EVALUATING MARITIME INTELLIGENT TRANSPORTATION SYSTEMS: THE CASE OF USING ELECTRIC FERRIES AND RENEWABLE ENERGY IN TÜRKİYE

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submitted by **CANER PENSE** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy** in **Earth System Science, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. İsmail Ömer Yılmaz
Head of the Department, **Earth System Science**

Prof. Dr. Bülent G. Akınoğlu
Supervisor, **Earth System Science, METU**

Assoc. Prof. Dr. Oğuz Atik
Co-Supervisor, **Marine Transp. Eng., Dokuz Eylül Uni.**

Examining Committee Members:

Prof. Dr. Ela Babalık
City and Regional Planning, METU

Prof. Dr. Bülent G. Akınoğlu
Supervisor, **Physics, METU**

Prof. Dr. İsmail Yücel
Civil Engineering, METU

Assoc. Prof. Dr. Merih Aydınalp Köksal
Environmental Engineering, Hacettepe University

Assist. Prof. Dr. Talat Özden
Electrical and Electronics Eng., Gümüşhane University

Date: 26.10.2022

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last name : Caner Pense

Signature :

ABSTRACT

EVALUATING MARITIME INTELLIGENT TRANSPORTATION SYSTEMS: THE CASE OF USING ELECTRIC FERRIES AND RENEWABLE ENERGY IN TÜRKİYE

Pense, Caner
Doctor of Philosophy, Earth System Science
Supervisor : Prof. Dr. Bülent G. Akınoğlu
Co-Supervisor: Assoc. Prof. Dr. Oğuz Atik

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Climate Change and Global Warming are among the most critical global problems today. Their effects can be seen all over the world. The maritime sector contributes to global Climate Change and Global Warming with greenhouse gas emissions from coastal structures and ships. At the local level, it also negatively affects all life with environmental pollution, especially air and sea. Today, drive technologies are developing at a dizzying speed. In land transportation, electric vehicles are frequently seen. Electric drive systems are used in automobiles and large vehicles such as trucks and buses, especially in the transportation sector. This technology not only protects the environment but also significantly reduces operating costs. With renewable energy sources, these effects can be further improved. Today, fuel costs make up a significant portion of the operating costs of a fossil fuel-powered ship. The most important advantages of full-electric ships over fossil fuel-powered ships are the significantly reduced operating costs and zero-emission operations. It was aimed to develop a feasible and sustainable maritime technology in Türkiye in the field of Intelligent Transportation Systems, with domestic and national technology suitable for the possibilities and conditions of Türkiye, within this dissertation. In this context, the case of operating full-electric propulsion ferries and taking advantage of renewable energy systems in Türkiye was evaluated with a multidisciplinary scientific approach.

Keywords: Intelligent Transportation Systems, Maritime Transportation, Electric Ferries, Renewable Energy, Solar Power

ÖZ

DENİZCİLİKTE AKILLI ULAŞIM SİSTEMLERİNİN DEĞERLENDİRİLMESİ: TÜRKİYE’DE ELEKTRİKLİ FERİBOTLAR VE YENİLENEBİLİR ENERJİ KULLANIMI ÖRNEĞİ

Pense, Caner
Doktora, Yer Sistem Bilimleri
Tez Yöneticisi: Prof. Dr. Bülent G. Akınoğlu
Ortak Tez Yöneticisi: Doç. Dr. Oğuz Atik

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İklim değişikliği ve küresel ısınma günümüzdeki en büyük küresel sorunlardandır. Bunların etkileri tüm dünya üzerinde görülebilmektedir. Denizcilik sektörü, kıyı yapıları ve gemilerden yapılan Sera Gazı salınımları ile hem küresel çapta iklim değişikliği ve küresel ısınmaya katkıda bulunmakta, hem de yerel çapta hava ve deniz başta olmak üzere çevre kirliliği ile tüm yaşamı olumsuz etkilemektedir. Günümüzde tahrik teknolojileri baş döndürücü bir hızla gelişmektedir. Kara ulaşımında elektrikli araçlar artık sıkça dünya yollarında görülebilmektedir. Sadece otomobiller değil, özellikle taşımacılık sektöründe kullanılan kamyon ve otobüs gibi büyük araçlarda da elektrik tahrik sistemleri kullanılmaktadır. Bu teknoloji sadece çevreyi korumakla kalmamakta, aynı zamanda işletme maliyetlerini de önemli ölçüde azaltmaktadır. Yenilenebilir enerji kaynaklarının kullanımı ile bu etkiler olumlu yönde daha da geliştirilebilmektedir. Denizcilik sektöründe bir fosil yakıt kullanan bir feribotun işletme maliyetlerinin önemli bir miktarının yakıt masrafı olduğu göz önüne alındığında, tam elektrik tahrik sistemli gemilerin sunduğu en önemli avantaj olan düşük işletme maliyetlerinin etkisi açıkça görülmektedir. Bu, fosil yakıt kullanan bir feribota oranla önemli oranda düşük yakıt ve işletme maliyeti anlamına gelmektedir. Bu doktora tez çalışması kapsamında Akıllı Ulaşım Sistemleri alanında ülkemizde yerli ve milli teknoloji ile ülkemiz imkan ve koşullarına uygun, uygulanabilir ve sürdürülebilir bir denizcilik teknolojisi geliştirme hedefi bulunmaktadır. Bu kapsamda Türkiye özelinde tam elektrik tahrik sistemleri ile donatılmış feribotların ve yenilenebilir enerji sistemlerinin işletilmesi hususu multidisipliner yaklaşımla bilimsel açıdan değerlendirilmiştir.

Anahtar Kelimeler: Akıllı Ulaşım Sistemleri, Deniz Ulaşımı, Elektrikli Gemiler, Yenilenebilir Enerji, Güneş Enerjisi

Dedicated to the Pense family.

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AGV	Automated Guided Vehicles
BSFC	Brake Specific Fuel Consumption
DoD	Depth of Discharge
EoL	End of Life
ESS	Energy Storage Systems
EU	European Union
GHG	Greenhouse Gas
GT	Gross tonnage
GTFS	General Transit Feed Specification
HSC	High-Speed Craft
ICE	Internal Combustion Engine
IMO	International Maritime Organization
ITTC	International Towing Tank Conference
LC	Light Craft
LRT	Light Rail Transport
MCR	Maximum Continuous Rating
M/F	Motor Ferry
MSC	Maritime Safety Committee

NM	Nautical Mile
NPV	Net Present Value
PV	Photovoltaic
RCW	Revised Code of Washington
REPP	Renewable Energy Power Plants
SCT	Special Consumption Tax / Excise Duty
SOH	State of Health
ULSD	Ultra Low Sulphur Diesel
UNFCCC	United Nations Framework Convention on Climate Change
VAT	Value Added Tax
WSF	Washington State Ferries
YÖK	Council of Higher Education (TR: Yükseköğretim Kurulu)

CHAPTER 1

INTRODUCTION

Today, electric drive technologies have become feasible alternatives to systems running on fossil fuels. Electric vehicles are gaining popularity in road transportation, railways, maritime, and aviation; they also promise to reduce the anthropogenic pressure and effects of global warming on Earth.

The pressure is increasing on every polluter, as International Maritime Organization (IMO) stated in 2011 [1]. In 2011, IMO was the first international regulatory body to implement energy efficiency schemes in the maritime industry, called Energy Efficiency Design Index for new ships and the Ship Energy Efficiency Management Plan for all ships [2], [3]. Since then, IMO has supported alternative fuel innovation in the maritime industry, adopted or revised regulations, and created new enforcement instruments and platforms that aim to increase fuel efficiency and reduce GHG output from international shipping [2]–[4]. IMO aims to contribute to the global efforts to reduce the anthropogenic sources of climate change. Following the Paris Agreement's goal of limiting the average global warming below the 2°C target, IMO aims to cut the annual Greenhouse Gas (GHG) and CO_2 emissions from international shipping by 50% and 70%, by 2050 [4].

The Ministry Of Transport and Infrastructure of Türkiye prepared the 2053 Transportation and Logistics Master Plan as a result of the 11th Development Plan (2019-2023) and the 2020 Presidential Annual Program [5]. The 2053 Transportation and Logistics Master Plan focuses on solving economic, efficiency, and environmental issues. There is a strong emphasis on the determination of Türkiye in the context of solving environmental problems created by the transportation sector by guiding the sector and taking necessary legislative and executive steps.

There are six goals within the 2053 Transportation and Logistics Master Plan that prioritize social sustainability, efficiency, environmental awareness, emissions, costs, global and local competitiveness, and legislative matters [5].

Goals 2 to 6 directly take matters related to maritime transportation into account [5]. These goals are briefly summarized below:

- Goal 2: The goal states that it is vital to reach a balance between different transportation modes by giving priority to rail and maritime transportation, allowing users to switch between modes effectively and cost-effectively and in an uninterrupted manner.
- Goal 3: The goal states that increased efficiency, productivity, quality, and competency of transportation services will be ensured while reducing costs. It was stated in the Master Plan that the steps necessary to reduce traditional fuel use and oil dependency. It is stated that the rise in fuel prices due to reducing oil resources and inventories and increasing cost of environmental issues needs principles of mobility and efficiency to be ensured by the state.
- Goal 4: The goal states that sustainable mobility supported by Intelligent Transportation Systems will be ensured by creating a cooperative environment that brings relevant institutions together to work on Intelligent Transportation Systems, especially on sustainable urban transportation and mobility. It is also stated that a special fund will be created to support studies and projects that focus on adding value, reducing environmental issues, and increasing safety and security.
- Goal 5: The goal states that measures will be taken to act within the framework of international measures against climate change and increase energy efficiency. The aim to ensure compatibility with the Paris Climate Agreement and EU legislation is addressed explicitly in this goal. The most significant proposal of the goal is the “Polluter Pays” principle. It is stated that renewable energy production will be encouraged while taking

preventative action to reduce negative environmental impacts by internalizing the external (social) costs of those who create it.

- Goal 6: The goal states that measures will be implemented to ensure that the transportation sector's overall safety and security are increased while considering public and environmental health.

The 2053 Transportation and Logistics Master Plan's goals are clear and encompass the same aims as this dissertation. They are created to take responsibility on the way to reaching the Paris Agreement’s 2100 global warming goal. As this study evaluates the economic and environmental costs and benefits of using electric ships in Türkiye, it will be significantly helpful on the way to reaching the sustainability, efficiency, environmental and economic targets adopted in the 2053 Transportation and Logistics Master Plan.

Paris Agreement’s 2100 global warming goal requires low and zero-emission ships to be built well before 2050, and hopefully by 2030s [2]. The main reason behind this requirement is that even if all GHG emissions were eliminated today, the committed warming effect of the existing GHG would still take several decades to stabilize [6].

Even though the IMO’s ambitious emission goals, the global maritime industry’s GHG emissions are still comparable to an industrialized nations’ total GHG emissions today [7], [8]. Moreover, if the maritime industry was a nation, it would be the 6th nation in total GHG emissions. Therefore, electric ships that offer significantly reduced or zero emissions will substantially contribute to the IMO’s GHG emission reduction efforts [2].

Studies show that full-electric ships[1] are already getting better than fossil fuel-powered ships in terms of economic feasibility and environmental protection; especially in more vulnerable areas such as the coastal cities where the population is living and the coastal ecosystems which provide essential services to all living [9]–[14]. Moreover, these benefits of full-electric ships are only expected to improve in time as their ranges are expected to improve distances scaled by thousands of nautical miles as early as the 2030s [15].

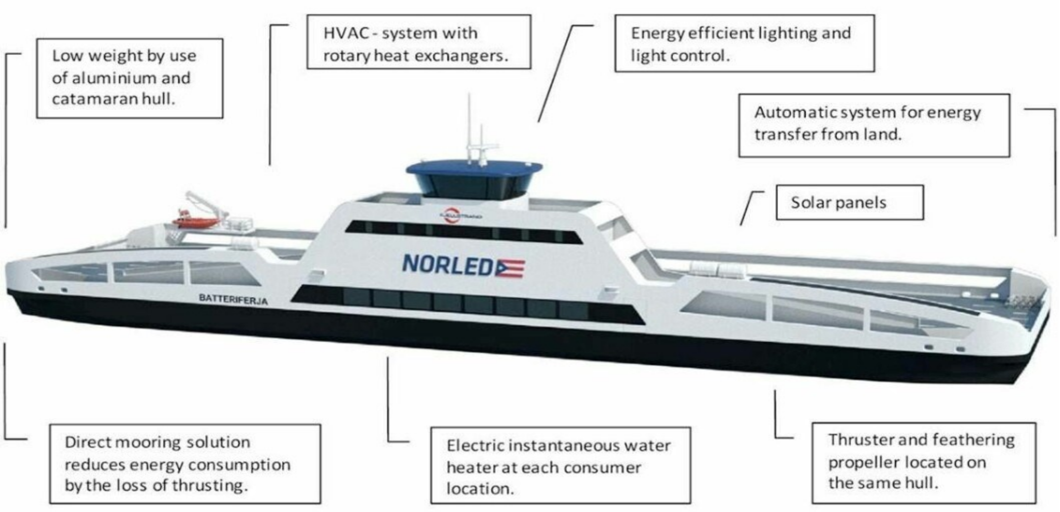

Figure 1.1. M/F Ampere, the first full-electric ferry in the world.

The idea of using renewable energy and electric ships in tandem has been gaining traction recently due to increasing awareness of Climate Change and Global Warming, *as well as the recent oil shock and the energy crisis.* However, the idea is not new; electric drive systems were used on civilian vessels as early as the 1880s.

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[1] It was observed that there are two terminologies used prominently today: Full-electric ships and all-electric ships. The author chooses to use the first terminology in the study.

The idea of ecological, pollution-free, efficient, and safe electric ships evolved into the modern meaning of full-electric ships in the 2010s. One known example of full-electric ships is the M/F Ampere (Figure 1.1), the first full-electric ferry in the world [16]. M/F Ampere has been operational since 2015, and her batteries are charged using the local power grid that is solely powered by renewable (hydro) energy power plants [17].

With the ever-increasing R&D on solar cell technologies and reducing cost per kW capacity installed, the global total installed capacity of solar photovoltaic (PV) power plants has increased to 843.1 GW in 2021, which has grown 19% in 2021 [18], [19]. This 19% increase in installed capacity resulted in a record-breaking 1 PWh solar PV electricity generation in 2021 [18], [19]. However, to reach the Net Zero Emission target of the Paris Agreement, solar PV electricity generation needs to reach a global total of 7.4 PWh by 2030 [19], meaning that there is much to accomplish and many records to break ahead of us.

As Patrick Geddes stated in 1915 [20], the solution is to;

Think global, act local.

Therefore, a global mindset and cooperation that drives localized electric revolution efforts are essential to mitigate the anthropogenic sources of global warming. Every polluter must be considered when it comes to reducing global emissions; maritime transportation is no exception.

Furthermore, the maritime and aviation industry is not expected to catch up to the emission reduction values seen in the road transportation industry today, any sooner. It is argued that the increasing emission levels due to fleet growth is expected to nullify about half of the global emission reductions achieved by the road transportation industry [21].

Figure 1.2. Prominent seaway public transportation services in Türkiye are located in the centers of large cities such as Bursa, Çanakkale, İzmir and Yalova, and the megacity İstanbul.

The seaway passenger and vehicle transportation service, or in the more known form, the seaway public transportation, has been selected as the focus of this study. This subject was adopted because the most prominent seaway public transportation services in Türkiye are located in the heart of large cities such as İzmir, Bursa, Çanakkale, and megacities such as İstanbul, where millions of people live and use these services every year [22], [23], as shown in Figure 1.2.

Citizens located nearby are directly affected by the GHG and particulate matter emissions from the ferries. Additionally, the ferry operators in Türkiye, primarily the municipalities, are affected by the rapidly increasing operating costs due to the oil shock. However, as we get closer to the 2030s, it is envisioned that a regulated carbon market will be formed to force emitters to internalize the external costs or *social costs* related to their emissions. These external costs are usually paid by society as a whole without a carbon market, and this transaction is not necessarily strictly in economic terms. It could be paid in terms of changed land use, increased healthcare costs, reduced welfare, damaged ecosystem health, and reduced ecosystem services [24].

Therefore, in simple terms, carbon taxes will be introduced in the near future. Undoubtedly, this is expected to increase the operational costs of seaway public transportation operators. Therefore, considering earlier applications in the world and research results, operating full-electric ferries in Türkiye shall be significantly beneficial in economic and environmental terms.

As there were no recent theses found that conducted a techno-economic analysis on operating full-electric ferries in Türkiye and no other studies found to investigate the technical aspects of Energy Storage Systems (ESS) batteries (such as capacities, charging rates etc.) onboard ferries to be operated in Türkiye, the subject of techno-economic and environmental evaluation of full-electric ferries to be operated in Türkiye was selected.

Various technical and operational information, including the arrangement of piers, lines, ferry particulars, maneuvering characteristics, drive systems, and fuel consumption were needed to study existing fossil fuel ferries to create the basis for full-electric ferries. The General Management of İzdeniz kindly agreed to share the required data within the scope of this thesis work. For this reason, the technical specifications of the full-electric ferries, ESS, Renewable Energy Power Plants (REPP), and ferry chargers are determined based on the seaway passenger and vehicle transportation service provided in İzmir.

1.1 Methodology

The secondary data gathered from the publications of international organizations such as the IMO and the literature on Solar energy, Earth System Sciences, Maritime Transportation, Intelligent Transportation Systems, Economics, and the Environment were analyzed.

Three main topics that are included in this study can be outlined as follows:

- The costs of using fossil fuels in the maritime sector,
- Benefits of using the full-electric drive and charging systems in maritime,
- Reducing operational costs further by using renewable energy sources for electric drive systems onboard electric ships.

These topics are adopted to evaluate the costs of using fossil fuels in the maritime sector and how they can be mitigated by converting to electric drive systems and further reduced by using shore and ship-based solar PV systems.

