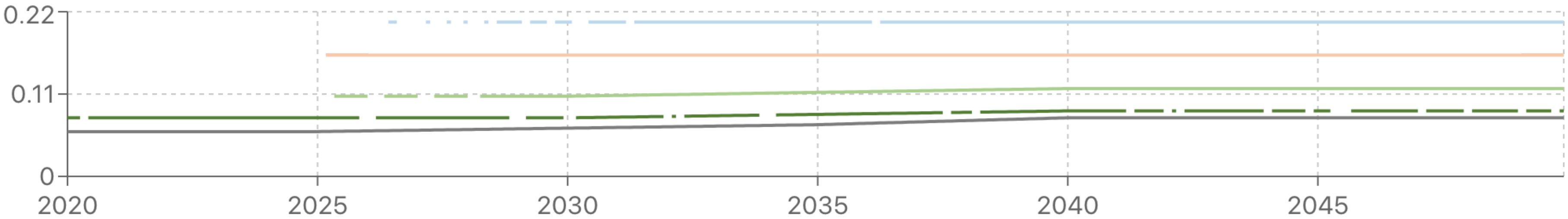
Monthly Fuel Consumption [MWh]



Monthly GHG emission [kTon CO2eq]



Monthly Fuel Price [Euro per kWh]



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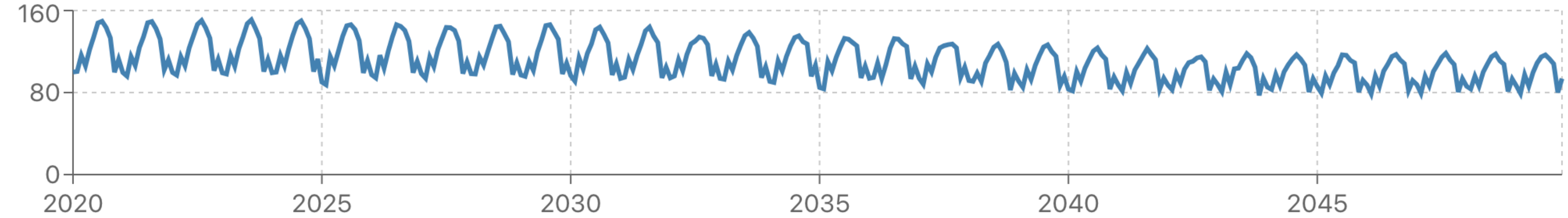
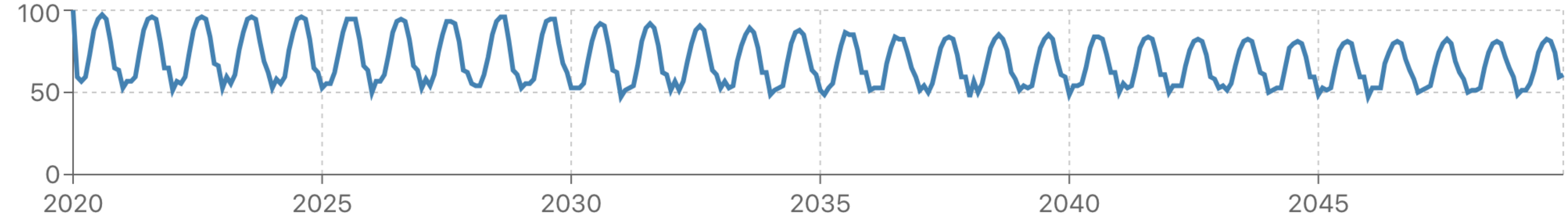
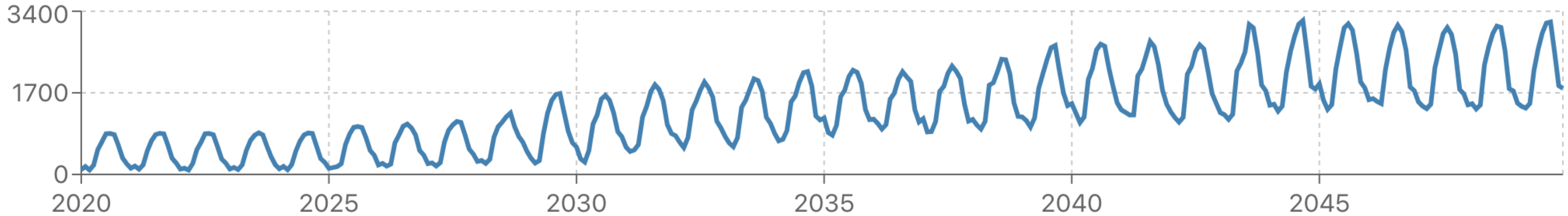
Monthly Transport Capacity [Relative to simulation start]