The methodology of the study is separated into five main phases:

- Literature review, data extraction, and analysis,
- Simulation model creation,
- Analysis of simulation findings,
- Finalization of the design of ship and shore ESSs and REPPs, and
- Conducting techno-economic evaluation.

Sustainability, electric ships, and renewable energy for maritime transportation are relatively new matters of concern. A comprehensive literature review revealed a limited number of scientific publications related to electric ships, renewable energy in maritime, and techno-economic evaluation of electric ships.

Ship ESS, electric drive and propulsion systems, and battery management systems are the main subjects of the literature on electric ships. It is also observed that many of these publications are purely technical, meaning they have an engineering and technical perspective on matters related to electric ships. Only a limited number of studies included an economic analysis of using electric ships.

The literature on the cost-benefit evaluation of using full-electric ships is rare. The rarity of such literature is thought to be due to the scarcity of data on full-electric ships. The studies that include a cost-benefit analysis of full-electric ships have two different approaches due to their various objectives and scales.

In one approach, several studies focus on a single ship and compare it with "what if" scenarios, such as "What if we converted a fossil fuel ferry to electric?". It was observed that those studies were funded by international or national organizations and utilized special in-house tools to conduct in-depth analyses of several different scenarios.

In the other approach, several studies focus on a maritime area where electric ships are operated or are to be operated. These studies focus on the environmental and economic analysis of using electric ships in a specific geographical area.

This study takes a blended approach. The study evaluates the technical aspects and environmental and economic costs and benefits of using full-electric ferries as a fleet in a specific geographical area in Türkiye, with several "what if" scenarios.

Determining the battery capacities of ferries to be used in Türkiye is the first step to be completed to lay a foundation for the rest of the analysis in the study. However, to do that, the real-life operational data must be known, including internal company matters with direct financial implications, such as the fuel consumption of existing fossil fuel ferries.

The author contacted several ferry operators in Türkiye and requested data about the ferries they operate to be used in this study. İzdeniz was kind to share the data and provide professional insight when needed. The General Management and

Superintendent Departments of İzdeniz kindly cooperated throughout the research. They provided information on ferry lines, ships, and related operational information and technical data, on a strictly need-to-know basis. As a result, the focus of the study was set on İzmir, where İzdeniz operates its ferries.

1.2 Research questions and hypotheses

This study has four main research questions and hypotheses, each of which aims to take a different aspect of the environmental and techno-economic evaluation of full-electric ferries:

- Q1: Is operating full-electric ferries in İzmir helpful for Türkiye to reach the Paris Agreement’s goals by 2050?
- Q2: Is it technologically possible to convert existing ferries to full-electric ferries that can operate in İzmir without decreasing the frequency of trips?
- Q3: Can the economic costs and benefits of using full-electric ferries in İzmir reach the break-even point in 10 years?
- Q4: Can the sum of economic and environmental costs and benefits of using full-electric ferries in İzmir reach the break-even point in 10 years?

The following research hypotheses were created as per the research questions above:

- H1: Operating full-electric ferries in İzmir is helpful for Türkiye to reach the Paris Agreement goals by 2050.
- H2: It is technologically possible to convert existing ferries to full-electric ferries that can operate in İzmir without decreasing the frequency of trips.
- H3: The economic costs and benefits of using full-electric ferries in İzmir can reach the break-even point in 10 years.
- H4: The sum of economic and environmental costs and benefits of using full-electric ferries in İzmir can reach the break-even point in 10 years.

CHAPTER 2

REVIEW OF LITERATURE

The national thesis center database of the Council of Higher Education (YÖK) of Türkiye was searched for keywords related to electric ships. The keywords include but are not limited to the following keywords: Electric ship(s), electric vessel(s), electric ferry(s), electric maritime, electric propulsion, battery ship(s), battery vessel(s), and their Turkish translations.

A total of nine theses were found to include these keywords. A detailed review showed that there had been a significant focus on the technical aspect of electric ships, especially on electrical engineering, marine engineering, and power systems engineering. However, none of them adopted a holistic approach that combined technical, environmental, and economic evaluation of full-electric ships.

- Yılmaz [25] conducted an environmental and technical analysis of the energy system of a full-electric or hybrid ship. The study also extensively examines national and international maritime regulations in favor of electric ships and makes recommendations. A single 4S class Ro-Ro ferry that IDO operates was taken as the basis for the study. A comprehensive analysis of the power systems of the ferry and its' environmental effects was conducted, including an emission analysis via LEAP software. The conclusion stated that a hybrid ferry would reduce emissions by 50% and a full-electric ferry would reduce them to the absolute minimum while providing no calculations or technical details about the ESS battery (e.g., type, capacity, consumption rate, charging rate, etc.). The study does not include any economic analysis.
- Yiğit [26] conducted an environmental, technical, and economical analysis of an Internal Combustion Engine (ICE) powered cargo ship's electric energy management system. The energy management system in the study is to be

used while only docked at a port, which is also compliant with smart grid infrastructure and capable of two-way energy transfers. The usage of renewable energy is also thoroughly investigated in the study. It is stated that there could be significant energy and emission reductions due to the two-way energy transfer ability, smart grids, and energy management systems. It is also stated that the green port and smart city mentality will pave the road for more sustainable maritime transportation. However, the thesis is not intended to operate or evaluate an electric ship but rather to develop energy management algorithms as a result of the study. Therefore, a design that includes technical details on the ESS batteries is not directly stated. Furthermore, the indirectly mentioned design in the study is not a hybrid electric ship by definition, as onboard generated energy is used for purposes other than propulsion.

- Çelik [27] conducted a technical and economic analysis of infantry-type leisure craft operated in the Azmak river in Akyaka, Muğla. It is stated that infantry-type leisure crafts are wooden crafts that are perfected as a result of over a century of naval engineering and are now commonly used for fishing and touristic sightseeing purposes. The conversion of such crafts into full-electric crafts, including the technical aspects, such as the power consumption and ESS batteries, was given in great detail. The environmental benefit of emission and noise elimination is briefly commented on without any systematic analysis or economic evaluations.
- Erdoğan [28] conducted a technical study to create an electric ship design using primary data and combining naval and electric engineering fields. The study includes a technical analysis of hull characteristics, electric propulsion and drive systems, and ESS batteries in great detail. As a result of the study, the construction of a catamaran ship was planned, and a prototype hybrid electric propulsion system was built. There is no environmental or economic analysis in the study.

- Konur [29] conducted a technical analysis of electric system optimization. The research studied various power consumption and generation efficiency optimization methods that can be applied to the electric boat with ESS batteries and solar PV REPP onboard. Konur introduced a thermal management solution to solar PVs and studied the theoretical effects of an energy management system and higher-efficiency electric motors on overall energy efficiency. In the study, it is stated that the energy efficiency of the boat can be increased by up to 147% when all optimizations are applied, which could double the range of the boat. There is no environmental or economic analysis in the study.
- Akten [30] conducted a technical analysis of alternative energy sources (especially fuel cells) to supply hybrid electric ships, in great detail. Moreover, Akten designed a boat and its electric drive system that utilizes fuel cells to produce electricity onboard. It is stated that while fuel cells are environmentally friendly and have no noise or vibrations, the capital costs of fuel cells are prohibitive to the extent that they are not feasible alternatives to ICE engines at the time of writing. However, it has been observed that the operational costs and savings of ICE and fuel cells were not compared, as there is no further environmental or economic analysis in the study.
- Görgülü [31] conducted a comprehensive technical and economic analysis that compared the costs and benefits of generating electricity onboard cargo ships using diesel ICEs or gas turbines. The ships in question are not particularly electric and are traditional fossil fuel-powered ships; however, these power plants could be applied to hybrid electric ships. Significant work was done to conduct the technical and economic analysis, considering all operational aspects of operating cargo ships, in great detail. The study states that gas turbines generate the highest power per unit of volume, which could be significantly beneficial for hybrid ships as the maritime industry evolves due to emission reduction aims. There are brief comments on the

environmental aspect of implementing such power plants without further analysis in the study.

- Özsu [32] conducted a comprehensive technical analysis of the emerging hybrid electric drive technologies, as of 2002. The ships in question are not particularly electric and are hybrid fossil fuel-powered ships. The only alternative energy source mentioned in the study is fuel cell technology. It could be argued that this is due to the battery technology not having the energy density today as a practical alternative. There is no environmental or economic analysis in the study.
- Yağmur [33] conducted a comprehensive technical analysis of electric drive systems on ships. The indirectly mentioned ships in question are hybrid ships. There is no environmental or economic analysis in the study.

The focus of international studies on the general subject of electric ships and relative subjects has attracted attention in recent years. According to Google Scholar, there are approximately 232 000 published studies before 2000, and 462 000 after 2000 related to electric ships, as shown in Figure 2.1 [34].

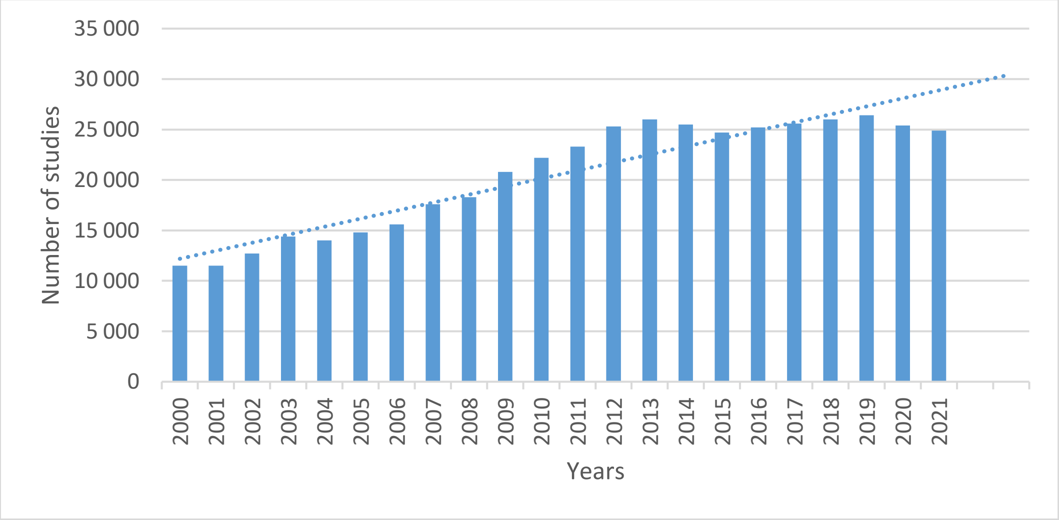


Figure 2.1. The yearly number of studies published on electric ships [34].

The literature on the electric ship subject is vast and includes a broad spectrum of scientific fields. As expected, the literature on the specialized full-electric ferry subject is significantly narrower than on the electric ship subject. Again, publications on full-electric ferries are from a large variety of different scientific fields.

The most prominent and relatively recent studies on full electric ferries were reviewed during the literature review phase. It has been observed that there are large-scale studies on full electric ferries funded by national or international bodies. While not limited to, the EU-funded e-Ferry project [9], the Inter-American Development Bank's study on electric ferries in Latin America [10], and Washington State Ferries' study on the electrification of their ferry system [35] were reviewed in this study.

All of the studies mentioned above have reports of their findings in an open-access manner. It has been observed that the economic, technical, and environmental aspects of full electric ferries are the most prominent concerns in these studies. It was stated that electric ferries are among the first feasible steps toward an emission-free maritime, along with fuel cell technology [9], [10], [35]. It is also stated that the electric ferry market will grow into a multi-billion dollar industry by the 2040s [10].

The EU-funded e-Ferry project aimed to showcase the applicability of emission-free electric ferries. The 4 MWh batteries of the experimental e-Ferry MF Ellen had an unprecedented range, replacing the ICE ferries operated on the 22 NM long Søby-Fynshav-Søby line in south Denmark. MF Ellen is expected to have an operational lifetime of 30 years. It is stated that MF Ellen will reduce the total operational costs by up to %36 during the operational life of the ferry due to its significantly more efficient full electric propulsion system. The expected break-even point of the ferry was calculated as 4 to 8 years, depending on the scenario [9].

Overall passenger satisfaction was very high, and a survey was carried out as a part of the social evaluation of the study. 86% of the passengers were very satisfied or extremely satisfied among the daily maximum of 180 passengers transported during the COVID pandemic, stating that the ferry's shorter travel duration, noiselessness, and environmental friendliness was the most contributing factor to their satisfaction [9].

It is stated that the ferry has significantly reduced environmental pollution and will reduce annual GHG emissions by 2 520 tons of CO_2, 14.3 tons of NO_x, 1.5 tons of SO_2, 1.8 tons of CO, and half a ton of particulate matter compared to a newer generation ICE ferry [9].

One of the most significant findings in the study was discovered during the design and approval phase of the battery capacities. As recommended by the IMO MSC.1/Circular 1455, the requirement of emergency reserves for full electric ships was taken into account, and the emergency reserve was increased to 800 kWh -which is 20% of the total ESS battery capacity- from the initially assumed 400 kWh. However, it is also stated that this value is lower than the intended Depth of Discharge (DoD) limit of the ESS batteries and should not be reached under normal operational conditions [9]. This vital lesson was also taken into account while considering this study's emergency reserve capacities and DoD levels of ESS batteries.

The study Opportunities For Electric Ferries In Latin America by the Inter-America Development Bank was published in 2021. The report includes data on several electric ferries operated at the time of writing, an electric ferry market forecast, and the feasibility analysis of operating electric ferries in Latin America to create an economic model [10]. Three major supply chains were identified for the model, namely battery supply chain, system, and vessel design and build chain, and onshore infrastructure and power procurement, as shown in Figure 2.2.

It is stated that the study contains a comprehensive technical analysis of 35 existing and 20 planned electric ferry operations at the time of writing [10]. A total of seven electric ferries *-including MF Ampere and MF Ellen-* have detailed technical, operational, and historical information given as example cases in the study.

It is stated that battery technology will develop, and as a result, the battery prices will diminish by 80% as of 2040. It is also stated that the battery energy densities will increase significantly, allowing a 200% increase in the range of fast catamarans [10].

It is also stated that if all possible lines are converted to full-electric, there would be 250 full-electric ferries traveling on 90 routes. Moreover, an annual reduction of 554 million liters of diesel fuel used by ferries and 1.3 million tons of CO_2 emissions is expected. It is also stated that the energy costs will reduce by 136 million USD annually, especially if renewable energy sources are preferred [10].

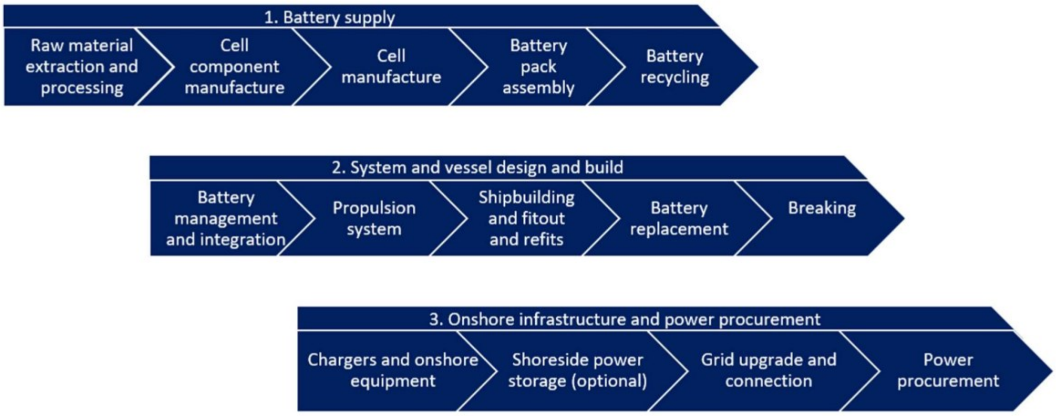


Figure 2.2. The three major electric ferry value chains [10].

It is also stated that a significant development in battery manufacturing is needed in Latin America as electrification of all modes of transportation advances, and the resources needed to accomplish that are abundant [10].

A striking statement in the study is that the cost of carbon fiber applications has reduced to feasible levels since the 1990s. They can offer significant savings due to reduced weight -meaning reduced ESS costs due to less capacity required- especially for larger ferries. Moreover, the usage of carbon fiber designs in the maritime has increased since the 2000s at a steep rate, signifying the recent trend of carbon fiber designs in the maritime industry [10].

The System Electrification Plan of Washington State Ferries (WSF) is a part of the 2040 long-range plan of WSF. WSF owns and operates the largest ferry fleet in the USA, transporting 24 million passengers annually. The 3.98 billion USD plan was created, considering reliable service, customer experience, managing growth, and sustainability and resilience themes [35].

While fleet electrification is only part of the plan and is not the final aim, it is vital in increasing efficiency and reducing operational costs and emissions. It is stated that the CO_2 emission levels from the ferries will be decreased below the required 2050 levels stated by the Revised Code of Washington (RCW) 70A.45.020 as 57.5%, as of 2033 [35]. However, as stated in Appendix A of the plan dated December 2020, the RCW 70A.45.050 was later amended by Engrossed Second Substitute House Bill 2311 (2020 c 79 § 3), and it is now required that the overall GHG emission should be 70% below 1990 levels as of 2040 [36]. As a 79% GHG emission reduction is expected by WSF as of 2037, the emission requirements for 2030 -as it is today- should be met. However, the plan does not state whether the 95% GHG emission reduction target of 2050 could be met without implementing full electric ferries.

According to the 2040 long-range plan, all piers will be converted to have full electric charging capabilities between 2027 and 2037. Moreover, six existing ICE ferries are planned to be converted to hybrid electric ferries by 2033, and 16 new-built ferries will be added to the fleet by 2037 [35].

The plan states that the ESS battery lifetimes would be engineered to be between 4 to 10 years. A steep drop followed by a stagnation in the per kWh prices of ESS batteries is expected, as it is stated that the expected prices are as follows [35]:

- 650 USD in 2020,
- 340 USD in 2025,
- 302 USD in 2027,
- 265 USD in 2029,
- 227 USD in 2031,
- 218 USD as of 2033 and after.

One of the most striking analyses in the plan is that the hybrid plugin ferries would not meet the emission requirements if there were no shore charging available [35].

CHAPTER 3

ANALYSIS OF ELECTRIC SHIP DESIGNS

It was necessary to analyze all existing and new building electric ships worldwide to identify a particular relation between the battery capacities of electric ships. This relation could then be formulated, and the ESS capacity estimations in the study can be tested against it. Therefore, a list of technical specifications and related navigational data was needed. However, it has been found that such a holistic list did not exist in the free or non-paid-subscription required domains of classification societies, ship register domains, governmental bodies, or similar organizations at the time of writing.

As a result, there was a need to create such a list. Several online databases, sources, blogs, and websites [9], [10], [35], [37]–[52] were analyzed to create a list that includes technical data on a total of 242 electric ships at the time of writing. The list can be found in Appendix A.

It was aimed to gather the following information about any electric ship that was found:

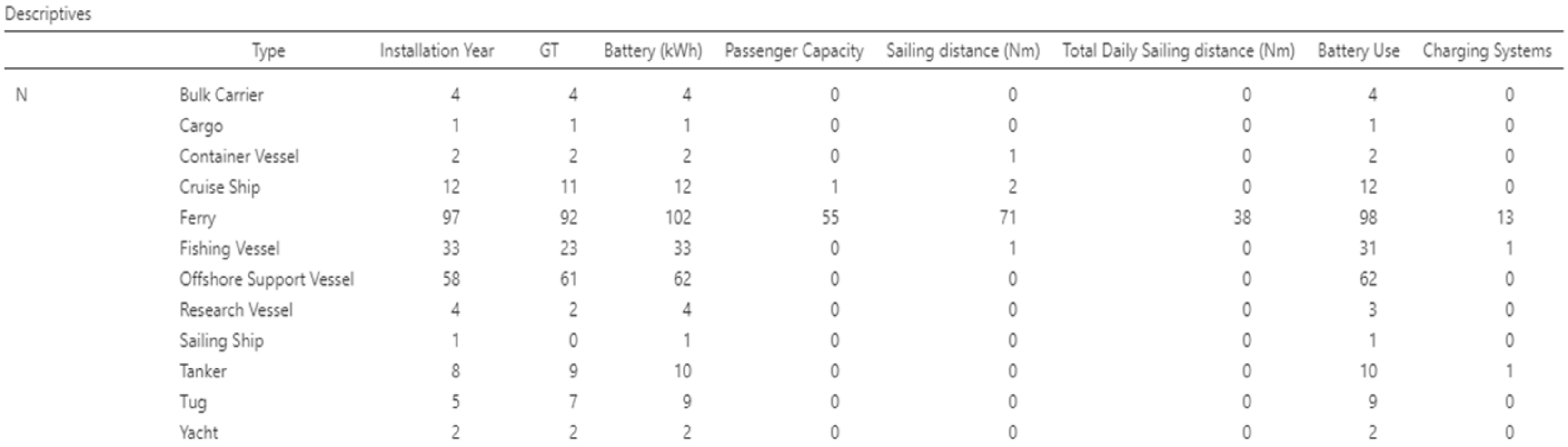
- Type,
- Battery Installation Year,
- Gross Tonnage,
- ESS Battery Capacity,
- Passenger & Vehicle Capacity,
- Sailing Distance (NM) and Total Daily Sailing Distance (NM),
- Battery Use Scenarios, and
- Charging Systems.

As a result, it has been observed that the number of electric ships increased after 2017, as Table 3.1 clearly shows. The increase in the number of electric ships could be a sign that a wider acceptance of electric ships in the maritime transportation industry is already happening. However, it should also be noted that critical global events such as global pandemics, energy crises, oil shocks, shifting balances in large-scale economies, and regional and global instabilities are expected to affect the maritime industry, especially on new ship orders.

It should be noted that electric ships have a near-perfect track record on safety. according to the IMO GISIS database, no serious maritime accident occurred involving an electric ship. However, to be more precise, only one electric ship has been involved in a maritime accident, a small fire and an explosion in the ESS compartment due to seawater sprinkler system failure. As the Norwegian Maritime Authority states, there were no casualties, and the ship safely reached the pier under its own power [53].

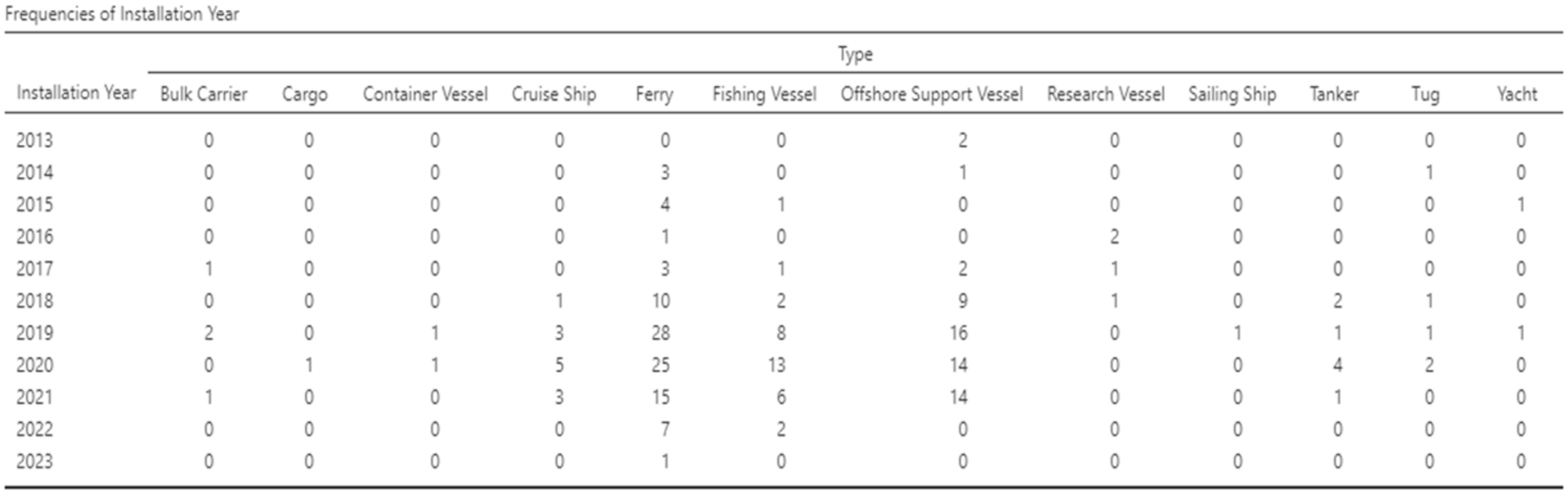
Therefore, it could be argued that the total number of electric ships has been increasing due to an exponential reduction in ESS costs, their near-perfect track record on safety, and international treaties and national policies related to modernizing maritime transportation.

Table 3.1. Descriptive information on electric ships and the number of electric ships built over the years, worldwide.



Descriptives

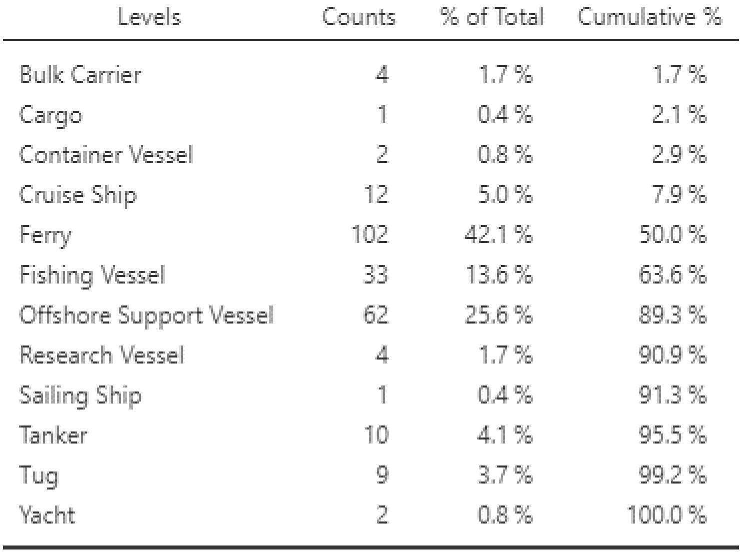
	Type	Installation Year	GT	Battery (kWh)	Passenger Capacity	Sailing distance (Nm)	Total Daily Sailing distance (Nm)	Battery Use	Charging Systems
N	Bulk Carrier	4	4	4	0	0	0	4	0
	Cargo	1	1	1	0	0	0	1	0
	Container Vessel	2	2	2	0	1	0	2	0
	Cruise Ship	12	11	12	1	2	0	12	0
	Ferry	97	92	102	55	71	38	98	13
	Fishing Vessel	33	23	33	0	1	0	31	1
	Offshore Support Vessel	58	61	62	0	0	0	62	0
	Research Vessel	4	2	4	0	0	0	3	0
	Sailing Ship	1	0	1	0	0	0	1	0
	Tanker	8	9	10	0	0	0	10	1
	Tug	5	7	9	0	0	0	9	0
	Yacht	2	2	2	0	0	0	2	0



Frequencies of Installation Year

	Type											
Installation Year	Bulk Carrier	Cargo	Container Vessel	Cruise Ship	Ferry	Fishing Vessel	Offshore Support Vessel	Research Vessel	Sailing Ship	Tanker	Tug	Yacht
2013	0	0	0	0	0	0	2	0	0	0	0	0
2014	0	0	0	0	3	0	1	0	0	0	1	0
2015	0	0	0	0	4	1	0	0	0	0	0	1
2016	0	0	0	0	1	0	0	2	0	0	0	0
2017	1	0	0	0	3	1	2	1	0	0	0	0
2018	0	0	0	1	10	2	9	1	0	2	1	0
2019	2	0	1	3	28	8	16	0	1	1	1	1
2020	0	1	1	5	25	13	14	0	0	4	2	0
2021	1	0	0	3	15	6	14	0	0	1	0	0
2022	0	0	0	0	7	2	0	0	0	0	0	0
2023	0	0	0	0	1	0	0	0	0	0	0	0

Table 3.2. The total number of ships distributed to types.



Levels	Counts	% of Total	Cumulative %
Bulk Carrier	4	1.7 %	1.7 %
Cargo	1	0.4 %	2.1 %
Container Vessel	2	0.8 %	2.9 %
Cruise Ship	12	5.0 %	7.9 %
Ferry	102	42.1 %	50.0 %
Fishing Vessel	33	13.6 %	63.6 %
Offshore Support Vessel	62	25.6 %	89.3 %
Research Vessel	4	1.7 %	90.9 %
Sailing Ship	1	0.4 %	91.3 %
Tanker	10	4.1 %	95.5 %
Tug	9	3.7 %	99.2 %
Yacht	2	0.8 %	100.0 %

It has been observed that there are 102 ferries (42.1%), 62 offshore support vessels (25.6%), and 33 fishing vessels (13.6%) out of 242 electric ships on the list, as shown in Table 3.2. It could be argued that electric ferries, offshore support vessels, and fishing vessels are the types of ships that generally travel short distances in a particular geographical area.

It has been observed the least number of electric ships are 2 container vessels (0.8%), 2 yachts (0.8%), 1 sailing ship (0.4%) and 1 cargo ship (0.4%). It could be argued that these types of electric ships generally travel longer distances and could travel through various geographical areas.

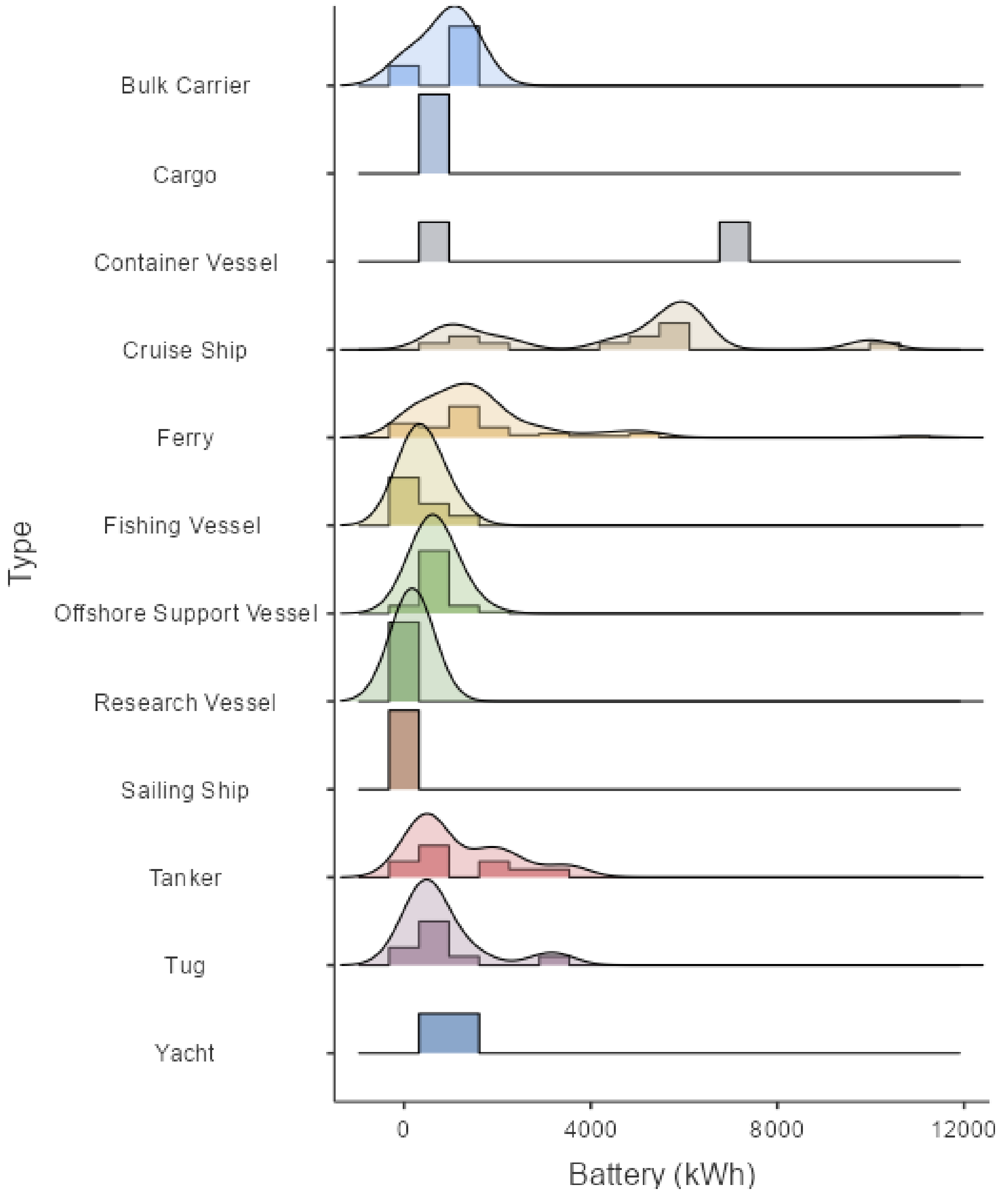


Figure 3.1. ESS Battery capacity distribution per electric ship type.

There is no clear relation between ship types and electric ships' battery capacities. However, as Figure 3.1 shows, the distribution in this graph is left heavy, indicating that most electric ships have 4 000 kWh or less ESS battery capacities.

The types of ships alone do not give a clear picture of the correlation of the ESS battery capacities of an electric ship. Therefore, another quantifiable value of a ship that indicates its size, the Gross Tonnage (GT), was introduced. GT is defined as the moulded volume of all enclosed spaces of the ship [54].

It is necessary to mention that GT is a non-linear volumetric valuation of a ship's entire internal volume. As a general simplified rule, the GT to volume ratio is higher for smaller ships, whereas, for larger ships, the GT to volume ratio is lower. As the GT value increases, the volume and hence the size of the ship increases less than the GT value. For example, a ship with 10 000 m^3 volume is rated as 2 800 GT, whereas a ship with 100 000 m^3 volume is rated as 30 000 GT, not 28 000 GT.

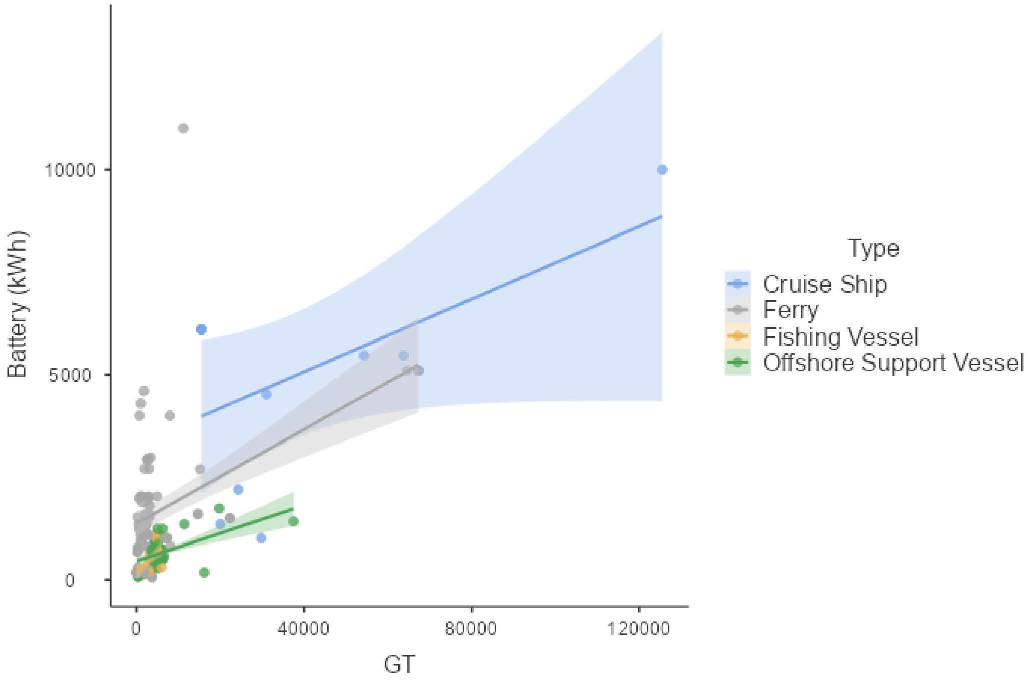


Figure 3.2. Correlation between electric ferry types, ESS battery capacities, and Gross Tonnage.