% of Sailing Ships [Relative to simulation start]



% of monthly bunker events [Relative to simulation start]



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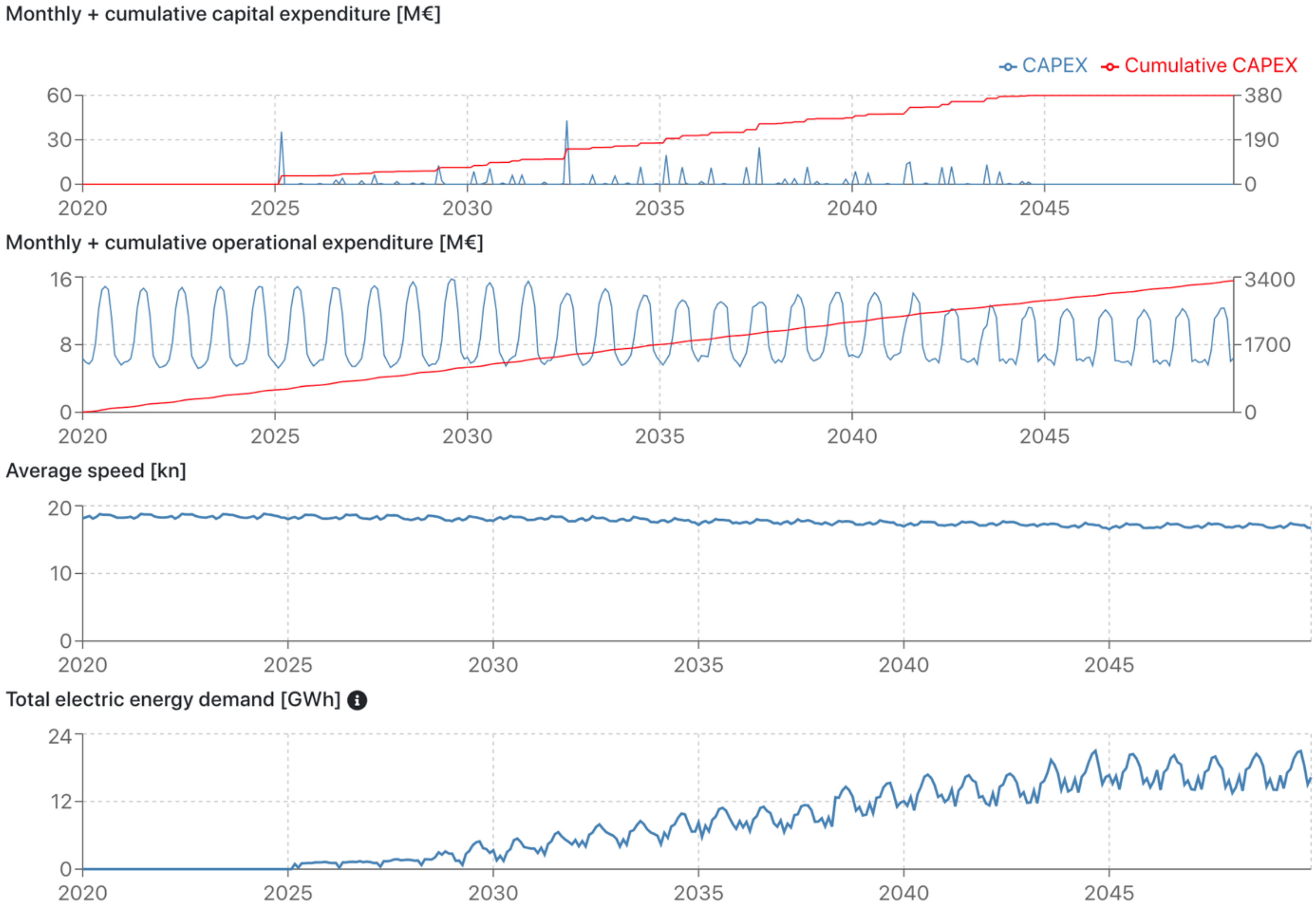

Figure 8: Development of key attributes over time for SC6

4. Comparative view of scenario results

A comparative view of scenario results is being adopted herein for facilitating the extraction of some valuable insights on promising energy transition pathways. As depicted in Figure 9 below, fossil diesel continues to be the dominant fuel in SC1, SC2 and SC6 while it has been completely phased out in the other three scenarios. BioLNG holds the largest share in SC5, since it is being considered for both catamarans and RoPax vessels operating on long routes, while important is also its share in SC3 and SC4. Grid electricity swapping accounts for the larger share in consumption in SC3, since electrification of all RoPax vessels is assumed, while green hydrogen dominates the domestic market in SC4 powering RoPax vessels providing services over long routes. SC3, SC4 and SC5 are thus the ones to be taken into account for identifying the most appropriate energy transition pathway.