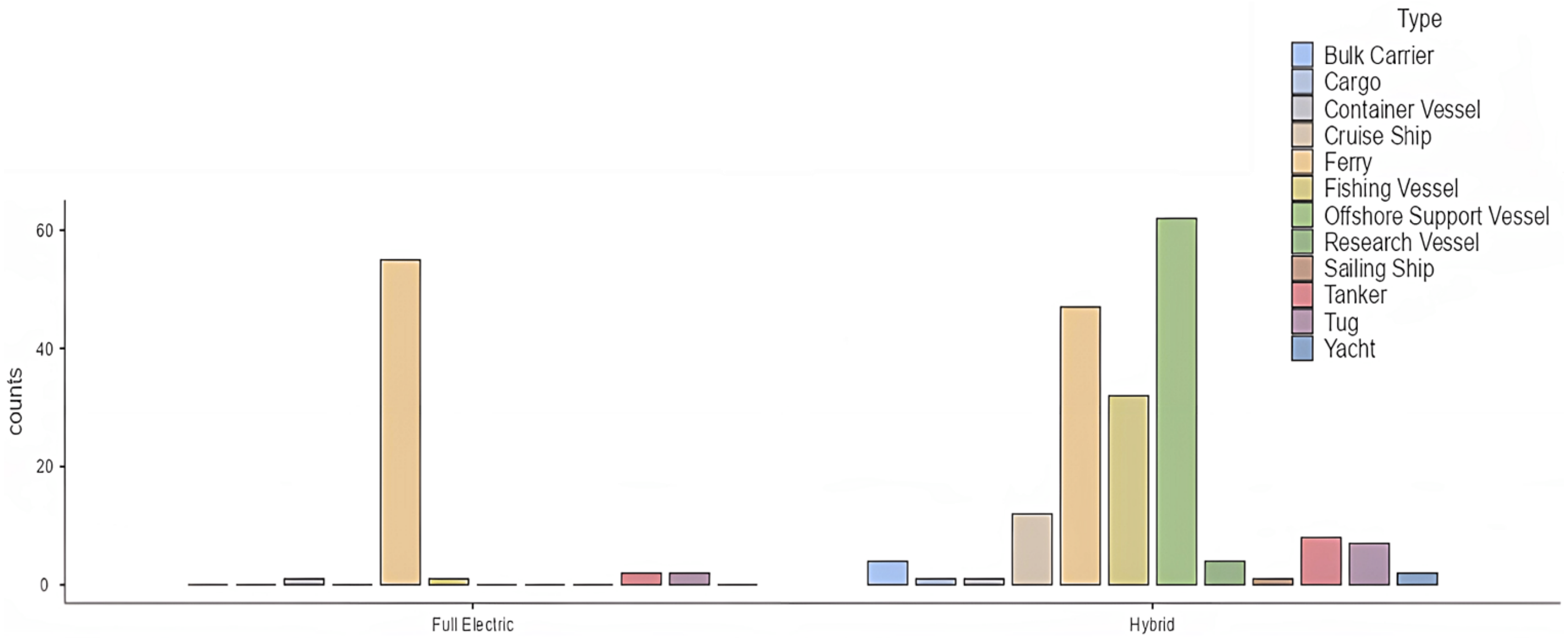
It was expected that as the ships get larger, the ESS battery capacity should get exponentially larger. There is a clear correlation between GT and the ESS battery capacity of electric ships segregated per type, as shown in Figure 3.2, where ship types with more than 15 ships are included in the graph to avoid outliers.

Ferries, fishing vessels, offshore support vessels, and cruise ships show a positive correlation between GT and ESS battery capacities, meaning that the battery capacity increases as the ship size increases, as expected. However, this is not the case for other types of ships.

Therefore, another variable, the propulsion system type of electric ships, was introduced, as shown in Figure 3.3. Two kinds of propulsion systems exist in electric ships: Hybrid and full-electric. Hybrid ships utilize other sources to generate energy onboard ships, e.g., generators with ICE that use stored fossil fuels in fuel tanks to charge batteries. Hybrid ships' systems can also run on a different combination of modes to provide full power, conserve energy, or increase maximum distance. On the other hand, full-electric ships use only onboard ESS batteries.

It was determined that the total number of hybrid ships is 181 on the list. Therefore, virtually all electric fishing and offshore support vessels are hybrid ships on the list, as only one fishing ship is determined as full-electric. There are 47 ships determined to be hybrid ferries.

It was also determined that the total number of full-electric ships is 61 on the list. Most of the full-electric ships are ferries (n = 55). Therefore, it is observed that there are more full-electric ferries than hybrid-electric ferries (n = 47) worldwide.



	Type											
Engine Type	Bulk Carrier	Cargo	Container Vessel	Cruise Ship	Ferry	Fishing Vessel	Offshore Support Vessel	Research Vessel	Sailing Ship	Tanker	Tug	Yacht
Full Electric	0	0	1	0	55	1	0	0	0	2	2	0
Hybrid	4	1	1	12	47	32	62	4	1	8	7	2

Figure 3.3. Engine types per propulsion type.

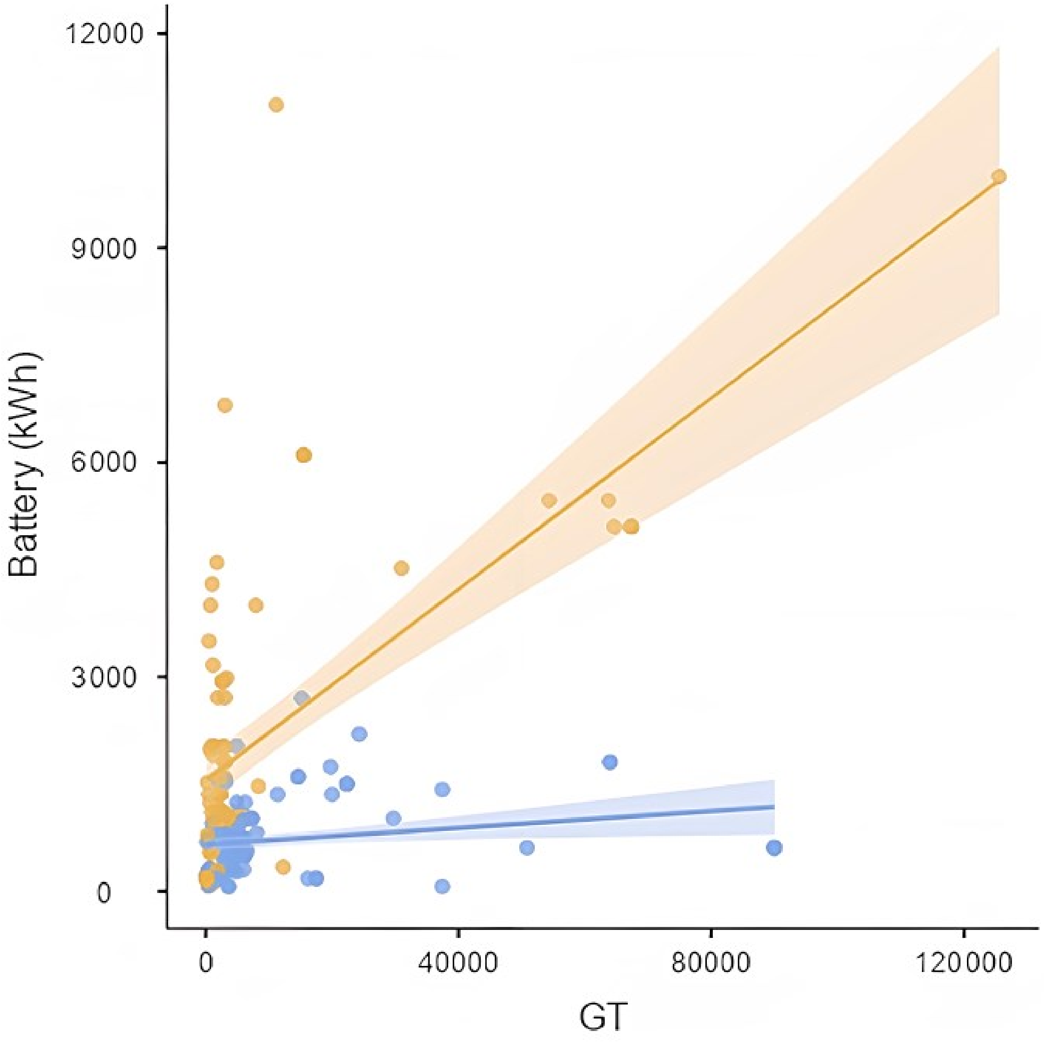


Figure 3.4. Gross Ton versus ESS battery capacity, grouped per propulsion type. Orange represents full-electric ships, while blue represents hybrid ships.

The correlation between ship battery capacities and GT becomes apparent when electric ships are grouped per propulsion type and ESS type. Figure 3.4 shows the positive correlation between GT and battery capacities when grouped per type of electric ship. Moreover, full-electric ships (shown in orange) have larger batteries than hybrid ships (shown in blue) at the same GT values.

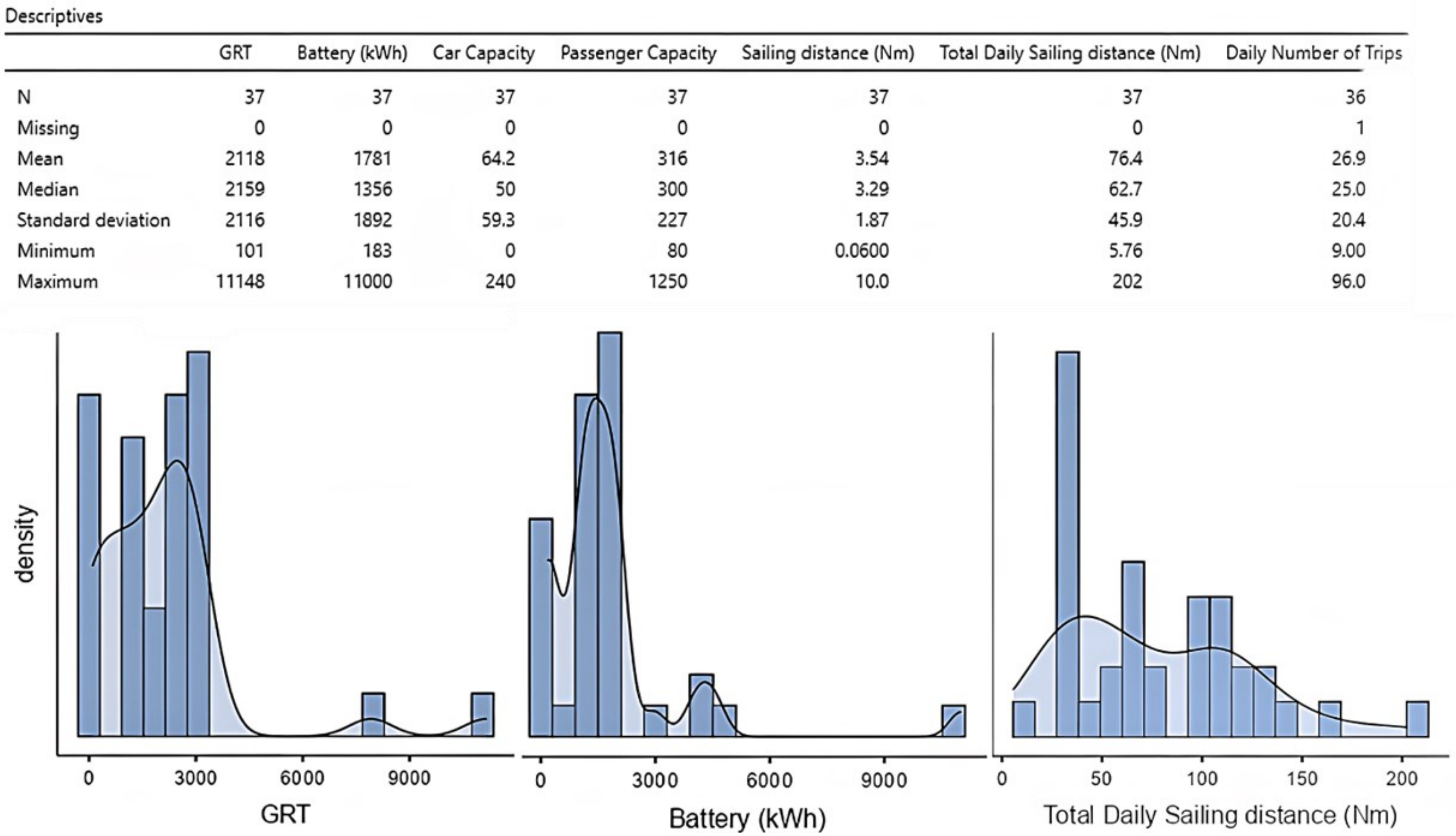
It was observed that while smaller electric ships have relatively similar battery capacities, the ESS capacity difference between full-electric and hybrid ships becomes more evident as the GT and size of the ship increase. The reason for this difference in battery capacities is the use cases of ESS. While full-electric ships use ESS for Zero Emission Operations, hybrid ships often use ESS to increase overall efficiency, improve power saving, reduce energy consumption (such as peak shaving) and boost total power output.

In the list, there are 37 full-electric ferries worldwide identified as currently operational. Technical and navigational data on these full-electric ferries were gathered or created using several databases, AIS tracking history, and information from ferry operators and news outlets. Only one ferry did not have any information on the number of trips it makes daily.

The largest ESS on a full-electric ferry has an 11 000 kWh battery capacity, while the smallest ESS on a full-electric ferry has a 183 kWh battery capacity. The ESS battery and battery management systems are scalable between miniature and gigantic proportions within ships' design limitations. For example, the largest ESS has four dedicated battery compartments, two of which are on the top deck and the other two to the fore and aft battery rooms, while the smallest ESS is located in the engine room.

All three graphs in Figure 3.5 showing the battery, vehicle, and passenger capacity, sailing distances, and the daily number of trip data of full-electric ferries are left heavy. As a result, it is arguable that full-electric ferries in the list are concentrated below 3 000 GT and 3 000 kWh ESS and travel less than 200 NM daily. These values give a general idea of full-electric ferries' sizes, ESS battery capacities, and service areas.

The service areas of such ships were observed to be geographically located in or near city centers, especially at rivers, bays, and islands. As the description shows, the trip distance between two ports or the Sailing Distance varies between 0.06 NM and 10 NM (M = 3.54 NM), while the Total Daily Sailing Distance varies between 5.76 NM and 202 NM (M = 76.4 NM).

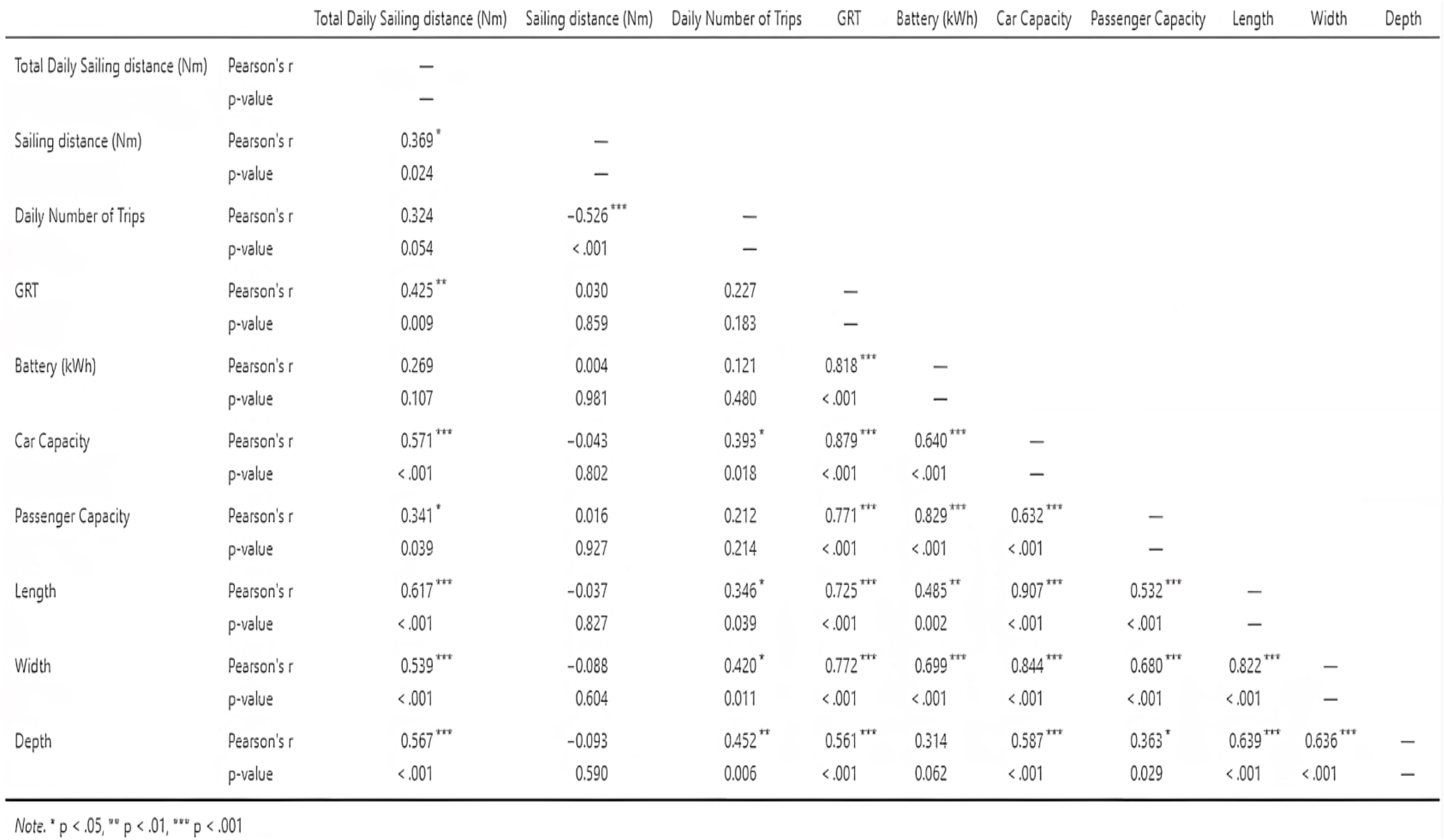


Descriptives

	GRT	Battery (kWh)	Car Capacity	Passenger Capacity	Sailing distance (Nm)	Total Daily Sailing distance (Nm)	Daily Number of Trips
N	37	37	37	37	37	37	36
Missing	0	0	0	0	0	0	1
Mean	2118	1781	64.2	316	3.54	76.4	26.9
Median	2159	1356	50	300	3.29	62.7	25.0
Standard deviation	2116	1892	59.3	227	1.87	45.9	20.4
Minimum	101	183	0	80	0.0600	5.76	9.00
Maximum	11148	11000	240	1250	10.0	202	96.0

Figure 3.5. Battery, vehicle, and passenger capacity, sailing distances, and the daily number of trip data of full-electric ferries.

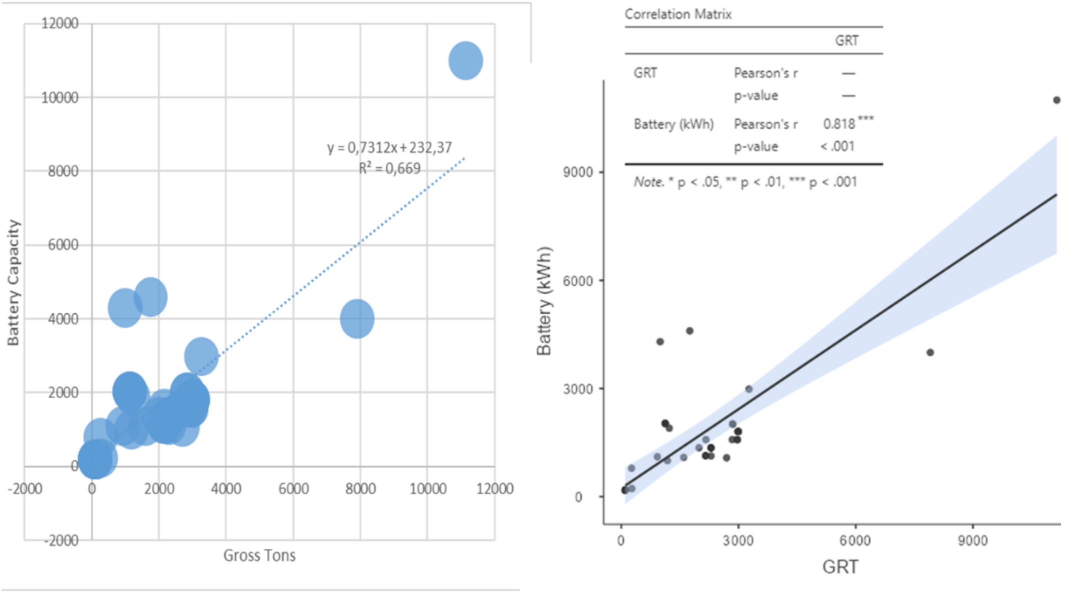
Table 3.3. Correlation matrix of all full-electric ferry variables.



		Total Daily Sailing distance (Nm)	Sailing distance (Nm)	Daily Number of Trips	GRT	Battery (kWh)	Car Capacity	Passenger Capacity	Length	Width	Depth
Total Daily Sailing distance (Nm)	Pearson's r	—									
	p-value	—									
Sailing distance (Nm)	Pearson's r	0.369*	—								
	p-value	0.024	—								
Daily Number of Trips	Pearson's r	0.324	−0.526***	—							
	p-value	0.054	< .001	—							
GRT	Pearson's r	0.425**	0.030	0.227	—						
	p-value	0.009	0.859	0.183	—						
Battery (kWh)	Pearson's r	0.269	0.004	0.121	0.818***	—					
	p-value	0.107	0.981	0.480	< .001	—					
Car Capacity	Pearson's r	0.571***	−0.043	0.393*	0.879***	0.640***	—				
	p-value	< .001	0.802	0.018	< .001	< .001	—				
Passenger Capacity	Pearson's r	0.341*	0.016	0.212	0.771***	0.829***	0.632***	—			
	p-value	0.039	0.927	0.214	< .001	< .001	< .001	—			
Length	Pearson's r	0.617***	−0.037	0.346*	0.725***	0.485**	0.907***	0.532***	—		
	p-value	< .001	0.827	0.039	< .001	0.002	< .001	< .001	—		
Width	Pearson's r	0.539***	−0.088	0.420*	0.772***	0.699***	0.844***	0.680***	0.822***	—	
	p-value	< .001	0.604	0.011	< .001	< .001	< .001	< .001	< .001	—	
Depth	Pearson's r	0.567***	−0.093	0.452**	0.561***	0.314	0.587***	0.363*	0.639***	0.636***	—
	p-value	< .001	0.590	0.006	< .001	0.062	< .001	0.029	< .001	< .001	—

Note. * p < .05, ** p < .01, *** p < .001

Using the data available, it is also possible to test whether other variables of full-electric ferries correlate. Therefore, the correlation between the Vehicle Capacity, Passenger Capacity, per trip Sailing Distance in Nautical Miles, the daily number of trips, and Total Daily Sailing Distance in Nautical Miles were analyzed. The correlation analysis shows strong statistical relationships or associations between the variables identified for full-electric ferries, as shown in Table 3.3. Two variables were observed to be directly related to the battery size.



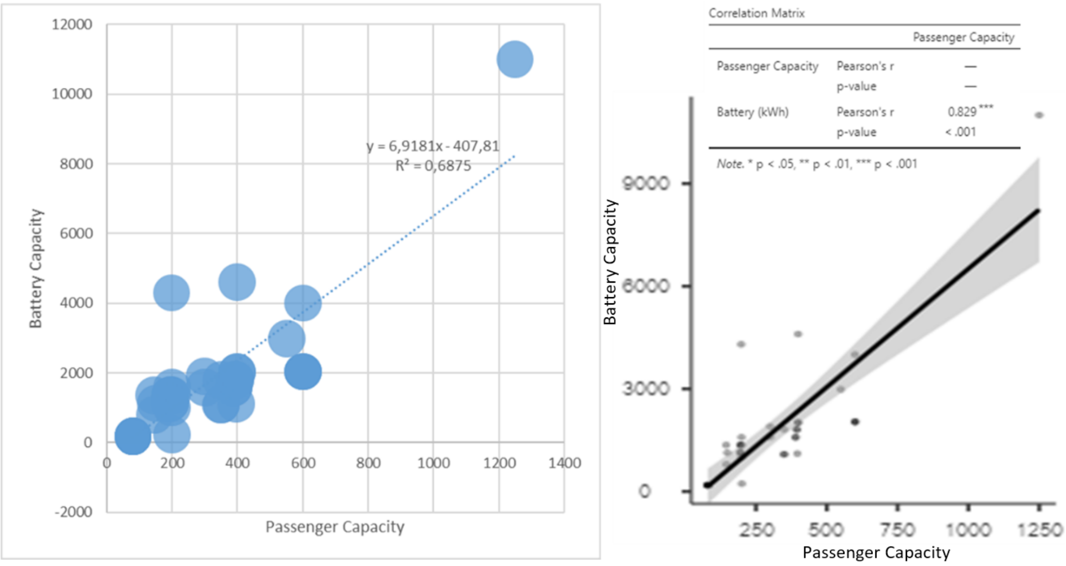
Correlation Matrix

		GRT
GRT	Pearson's r	—
	p-value	—
Battery (kWh)	Pearson's r	0.818 ***
	p-value	< .001

Note. * p < .05, ** p < .01, *** p < .001

Figure 3.6. The graphical representation of the correlation between ESS battery capacity and GT.

It could be hypothesized that as the size of a full-electric ferry increases, its' ESS battery capacity needs to get larger to travel the same distance due to higher total resistance. This hypothesis seems to be correct. There is a very strong positive correlation between the ESS battery capacity of a full-electric ferry and GT (Pearson's r = 0.818 and α level below 0.001), as shown in Figure 3.6. Moreover, the linear function of "y = 0.7312x + 232.37" where y is ESS battery capacity and x is GT has the 66.90% explanatory power of the correlation (R^2 = 0.669 and α level below 0.001).



Correlation Matrix

		Passenger Capacity
Passenger Capacity	Pearson's r	—
	p-value	—
Battery (kWh)	Pearson's r	0.829 ***
	p-value	< .001

Note. * p < .05, ** p < .01, *** p < .001

Figure 3.7. The graphical representation of the correlation between ESS Battery Capacity and Passenger Capacity.

There is an even stronger correlation with ESS battery capacity is the Passenger Capacity (Pearson’s r = 0.829 and p-value < 0.001), as shown in Figure 3.7. Moreover, the linear function of “y = 6.9181x – 407.81” where y is ESS battery capacity and x is Passenger Capacity has the 68.75% explanatory power of the correlation ($R^2 = 0.6875$ and α level below 0.001).

It could also be hypothesized that there is a limit to the maximum Total Daily Sailing Distance of a full-electric ferry, which results from the Sailing Distance multiplied by the Number of Daily Trips. The negative correlation between Sailing Distance and the Number of Daily Trips could indicate that this hypothesis is correct (Pearson’s r = -0.526 and α level below 0.001). Therefore, it is possible to state that the Sailing Distance and Number of Daily Trips are inversely correlated; as the Sailing Distance increases Number of Daily Trips decreases and vice versa.

3.1 Analysis of electric ship ESS batteries

The ESS manufacturers of 98% of *(237 out of 242)* electric ships in the list were identified.

Table 3.4. ESS manufacturers of all electric ships.

ESS Manufacturers	*Counts*	*% of Total*	*Cumulative %*
Corvus	211	87.2 %	87.2 %
Leclanché	14	5.8 %	93.0 %
Echandia	9	3.7 %	96.7 %
Unknown	5	2.1 %	98.8 %
Siemens	2	0.8 %	99.6 %
AKASOL	1	0.4 %	100.0 %

For all electric ships, it was observed that Corvus is the most prominent ESS manufacturer by a large margin, as shown in Table 3.4. The remaining manufacturers were, by order of their share, Leclanché, Echandia Marine AB, Siemens, and AKASOL. There is no specific manufacturer information available on five of the electric ships.

Table 3.5 ESS manufacturers of full-electric ferries only.

ESS Manufacturers	*Counts*	*% of Total*	*Cumulative %*
Corvus	24	64.9 %	64.9 %
Echandia	6	16.2 %	81.1 %
Leclanché	3	8.1 %	89.2 %
Siemens	2	5.4 %	94.6 %
Unknown	2	5.4 %	100.0 %

For full-electric ferries only, it was observed that Corvus is again the most prominent ESS manufacturer by a large margin, as shown in Table 3.5. Corvus's share is followed by Echandia Marine AB, Leclanché, and Siemens. There is no specific information available on two full-electric ferries. Literature states that ESS modules' energy densities and volumes vary depending on manufacturers and their technologies [35].

Table 3.6 There are different energy densities of products of marine ESS manufacturers [35].

ESS Manufacturers	*Capacity (kWh)*	*Weight (kg)*	*Volume (m^3)*	*Energy Density (Wh/L)*	*Specific Energy (Wh/kg)*
Corvus	124	1 628	1.4	87.1	76.4
Spear	124	1200	1.3	96.9	103.6
Siemens	59	900	1.1	53.3	65.9
SPBES	65	950	1.3	50.9	68.4
Leclanché	58	616	0.6	90.2	93.8
XALT	142	2 000	2.8	51.4	71.0
Saft	53	560	1.0	53.0	71.0

As a result, to get 1 MWh of installed capacity with the manufacturers and product lines in Table 3.6, the number of units needed to be installed is indicated in Table 3.7. It was observed that the product that Spear offers has the lowest total volume and weight among others, as per having the highest Specific Energy.

Table 3.7 Weight, volume, and unit information of different ESS products for forming an ESS with ~1 MWh capacity, based on [35].

Manufacturer	*Number of Units Installed*	*Installed Capacity (kWh)*	*Total Weight (kg)*	*Total Volume (m^3)*
Corvus	8	992	13 024	11.2
Spear	8	992	9 600	10.4
Siemens	17	1 003	15 300	18.7
SPBES	15	975	14 250	19.5
Leclanché	17	986	10 472	10.2
XALT	7	994	14 000	19.6
Saft	19	1 007	10 640	19.0

3.1.1 Safe operation, lifetime, and degradation of ESS batteries

Thermal management is an essential element for the safe operation of ESS batteries and the life span of the batteries. Studies show that when Li-NMC battery cells are operated in high temperatures for extended periods, they can lose a significant portion of their capacity. For example, in one study comparing the effects of overtemperature on the aging of Li-MNC cells, it was observed that cells lost 24% of their capacity when subjected to 1 000 full charge and discharge cycles at the constant temperature of 45°C [55]. Furthermore, it was also observed that the cell temperatures reached over 750°C, and as a result, cells emitted highly flammable gasses such as H_2 and C_2H_4 [55].

Degradation is a crucial aspect to consider when powering vehicles with Li-ion batteries. The State of Health (SOH) degrades as batteries complete a cycle consisting of a charging and discharging operation. An 80% SOH is usually considered as End of Life (EoL) for a Li-ion battery.

Studies show that Li-NMC batteries have a lifespan generally dependent on the Depth of Discharge (DoD) [56], [57]. As a rule, for all Li-ion batteries, a cell with low DoD has a lower degradation ratio than a cell with high DoD, while all others are kept static.

The Woehler curve in Figure 3.8 shows that the relation between DoD and lifespan is inversely correlated. As the DoD decreases, the cell's lifespan increases exponentially [56], [57]. Moreover, the rate of degradation increases as the SOH of the battery decreases. The degradation rate depends on variables such as operating temperatures, DoD, initial SOH, and others. However, the initial SOH is typically the main contributing factor affecting the degradation rate [56], [57].

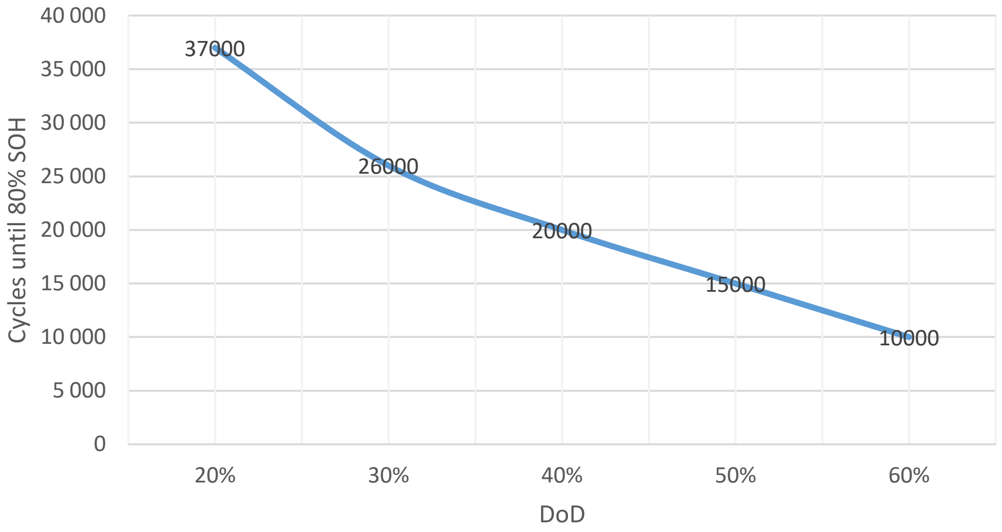


Figure 3.8. The DoD and life cycle values used in this study using the averages of the data for marine Li-NMC batteries produced by several manufacturers [58].

Therefore, assuming the energy consumption profile is kept the same, it could be argued that as the batteries in a ferry ESS age, their capacity will reduce. Moreover, it will degrade to its EoL faster as it ages. As a result, it is necessary to take data related to the marine ESS battery degradation and capacity reduction into account for estimating the total cost of operating electric ferries with higher precision.

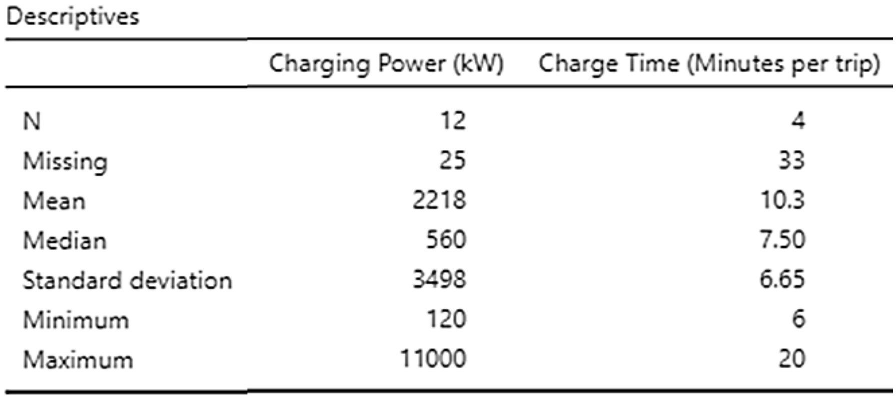
DoD mainly depends on the capacity of the battery. Therefore, if the energy consumption pattern of a ferry is unchanged, the first method for decreasing the DoD would be to have a larger ESS. The second method would be lowering energy consumption by traveling at slower speeds. However, traveling at slower speeds reduces the possible frequency of trips, requiring more ferries to be operated to sustain the same frequency. Therefore, decreasing the DoD to increase the ESS battery lifespan on a full-electric ferry can increase capital costs and lengthen the break-even period [58].