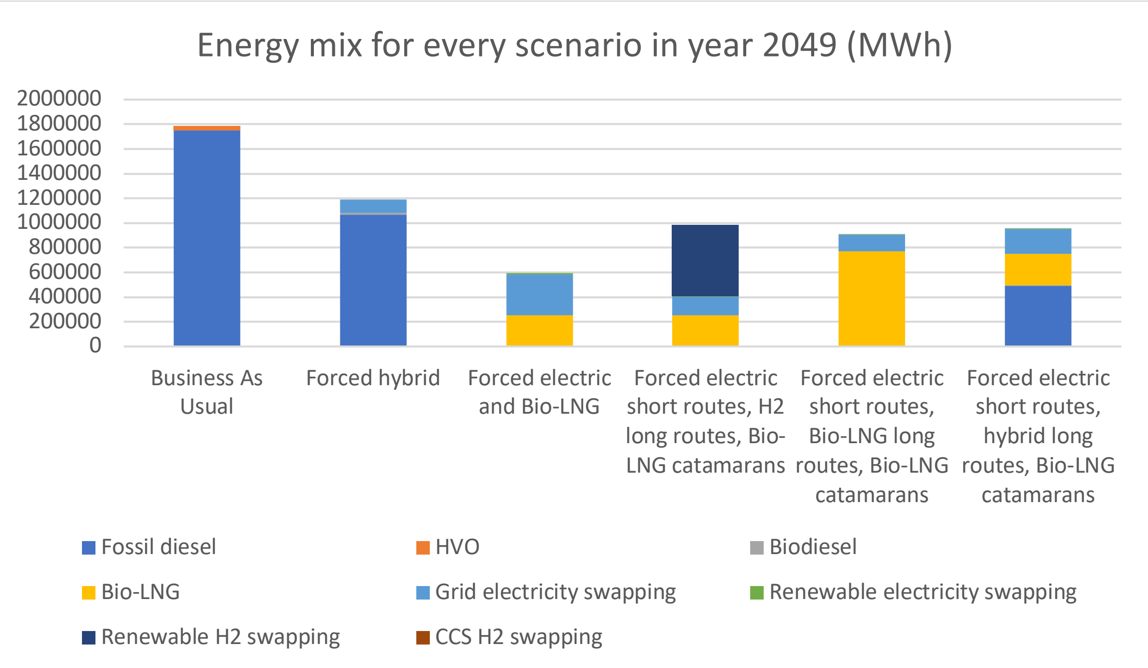

Figure 9: Consumption of selected energy carriers in the six scenarios in 2049

Key results for those three scenarios in 2049 are therefore summarized in Table 10 below.

Table 10: Key results in 2049 for SC3, SC4 and SC5

Scenario	GHG emissions reduction	Transport capacity reduction	Total CAPEX	Total OPEX	Average speed reduction	Electric energy demand
SC3	-93,69%	-55,35%	217,9 M€	2.811,3 M€	-11,67%	28,27 GWh
SC4	-94,55%	-49,52%	1.928,6 M€	3.492,0 M€	-7,87%	90,35 GWh
SC5	-89,70%	-18,55%	397,1 M€	3.436,3 M€	-7,06%	11,66 GWh

SC3 and SC4 surpass the 90% GHG emissions reduction target, with SC5 failing to meet it by just 0,3%. Taking into consideration however the other attributes, among the three scenarios, SC4 proves to be the least preferred since it accounts for a very high CAPEX (i.e. four times that of SC5) as well as a large demand for additional electric energy (i.e. three times that of SC3). Among the two remaining scenarios, SC5 proves to be providing the best compromise between all attributes. More specifically, besides almost meeting the GHG reduction target[32], it accounts for the smallest reduction in transport capacity and average speed, whilst requires the least amount of additional electric energy. Only CAPEX and OPEX are higher than that of SC3, but at levels that are similar to the other scenarios that were taken into consideration. Furthermore, when considering this last point, it is important to note that outlays required for deploying extra ships so as to cater for the lost transport capacity were not incorporated into the model.