As a result, it could be argued that finding the correct DoD of the ESS on a full-electric ferry is essential for estimating the capital costs and other economic aspects of operating full-electric ferries.

3.2 Analysis of ship charging system designs

It was possible to gather information about a minimal number of full-electric ferries' charging systems in the study. There are too few differences between extreme values to make a meaningful analysis between charging systems. However, several statistical values should be mentioned. Only 12 ships with data related to their charging power and four with data on their charge times and charging rates are on the list and given in Table 3.8. The charging systems have a mean charging power of 2 218 kW. Additionally, a mean charging time of 10.3 minutes was observed.

Table 3.8 The number of ships with data on their charging systems and technical details of those charging systems.



Descriptives

	Charging Power (kW)	Charge Time (Minutes per trip)
N	12	4
Missing	25	33
Mean	2218	10.3
Median	560	7.50
Standard deviation	3498	6.65
Minimum	120	6
Maximum	11000	20

There are different types of ship charging systems, as shown in Figure 3.9. While virtually all charging system types have scalable charging power surpassing 10 MW [59], [60], there are high and low voltage and AC and DC versions of ship charging systems. Moreover, manufacturers offer wireless and plugged connector types.

Figure 3.9. Examples of different methods for transferring power from shore ESS to ferry ESS. Top row: Plugged power transfer system. Bottom row: Wireless power transfer system. Photos from [60].

The selection of which type of version to be used depends on both the shore-side power-line infrastructure and shipboard ESS used. The aim is to transfer and store electric energy with minimal losses.

It is optimal to minimize the losses in energy transfer as more losses in energy transfer result in lower cost-efficiency. Moreover, more losses in energy transfer also create higher heat output to the system. Active or passive cooling systems are needed to mitigate extra heat in the system. While passive cooling systems do not require extra energy to cool the system, they are often hindered and limited by weight, heat transfer capacity, and available space. On the other hand, active coolers require energy to operate, increasing the total energy while offering better performance characteristics.

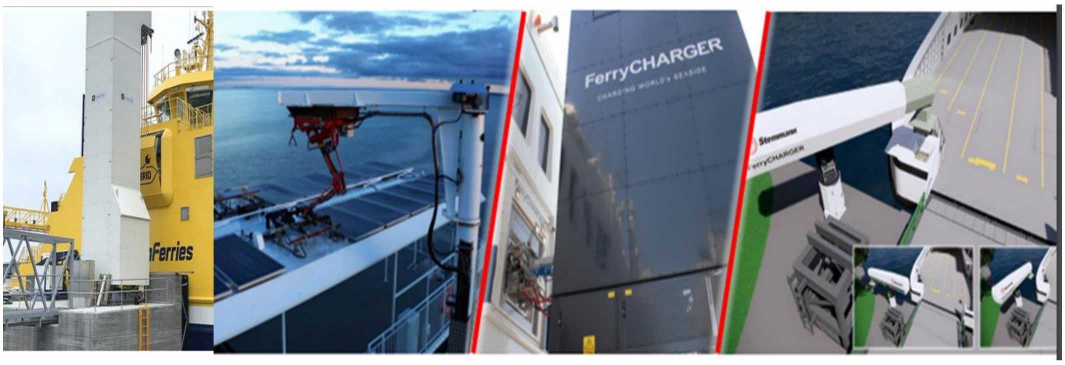


Figure 3.10. Different types of ferry charging stations and extensions. Left to right: Tower winch type, Panto type, Tower arm type, Bow type. Photos from [59], [60].

As shown in Figure 3.10, different ship charging system designs are available worldwide. Different ship charging systems offer different advantages and disadvantages. For example, tower-type solutions often offer higher power output than other charging systems, achieving a shorter charging time. However, their capacity to withstand the movement of a berthed ship (which can stay in place with mooring lines or while running on engine power) is relatively lower than bow-type chargers.

Tower-type and bow-type chargers often offer significant compensation for vertical movements. Panto-type chargers often provide lower charging power compared to other types of chargers. Moreover, the physical size of a ship can enable or limit the usability of certain types of chargers.

As a result, it is necessary to take the size of the ferry and the average weather and sea conditions in the service area into account while deciding on the design type of charging system for an electric ferry. Weather and sea conditions have different effects on different ferries due to having different docking locations, different form factors, and stability characteristics.

The study has two main hull types of ferries: Passenger ferry and Ro-Ro ferry. Passenger ferries are designed to dock by resting their bow fenders on the pier, as shown in Figure 3.11. They can stay stationary by mooring forward spring lines and engine power if required. Passenger ferries can make fore and aft movements rather than rotational movements during heavier weather and sea conditions. Therefore, it is ideal to utilize bow-type chargers for passenger ferries.

Figure 3.11. Bow-type chargers are ideal for charging passenger ferries in İzmir.

On the other hand, Ro-Ro ferries are designed to dock by resting on their broadside fenders on jetties and bow fenders to the piers, as shown in Figure 3.12. They can also stay stationary by mooring bow lines and engine power if required. Ro-Ro ferries can make rocking and rotational movements during heavier weather and sea conditions. Therefore, it is ideal to utilize tower-type chargers for the Ro-Ro ferries.

Figure 3.12. Tower-type chargers are ideal for charging Ro-Ro ferries in İzmir. Photo from [60].

Manufacturers claim that ferry chargers can sustain a maximum of 11 MW of charging power for tower-type chargers and 6 MW for bow-type chargers [59]. The calculations in the study suggest that the maximum charging power requested by the ferries should be within the charging power ranges of ferry chargers. However, the power provided to the ferries will depend on the configuration of the ferry and shore ESS batteries and the electrical infrastructure on piers. For example, some ferry chargers have a higher maximum charging power rating in AC configuration than in DC configuration.

3.3 Analysis and modelling of REPP designs

In the study, wind and solar PV energy were selected as the two most prominent REPP considered suitable for İzmir. There are specific criteria and limitations for evaluating the wind and solar power plants as the REPP in this study:

- Suitability,
- Reliability,
- Applicability, and
- Feasibility.

İzmir has a significantly large portion, *about 24.7%,* of the wind potential of Türkiye, while it is not uniform throughout the city, as shown in Figure 3.13. Moreover, the electrical infrastructure (380 kV and 154 kV lines passing through the city, large substations, and similar) is developed primarily around the city's urban core [61]. Therefore, producing and selling the power produced by wind power plants to the grid shall not be an issue in İzmir.

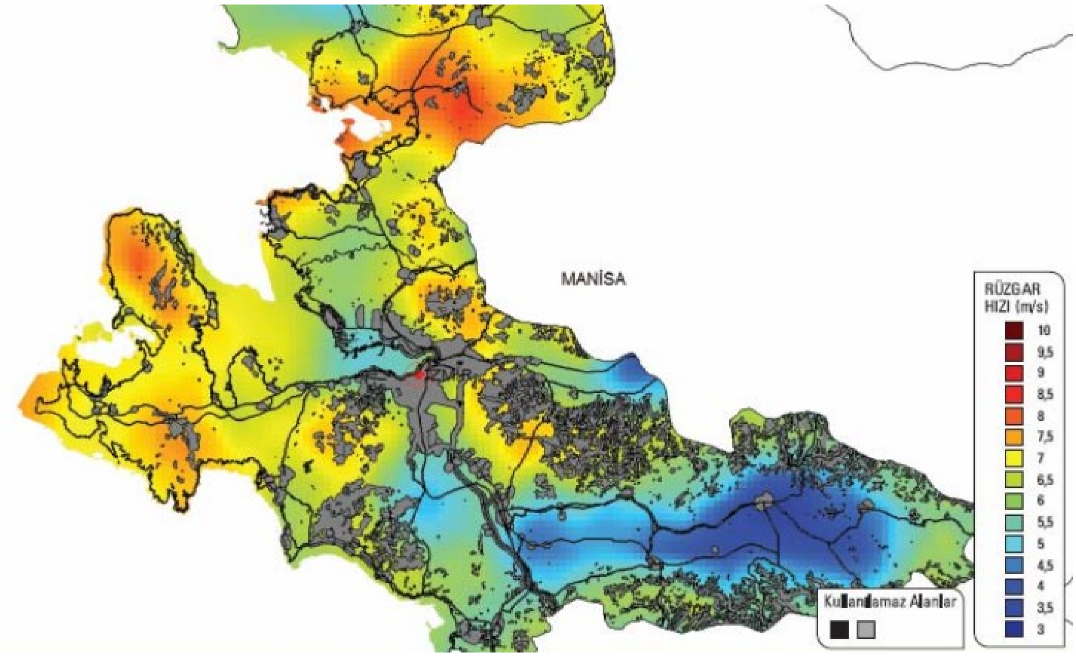


Figure 3.13. The wind potential map of İzmir. Black and grey areas show unsuitable locations for building wind power plants [62].

However, the high wind potential in İzmir is diminished by low local average wind speeds and high-density land use, as shown in Figure 3.13. The piers in this study are located in the inner bay. The surrounding high-density residential and commercial development around the inner bay practically makes the installation of wind power plants impossible. Moreover, even if the land use were suitable, the yearly low average wind speed among the shoreline of the inner bay *-where piers are located-* would significantly reduce the efficiency of wind power plants [61], [62].

Irrespective of the technology used, these two problems create significant feasibility issues by increasing the time it takes to return the investment compared to optimal land use and wind speed conditions. Therefore, wind power plants were not included in the model.

It could be argued that the solar PV energy potential of Türkiye is relatively high [63], especially compared to northern countries, as shown in Figure 3.14. However, as solar irradiation depends on multiple factors, including the latitude and the Earth's axial tilt, getting closer to the equator in the northern hemisphere generally increases the solar PV potential.

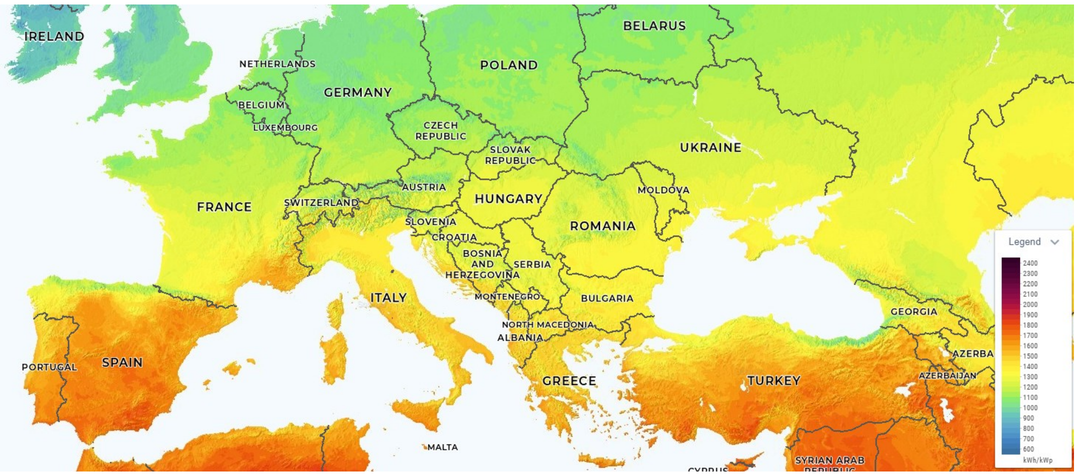


Figure 3.14. The average direct solar irradiation in Türkiye, neighboring countries, and several European countries [63].

İzmir also has a relatively high solar irradiance compared to the rest of the cities on the shoreline. The average direct irradiation in the inner bay is about 5 kWh/m^2/day or 1 824.4 kWh/m^2/year. If the tilt angle of the PV panels is optimized, the average irradiation increases to 5.46 kWh/m^2/day. Furthermore, the daytime duration or *hours of daylight* in İzmir increases up to 15 hours in June [64], [65].

Solar PV panels with 15% efficiency were used in this study to establish the performance baseline to estimate the lowest average solar PV energy output values. The estimated average hourly PV energy output of 1 kWp solar PV array located in İzmir is given in Table 3.9 [64]. Please note that the tilt of the array is fixed at 0 degrees, as the panels on ferries need to be set at this angle for continuous power generation.

In the study, fixed panels were used. However, it is possible to increase the energy output by using higher efficiency panels, setting panels to the optimal angles, and setting one or two-axis tracking systems at the cost of raising capital and operational costs.

Table 3.9. The estimated hourly solar PV energy output of 1 kWp panels with 15% efficiency. All values are in Wh.

	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	20 - 21
Jan	0	0	2	64	168	252	293	295	272	216	128	32	0	0	0
Feb	0	0	17	115	227	311	359	367	340	283	194	91	7	0	0
Mar	0	5	87	220	345	433	473	472	447	390	286	169	41	0	0
Apr	1	52	184	322	442	518	552	549	520	452	347	229	99	6	0
May	14	125	270	411	524	595	619	607	578	509	412	292	158	28	0
Jun	32	158	313	454	563	630	659	659	624	562	468	351	211	72	1
Jul	16	138	298	450	566	640	681	680	649	589	492	369	221	71	0
Aug	2	81	243	402	525	607	648	642	610	541	441	307	154	18	0
Sep	0	32	175	330	455	537	571	563	522	442	331	194	46	0	0
Oct	0	5	94	230	350	426	454	443	402	318	199	67	1	0	0
Nov	0	0	24	132	240	312	341	336	292	214	111	17	0	0	0
Dec	0	0	3	67	161	230	263	262	230	168	83	8	0	0	0

CHAPTER 4

DATA EXTRACTION

Piers and ferries in the model needed to be reflected correctly from their real-life twins. Therefore, relevant information and data had to be extracted from written forms and documents, online resources, and the literature. The following subsections give a detailed review of the findings as a result of the data extraction phase.

4.1 Ferries operated in İzmir

There are 13 Light Craft (LC) carbon composite catamaran passenger ships, two High-Speed Craft (HSC) carbon composite catamaran passenger ships, three 2015 series Ro-Ro ferries, and two 2020 series Ro-Ro ferries operated by İzdeniz. For ease of reading, all vessels mentioned above are addressed as *ferries* in the study unless necessary. Photographs of the ferries can be seen in Figure 4.1.

Carbon composite catamarans operated by İzdeniz were unique in many ways. They were the largest carbon composite catamarans in the world when they were billed for construction as of 2012 [66]. These catamarans were upgrades from ferries that have been operated since the 1970s in İzmir. They are luxurious, ergonomic, universally and accessibly designed, cost-effective, equipped with high-end navigational and modern infotainment systems, and significantly more environmentally conscious than the old ferries. Ferries were also built with the accessible ship design in mind. They have accessible restrooms, accessible parking, accessible elevators, a children's park, catering services, bicycle parking, and open decks.

The technical data on ship particulars and energy consumption characteristics of all ferries operated by İzdeniz as of 2022 were gathered and shown in Table 4.1.

The residents of İzmir publicly decided the ferries' names [67]. The names of ferries owned by İzdeniz are as follows:

Light Crafts:

1. ÇAKABEY
2. DOKUZEYLÜL
3. 1881 ATATÜRK
4. SOMA 301
5. DARIO MORENO
6. ATTİLA İLHAN
7. FOÇA
8. CENGİZ KOCATOROS
9. GÜRSEL AKSEL
10. SAİT ALTINORDU
11. VAHAP ÖZALTAY
12. METİN OKTAY
13. GEZİ

High Speed Crafts:

1. İHSAN ALYANAK
2. PROF. DR. AZİZ SANCAR

Roro Ferries (2015 Series):

1. HASAN TAHSİN
2. AHMET PİRİŞTİNA
3. KUBİLAY

Roro Ferry (2020 Series):

1. FETHİ SEKİN
2. UĞUR MUMCU

Figure 4.1. Photographs of the exterior of LC (a and b) and Ro-Ro (b and c) ferries. Photos from personal archive and İzmir Metropolitan Municipality.

The economic dimension of tendering such ferries was a publicized matter. The total cost of 13 LC and 2 HSC ferries was estimated as 117 000 000 EUR or 267 836 400 TL [68], while they had been on tender by İzmir Metropolitan Municipality in 2012. With such an ambitious project, there were technical challenges to be solved, time constraints, and high standards to be met. As a result, İzdeniz's carbon composite catamarans got nationwide attention from the tender phase to the delivery of the first ferry.

Table 4.1. Ship particulars and other relevant information of ferries operated by İzdeniz.