5. Conclusions and recommendations

A number of important conclusions can be drawn and a set of insightful recommendations can be provided for both the maritime application of the model, as well as for the most promising energy transition pathway as identified for the Greek coastal shipping network via the scenarios analysis that was performed.

For the NEEDS model and portal

The model itself proves to be a highly useful tool for driving the transition towards sustainable waterborne activities and transport. It can actively support (a) policy makers in laying down favouring regulatory frameworks and putting forward valuable incentives, (b) the shipping and port industry into taking well-informed investment decisions with regard to their fleet and infrastructure respectively, (c) the social dialogue driving the acceptance of new solutions, and (d) the research and academic community into devising additional, complementary tools that can further increase the relevant value provided to the aforementioned stakeholders.

With the model's IWT application preceding this one, its adjustability to a different business context was evaluated drawing valuable insights for its future exploitation. The model was found to adapt well to a highly complex network such as the one of coastal shipping in Greece, of course with the necessary adjustments and additions compared to the IWT case. Given the applicable business case, the power system selection logic was disabled herein whereas average speed was inserted as an attribute since any considerable reduction may have a substantial impact on demand negatively affecting quality of service (e.g. customer satisfaction), mode choice, etc.

The large datasets available by the different databases used to run the model make-up for any missing case study data, enabling to perform simulation runs and consult results of course with the understanding of the impact those default data may have on the latter. This is of

[32] The difference is marginal

increased importance, since in many cases relevant data are scarce, questionable or very hard to find. Time needed for completing the simulation runs is quite reasonable, enabling to (a) formulate new scenarios worth exploiting, and (b) re-run existing scenarios with additional or more accurate data, if found, consulting the new results to be generated.

Given the project's duration and the time available for developing the model, the final result (i.e. the final version delivered) is remarkable. Its integration in a portal environment and the functions / options provided there largely facilitate its easy acquittance with new users and thus its future exploitation. With that in place, and with the aim to further capitalize upon the work that was performed within the framework of the project, a number of recommendations for the future development of the model (and the portal) are being listed below:

- Develop graphical user interfaces that can facilitate the scenario formulation and data inclusion processes
- Consider costs associated with new vessel deployment for filling-up lost transport capacity successfully adhering in that way to existing and future levels of demand
- Update / improve assumptions on available energy carriers (e.g. price forecasts, etc.) and include new ones not currently incorporated (e.g. wind-assisted propulsion)
- Include additional vessel types in the fleet database (e.g. high-speed crafts)
- Map bunkering networks of considered energy carriers and incorporate them into the model limiting bunkering activities at those locations and/or identifying, over the targeted waterborne transport network, optimal locations where additional facilities should be constructed (insights on the sizing of those facilities may be also derived)

For the energy transition pathway

Considering the characteristics of the Greek coastal shipping network (D2.1) and the available and planned capacities of sustainable energy production at national level (D2.2), the scenarios formulated and analysed are acknowledged as realistic enough. Simulation results provided some useful insights on the energy carriers that should be adopted for meeting the 90% GHG emission reduction target that has been set for 2050, which can be of value to both policy makers (e.g. for setting-up relevant regulatory frameworks that can drive this transition) as well as the shipping and port industry (e.g. for taking well-informed investment decisions).

More specifically, the distinction made between RoPax vessels operating on short and long routes with regard to the selected energy carrier proved to have worked really well, falling perfectly in line with the views of both industry and policy-related stakeholders who regard electrification as the best fit for ferry services over a certain distance range. For RoPax vessels operating on longer routes, BioLNG proves to be a good option going along with the LNG vessel ordering trend that is clear when considering the current orderbook[33]. Same goes for catamaran vessels so that the impact imposed to their operational profile is retained at acceptable levels. Of course, local access to sufficient feedstock quantities is an important

[33] BioLNG can be used as direct substitute in traditional LNG-powered vessels

prerequisite for producing the required volumes of BioLNG so that the aforementioned operations are fully supported completely avoiding any risk of operational disruption. The development of fuel pricing over time will reasonably have a substantial impact on the time of investments and deployment of those energy carriers, highlighting the need of the latter to become more competitive (i.e. in terms of price) soon enough or stand alone as the only available options if fossil fuels are banned for example.

Such an energy transition pathway should be holistically considered for its materialization since several push-and-pull effects apply. A proper regulatory framework should be in place and attractive financial incentives should be provided for supporting investment decision making at all associated industries (i.e. shipping, ports, fuel production facilities, logistics, etc.) so that combined needs are met (i.e. better alignment of supply and demand).