	Light Craft Passenger Ferry	*High Speed Passenger Ferry*	*Ro-Ro Ferry (2015 Series)*	*Ro-Ro Ferry (2020 Series)*
TYPE:	Carbon Composite Catamaran	Carbon Composite Catamaran	Double Ended Monohull	Double Ended Monohull
LENGTH O.A. (m):	39.00	39.00	78.90	74.00
LENGTH B.P. (m):	38.12	38.12	68.37	66.93
BEAM O.A. (m):	11.60	11.60	17.40	15.60
DEPTH MOULDED (m):	3.50	3.50	3.40	3.00
DRAUGHT (HULL) (m):	1.67	1.67	3.00	2.80
GROSS TONNAGE:	479.00	479.00	1 233.25	1 341.00
LIGHTSHIP (tons):	139.10	148.70	1 143.00	1 106.60
NET TONNAGE (tons):	146	173	400	400
FUEL CAPACITY (liters):	10 180	16 590	51 620	57 500
FUEL CONSUMPTION (liters/NM):	18	28	41	25
MAX SPEED (knots):	16	32	14	13
SERVICE SPEED (knots):	12	24	11	11
MANEUVERING SPEED (knots):	8	10	5.50	5.50
MAIN ENGINES:	Baudouin 12M26.2	MTU 16V 4000 M53	MTU 16V 4000 M54	Baudouin 12M26.2
PROPELLERS:	2x CPP	2x CPP	2x CPP	2x Twin Azimuth
M. E. TOTAL POWER (kW):	1 472	3 680	3 370	1 472
PASSENGER CAPACITY:	426	404	300	322
VEHICLE CAPACITY:	N/A		71	51

4.2 Piers operated in İzmir

İzmir is the third biggest city in the Republic of Türkiye, with a population of 4.3 million [18]. Sitting on the eastern coast of the Aegean Sea and dating back 8 500 years, the city of İzmir has always been a center of attraction for people, businesses, and international trade [70]. The city houses heavy industrial, high-density residential, and commercial developments; along with an international airport, a cruise ship terminal and many large commercial ports, ship deconstruction/recycling facilities, extended light rail, and conventional rail transportation networks, and hundreds of kilometers of high-quality highways [71], [72].

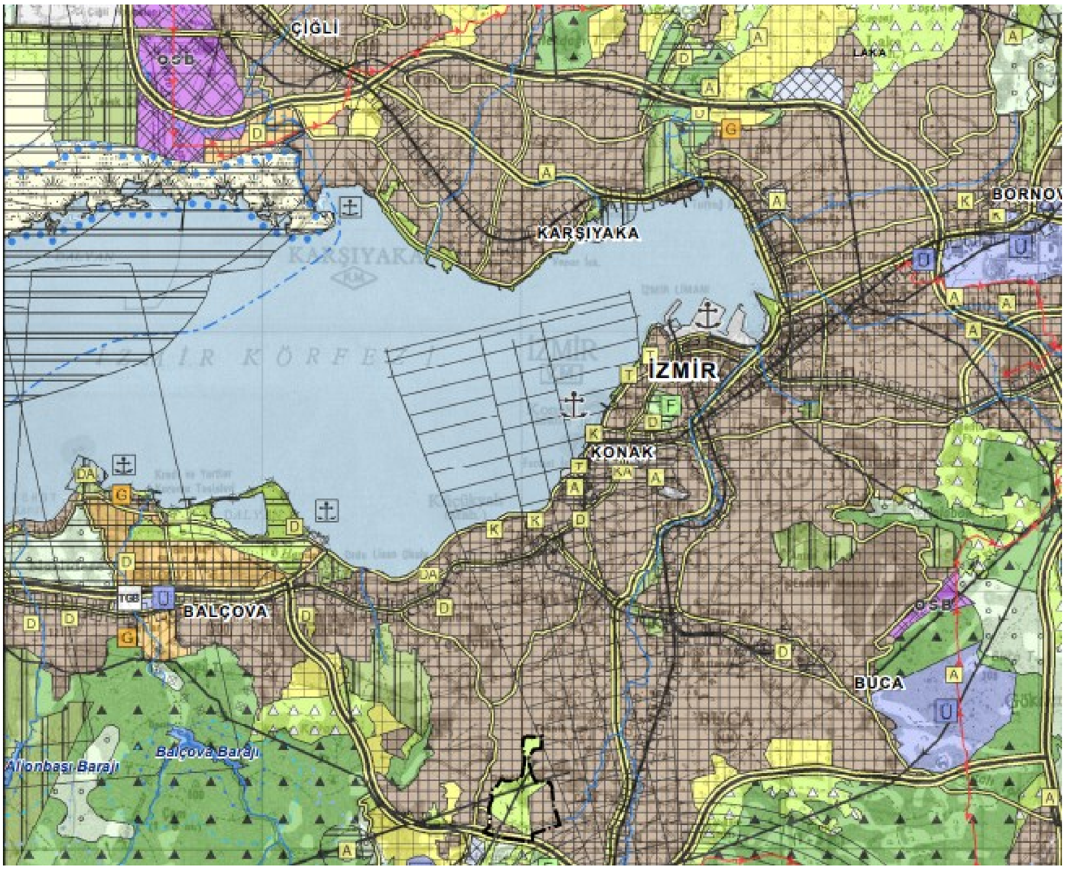


Figure 4.2. A cropped portion of the 100 000:1 scale proposed 2025 Zoning Plan for İzmir was prepared by the Ministry of Environment and Urbanization, showing the inner bay [73].

The inner bay houses the urban core of the city. A very high-density residential and commercial development and several government buildings surround the inner bay, as shown in Figure 4.2.

There is at least one pier in each district that has a coastline to the inner bay, namely the Bostanlı, Karşıyaka, Bayraklı, Alsancak, Pasaport, Konak, Karantina, Göztepe, and Üçkuyular piers, as shown in Figure 4.3. All piers are close to other public transportation modes, enabling transfers between different lines and modes. The available other transportation modes currently include road (buses), rail (LRT and subway), and non-motorized (bicycle rental stations on segregated bicycle pathways, separated pedestrian pathways) transport.

Figure 4.3. The İzmir ferry lines and piers map [74].

The outer bay has a relatively lower residential and commercial density and development. However, due to urban sprawl on the main intercity roads, several old town centers, and local tourism hotspots are located on the corridors along the bay. The Güzelbahçe, Urla, Mordoğan, and Foça piers are located in the vicinity of these town centers and local public transportation hubs.

Yassıca Ada is an island that is a domestic touristic destination. The only development on the island is the beach and related leisure and tourism businesses operated by the Metropolitan Municipality. There is no other commercial or residential development on the island. One seasonal passenger transportation line is activated in summer, with one or two ships operating on the line depending on the demand.

Table 4.2. Coordinates, types, and status of piers operated by İzdeniz.

Name	*Coordinates*	*Transport type*	*Status*
Bostanlı	38.451 9 N, 27.097 8 E	Passenger and Car	Active
Karşıyaka	38.454 7 N, 27.120 5 E	Passenger only	Active
Alsancak	38.438 8 N, 27.140 8 E	Passenger only	Active
Pasaport	38.428 6 N, 27.132 5 E	Passenger only	Active
Konak	38.418 6 N, 27.125 8 E	Passenger only	Active
Karantina	38.414 1 N, 27.121 4 E	Passenger only	Active
Göztepe	38.399 4 N, 27.083 3 E	Passenger only	Active
Üçkuyular	38.405 6 N, 27.070 8 E	Passenger and Car	Active
Güzelbahçe	38.378 8 N, 26.892 5 E	Passenger only	Seasonal
Urla	38.363 9 N, 26.772 2 E	Passenger only	Seasonal
Mordoğan	38.518 2 N, 26.626 7 E	Passenger only	Seasonal
Foça	38.666 4 N, 26.753 4 E	Passenger only	Seasonal
Yassıca Ada	38.408 2 N, 26.794 9 E	Passenger only	Seasonal
Bayraklı	38.463 6 N, 27.161 4 E	Passenger only	Inactive

There is a total of 14 piers available for passenger transportation. Two of the piers are also capable of vehicle transportation. Table 4.2 shows all piers' names, coordinates, transport types, and statuses.

The geographical information of the piers was gathered using the General Transit Feed Specifications provided by İzmir Metropolitan Municipality [75]. The exceptions are Yassıca Ada and Bayraklı piers, which did not have such information in the General Transit Feed Specification (GTFS) and were gathered manually.

4.3 Departure schedules

The seaway public transportation service is carried out according to a semiannual departure schedule announced by İzdeniz. There is continuous passenger and vehicle transportation in the inner bay between 07:00 and 23:45. A record of 18 million passengers and 1.4 million vehicles were transported annually by İzdeniz in 2019.

The author was provided with the data on the lines and schedules announced in October 2021 and given in Appendix B.

CHAPTER 5

MODEL CREATION

5.1 Challenges

The most complex challenge was selecting the appropriate software for modelling and simulations. Several simulation software were trialed, including but not limited to, Anylogic, Arena, PTV Visum, PTV Vissim, Flexsim. The frequent issues with the simulation modelling software faced were:

- Including general workflows rather than transportation-focused workflows,
- Designed for too general discrete event simulation purposes, which significantly lengthens the model design period,
- Designed for too specific discrete event simulation purposes, which limits the capabilities of the software,
- Lack of reporting components or tools or requiring reporting components to be built ground-up,
- Requires coding in C++ or similar programming languages even for the simplest things (like time, dimensional movement variables, naming and recalling a group of objects, defining acceleration and speed limit profiles, and similar),
- Non-user-friendly interfaces, hard-to-configure or non-windowed user spaces, and
- Lack of visual representation of dynamic objects.

After two months of trials, it was observed that Flexsim is a commercial discreet-event simulation software that is transportation-oriented, model-based, user-friendly, easily configured for user needs, and fully documented with online support availability. Therefore, FlexSim was chosen as the simulation software for this study.

5.2 Schedules

All departure times in the October 2021 schedule needed to be converted to hourly values with 10^{-2} accuracy, as the model was “hourly” based. A conversion table was created to automate the process and provide the departure times.

It is also necessary to mention that all the simulation starts at 00:00 on the last Monday before the new year. Therefore, all the runs of the model -or rather models, as it was developed incrementally over time- were exactly 52 weeks long.

5.3 Piers and Lines

To model the piers into a simulation, the coordinates of the piers, lines between those piers, and waypoint data for each line were needed. As of October 2021, line and schedule data were provided by İzdeniz. The coordinates of the piers were gathered via İzmir Metropolitan Municipality’s GTFS and are shown in Table 4.2.

5.3.1 Lines

İzdeniz announced 11 lines in October 2021. All lines except the Line 8 are included in the model.

Weekday passenger lines are given below.

1. Karşıyaka - Konak - Karşıyaka
2. Bostanlı - Konak - Bostanlı
3. Bostanlı - Karşıyaka - Konak - Karşıyaka - Bostanlı
4. Karşıyaka - Alsancak - Pasaport - Karşıyaka and Karşıyaka - Pasaport - Alsancak - Karşıyaka
5. Bostanlı - Alsancak - Pasaport - Bostanlı and Bostanlı - Pasaport - Alsancak - Bostanlı
6. Bostanlı - Karşıyaka - Pasaport - Alsancak - Karşıyaka - Bostanlı

7. Karşıyaka - Üçkuyular - Göztepe - Karantina - Karşıyaka
8. Üçkuyular - Göztepe - Pasaport - Alsancak - Göztepe - Üçkuyular

Weekend passenger lines are given below:

9. Bostanlı - Karşıyaka - Konak - Karşıyaka - Bostanlı
10. Bostanlı - Karşıyaka - Pasaport - Alsancak - Karşıyaka - Bostanlı

The all-week line is given below:

11. Bostanlı - Üçkuyular - Bostanlı (Passenger and Vehicle)

5.3.2 Segments

Each line is named after the piers visited on that specific line. The lines consist of segments that ferries travel between each departure and arrival at any pier. Therefore, travelling a segment means a ferry departing from a certain pier, travelling, and arriving at a certain pier. All segments on all lines were identified and given in Table 5.1.

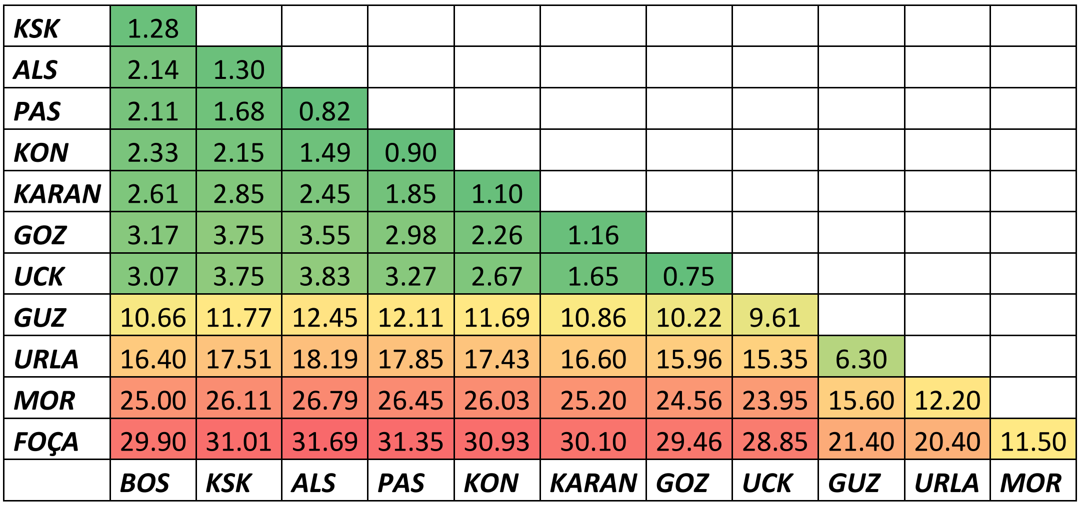
Table 5.1. Segments of all lines in the October 2021 schedule.

		ARRIVAL							
		BOS	***KSK***	***ALS***	***PAS***	***KON***	***KARAN***	***GOZ***	***UCK***
DEPARTURE	***BOS***	■	🟩 2	🟩 3	🟩 4	🟩 5	6	7	🟩 8
	KSK	🟩 9	■	🟩 11	🟩 12	🟩 13	14	15	🟩 16
	ALS	🟩 17	🟩 18	■	🟩 20	21	22	23	24
	PAS	🟩 25	🟩 26	🟩 27	■	29	30	31	32
	KON	🟩 33	🟩 34	35	36	■	38	39	40
	KARAN	41	🟩 42	43	44	45	■	47	48
	GOZ	49	50	51	🟥 52	53	🟩 54	■	🟥 56
	UCK	🟩 57	58	59	60	61	62	🟩 63	■
		BOS	***KSK***	***ALS***	***PAS***	***KON***	***KARAN***	***GOZ***	***UCK***

🟩	Included	(22 Segments)
🟥	Not Included	(2 Segments)
	Non-existing	
■	N/A	

Waypoints that all ferries go through were created to calculate the distances for each segment. Therefore, when a ferry travels along a segment in the model, the distance it travels shall be equal to the real-life distances. Ferry maneuvering characteristics, datum data, and real-life approach bearings were considered while creating those waypoints. As a result, the minimum distances that any ferry will have to travel to complete any given segment were calculated. The distance matrix in Table 5.2 shows the computed minimum segment distances between all piers. For example, the segment between Karşıyaka and Konak piers is 2.15 NM long, while the segment between Alsancak and Foça would be 31.69 NM long.

Table 5.2. Calculated minimum segment distances for all piers. Values are in nautical miles.



KSK	1.28										
ALS	2.14	1.30									
PAS	2.11	1.68	0.82								
KON	2.33	2.15	1.49	0.90							
KARAN	2.61	2.85	2.45	1.85	1.10						
GOZ	3.17	3.75	3.55	2.98	2.26	1.16					
UCK	3.07	3.75	3.83	3.27	2.67	1.65	0.75				
GUZ	10.66	11.77	12.45	12.11	11.69	10.86	10.22	9.61			
URLA	16.40	17.51	18.19	17.85	17.43	16.60	15.96	15.35	6.30		
MOR	25.00	26.11	26.79	26.45	26.03	25.20	24.56	23.95	15.60	12.20	
FOÇA	29.90	31.01	31.69	31.35	30.93	30.10	29.46	28.85	21.40	20.40	11.50
	BOS	***KSK***	***ALS***	***PAS***	***KON***	***KARAN***	***GOZ***	***UCK***	***GUZ***	***URLA***	***MOR***

The minimum time (in minutes) to complete any segment was also estimated, referencing the average service speeds of ferries owned by İzdeniz, as shown by the matrix in Table 5.3. Therefore, the data on realistic pier-to-pier navigational distances and estimated travel times for all possible segments in the model were calculated. Please note that for segments to or from GUZ, URLA, MOR, and FOÇA piers, the HSCs were operated at a maximum service speed of 20 knots. LCs were operated at a maximum service speed of 12 knots for all other segments.

Table 5.3. Calculated minimum time to complete segments. Values are in minutes.

KSK	6.4										
ALS	10.7	6.5									
PAS	10.6	8.4	4.1								
KON	11.7	10.8	7.5	4.5							
KARAN	13.1	14.3	12.3	9.3	5.5						
GOZ	15.9	18.8	17.8	14.9	11.3	5.8					
UCK	15.4	18.8	19.2	16.4	13.4	8.3	3.8				
GUZ	32.0	35.3	37.4	36.3	35.1	32.6	30.7	28.8			
URLA	49.2	52.5	54.6	53.6	52.3	49.8	47.9	46.1	18.9		
MOR	75.0	78.3	80.4	79.4	78.1	75.6	73.7	71.9	46.8	36.6	
FOÇA	89.7	93.0	95.1	94.1	92.8	90.3	88.4	86.6	64.2	61.2	34.5
	BOS	***KSK***	***ALS***	***PAS***	***KON***	***KARAN***	***GOZ***	***UCK***	***GUZ***	***URLA***	***MOR***

5.3.3 Ferries

In order to calculate the energy consumption of ferries, data on the fuel consumption of ferries are needed. Fossil fuel ferries use fuel tanks to store Ultra Low Sulphur Marine Diesel. Full-electric ferries use batteries to store energy to power their electric engines. Initial analysis shows that the fuel tank compartments' size is large enough for ESS to be fitted.

The existing hull design is used without significant alterations for ESS battery compartments as ICE ferries are to be converted to full-electric ferries in the study. Installing ESS batteries below deck level could increase the maximum righting lever. However, no other significant outcome is expected as the ESS battery weight distribution is uniform. Furthermore, the total weight of maximum fuel onboard and the total weight of the ESS to be installed could be similar, albeit entirely depending on the capacity, producer, and technology of ESS batteries.

Therefore, fossil fuel engines' acceleration, deceleration, and energy consumption profiles while ferries are travelling at their cruising speeds were used as a basis in the model. İzdeniz kindly provided the average fuel consumption values of the ferries in order to establish those base energy consumption profiles for converted ferries in the study.

The performance and fuel consumption profiles of ICE used on ferries were analyzed. It has been observed that there are three different types of main engines were installed onboard all ferries [76], [77]:

- LCs and 2020 Series Ro-Ro ferries are equipped with two sets of Baudouin 12M26.2 engines,
- HSCs were equipped with MTU 16V 4000 M53 engines, and
- 2015 Series Ro-Ro Ferries were equipped with MTU 16V 4000 M54 engines.

It has been observed that the main engines were operated at their optimal specific fuel consumption ranges. The lowest specific fuel consumption of all engines mentioned above is 197 g/kWh, while the highest specific fuel consumption is 210 g/kWh. Furthermore, it has also been observed that the ferries have at least 30% more power available on average until reaching their respective Maximum Continuous Rating (MCR) values from the power levels required to sustain service speeds on calm seas.

The nominal power required for ferries to travel at their service speeds was calculated using the formula below; where *k* is the coefficient of MCR value that is necessary to sustain service speeds, *n* is the number of main engines onboard, and *BSFC* is the Brake Specific Fuel Consumption (BSFC).

$$P_{Service\ Speed} = k\ x\ MCR\ x\ n\ x\ BSFC_{Service\ Speed} \tag{1}$$

It is also possible to calculate the energy consumption rates per nautical mile at the cruising speed of all motors by dividing the $P_{Service\ Speed}$ value by the service speed of the ferry. Calculated nominal power and energy consumption rate values for all ferry types are given in Table 5.4.

Table 5.4. The nominal engine/electric motor power and energy consumption rate of ferries at cruising speed.

	LC	*HSC*	*Ro-Ro Ferry (2015 Series)*	*Ro-Ro Ferry (2020 Series)*
Nominal power at cruising speed (kW)	956.80	2 760.00	1 853.50	1 177.60
Energy consumption rate at cruising speed (kWh/NM)	79.73	115.00	168.50	107.05

All ferries' acceleration, deceleration, and related energy consumption were analyzed to have complete energy consumption profiles. The acceleration and deceleration values for all ferries in the model match the duration of maneuvers in actual operations. Therefore, ferries in the model accelerate and decelerate similarly to their real-life twins.

Calculated nominal electric motor power and energy consumption rates in Table 5.4 are only valid while ferries travel at cruising speeds. By design, ICE have an increased BSFC when working at RPM values outside their rated service speeds, as shown in Figure 5.1. Therefore, ICE are less fuel efficient when working at the lower RPM range that is used for travelling at speeds slower than rated service speeds. Furthermore, ICE usually do not sustain maximum torque at their maximum power output range.

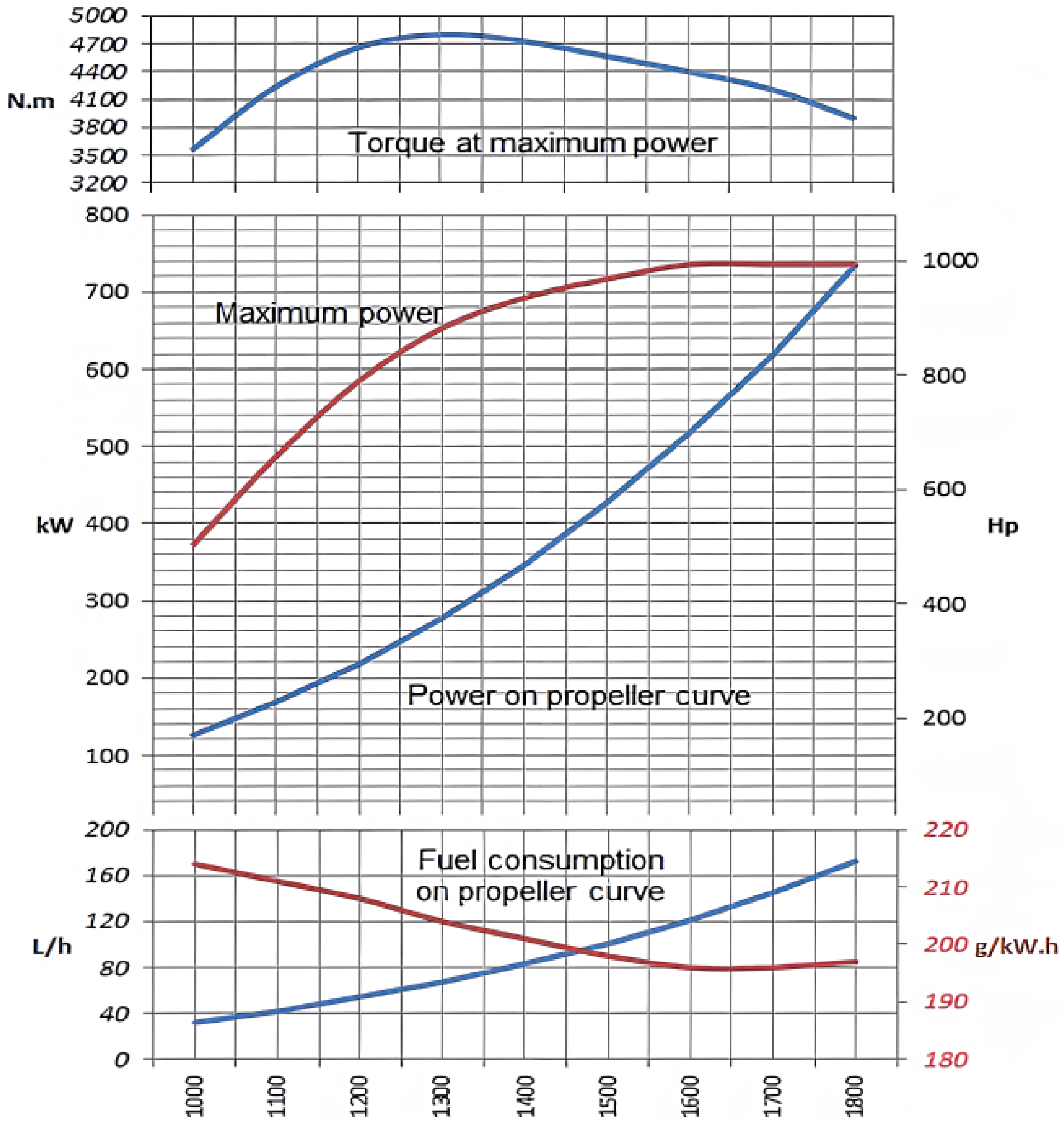
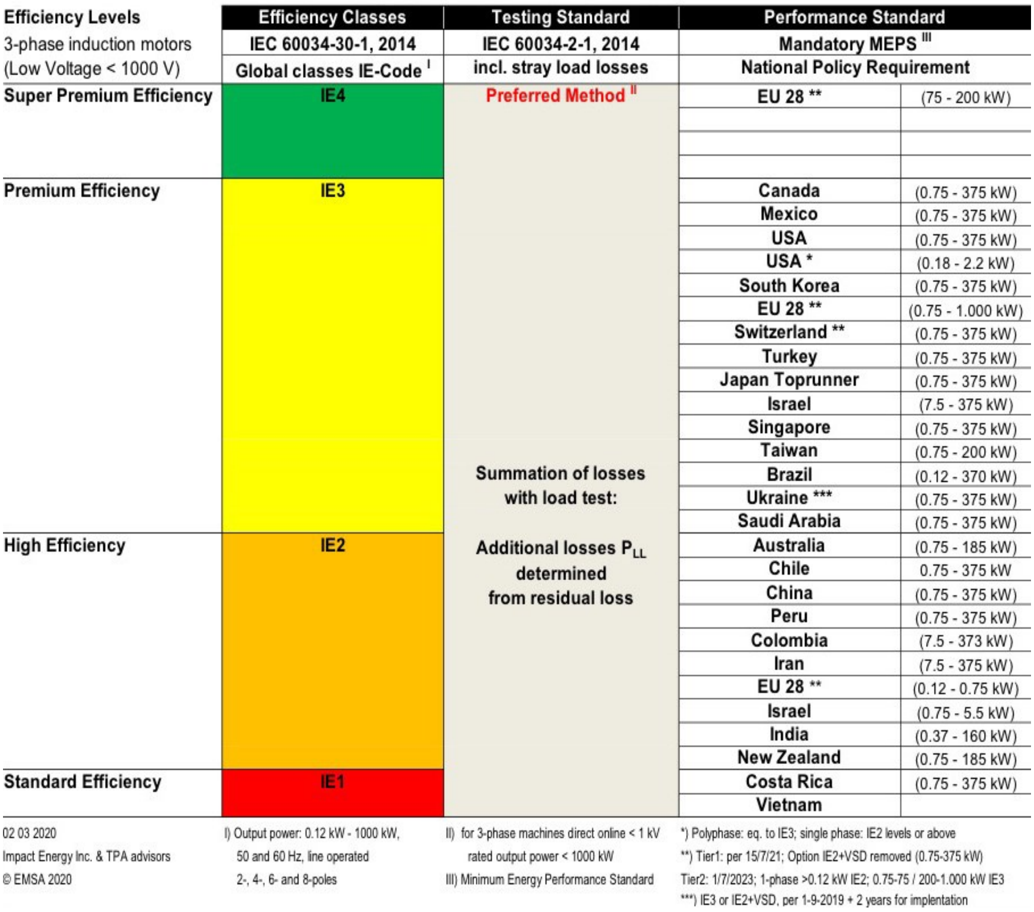


Figure 5.1. Fuel consumption profile of Baudouin 12M26.2 engine [76].

Modern and highly efficient electric motors are virtually immune to these effects. With EU and USA's premium efficiency electric motor programs, electric motors can sustain over 95% efficiency at virtually all RPM ranges they are primarily operated [78], [79]. Moreover, electric motors can maintain maximum torque at most of their RPM ranges while achieving very high-efficiency levels. Optimally, all selected electric motors to be used in full-electric ferries in the study shall comply with the IE3 Premium Efficiency class requirements, shown in Table 5.5.

Table 5.5. The IE3 Premium Efficiency class requirements [80].



Efficiency Levels	Efficiency Classes	Testing Standard	Performance Standard	
3-phase induction motors	IEC 60034-30-1, 2014	IEC 60034-2-1, 2014	Mandatory MEPS [III]	
(Low Voltage < 1000 V)	Global classes IE-Code [I]	incl. stray load losses	National Policy Requirement	
Super Premium Efficiency	🟩 IE4	Preferred Method [II] Summation of losses with load test: Additional losses P_{LL} determined from residual loss	EU 28 **	(75 - 200 kW)
Premium Efficiency	IE3		Canada	(0.75 - 375 kW)
			Mexico	(0.75 - 375 kW)
			USA	(0.75 - 375 kW)
			USA *	(0.18 - 2.2 kW)
			South Korea	(0.75 - 375 kW)
			EU 28 **	(0.75 - 1.000 kW)
			Switzerland **	(0.75 - 375 kW)
			Turkey	(0.75 - 375 kW)
			Japan Toprunner	(0.75 - 375 kW)
			Israel	(7.5 - 375 kW)
			Singapore	(0.75 - 375 kW)
			Taiwan	(0.75 - 200 kW)
			Brazil	(0.12 - 370 kW)
			Ukraine ***	(0.75 - 375 kW)
			Saudi Arabia	(0.75 - 375 kW)
High Efficiency	IE2		Australia	(0.75 - 185 kW)
			Chile	0.75 - 375 kW
			China	(0.75 - 375 kW)
			Peru	(0.75 - 375 kW)
			Colombia	(7.5 - 373 kW)
			Iran	(7.5 - 375 kW)
			EU 28 **	(0.12 - 0.75 kW)
			Israel	(0.75 - 5.5 kW)
			India	(0.37 - 160 kW)
			New Zealand	(0.75 - 185 kW)
Standard Efficiency	🟥 IE1		Costa Rica	(0.75 - 375 kW)
			Vietnam	

02 03 2020
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I) Output power: 0.12 kW - 1000 kW,
50 and 60 Hz, line operated
2-, 4-, 6- and 8-poles

II) for 3-phase machines direct online < 1 kV
rated output power < 1000 kW
III) Minimum Energy Performance Standard

*) Polyphase: eq. to IE3; single phase: IE2 levels or above
**) Tier1: per 15/7/21; Option IE2+VSD removed (0.75-375 kW)
Tier2: 1/7/2023; 1-phase >0.12 kW IE2; 0.75-75 / 200-1.000 kW IE3
***) IE3 or IE2+VSD, per 1-9-2019 + 2 years for implentation

The model's electric motor energy consumption baseline was created using the existing ferries' nominal power and energy consumption values at calm seas. However, it is necessary to mention that a ferry does not always navigate in calm sea conditions. Heavier weather and sea conditions that ferries can be operated require higher energy consumption rates than calm weather and sea conditions for travelling at the same speed. The effects of weather and sea conditions on fuel consumption were studied and explained in the respective subsection.

5.4 Optimizations and limitations

There were several optimizations and limitations while adding lines and ferries into the model. The optimizations are as follows:

- Only ferries that the İzmir Metropolitan Municipality owns were used in the study.
- An optimized number of ferries were operated on each line.
    - Currently, İzdeniz follows an operational model that combines owned and chartered ferries, aiming to reduce total operating costs.
    - Ideally, the number of ships owned by İzmir Metropolitan Municipality is also enough for operating most of the lines in the inner bay, albeit facing certain limitations mentioned below.
    - As a result, the model has a fleet of 13 LCs and 4 Ro-Ro ferries.

The ESS capacities are limited by the ship design and battery energy density. Therefore, there were certain limitations applied while implementing the inner bay lines to the model:

- Karşıyaka - Pasaport - Alsancak - Karşıyaka line: Weekday departures between 10:35 and 16:50 are being carried out by 3 ferries instead of 2 ferries on the schedule in order to increase charging time availability, therefore reducing the requested charge rate. İzdeniz currently operates 2 LC ferries and 1 chartered ferry, whereas 3 LC ferries were used on this line in the study.
- Bostanlı - Pasaport - Alsancak - Bostanlı line: Weekday departures between 10:35 and 16:50 are being carried out by 3 ferries instead of 2 ferries on the schedule in order to increase charging time availability. More charging time reduces the required charge rate. İzdeniz operates 2 LC ferries, whereas 3 LC ferries were used on this line in the study.
- Bostanlı - Üçkuyular - Bostanlı line: Weekday departures are being carried out by 4 ferries.

- Karşıyaka - Üçkuyular - Göztepe - Karantina - Karşıyaka line: Weekday departures of 10 out of 15 trips per week can be assigned to LC13.
    - The last trips for each weekday cannot be completed due to the ESS capacity limits.
- Üçkuyular - Göztepe - Karantina - Konak - Pasaport - Alsancak line: There are not enough ships to assign to this line. A total of 15 trips per week (3 trips per weekday) are not included.
    - This line is parallel to the coast. There are alternative modes of high frequency & high-capacity public transportation, such as busses and LRT, nearby the piers in this line.

A weekly total of 14 trips on outer bay lines that are operated on weekends only during the summer period cannot be included due to the ESS capacity limits:

- The shortest outer bay route, Karşıyaka - Konak - Urla, is 19.58 NM long, one way. An HSC would require approximately 2251.7 kW, while an LC would require 1561.1 kW to get to Urla from Karşıyaka.

- The longest outer bay route, Karşıyaka - Mordoğan, is 28.85 NM long, one way. An HSC requires approximately 3 317.8 kW, while an LC requires 2 300.1 kW to get to Mordoğan.
    - There is an estimated 20% increase in consumption in heavy weather states on top of these values.

As a result of the above optimizations and limitations, a weekly sum of 3 725 individual trips was defined in the model. The following number of trips are completed weekly in the model:

- 419 Bostanlı - Üçkuyular and 419 Üçkuyular - Bostanlı trips,
- 345 Karşıyaka - Konak and 345 Konak - Karşıyaka trips,
- 205 Bostanlı - Konak and 205 Bostanlı - Konak trips,

- 60 Karşıyaka - Alsancak trips, 60 Alsancak - Pasaport, and 60 Pasaport - Karşıyaka trips,
- 220 Karşıyaka - Pasaport, 220 Pasaport - Alsancak, and 220 Alsancak - Karşıyaka trips,
- 125 Bostanlı - Alsancak trips, 125 Alsancak - Pasaport, and 125 Pasaport - Bostanlı trips,
- 60 Bostanlı - Pasaport, 60 Pasaport - Alsancak, and 60 Alsancak - Bostanlı trips,
- 176 Bostanlı - Karşıyaka and 176 Karşıyaka - Bostanlı trips, and
- 10 Karşıyaka - Üçkuyular, 10 Üçkuyular - Göztepe, 10 Göztepe - Karantina, and 10 Karantina - Karşıyaka trips.

It is also necessary to mention that the October 2021 schedule was used for year-long simulations. Any other schedules that have been published since were not considered in this study.

There are not enough ferries *owned by İzmir Metropolitan Municipality* to fully complete the October 2021 schedule. Moreover, there are not enough ferries to meet the additional lines opened in the summers for the same reason.

5.5 Model logic

The model has three main logics to manage lines, weather, sea states, and ESS battery discharging and charging. Each logic is explained in detail in their respective subsections.

5.5.1 Line logic

In FlexSim, users must define sources, transports, and sinks to assign process flows or transport cargo. In the model, the piers are the sources of all cargo on a line, and the cargo is the passengers and vehicles. The passengers and vehicles to be carried are created on the sources attached to piers. Then, passengers and vehicles are shifted to queues to be loaded on the correct ferry. Following the travel phase, ferries arrive at the pier and unload passengers and vehicles. Figure 5.2 shows the ferries, cargo, piers, and routes in 3D.

In the model, there is at least one source, stack, and sink at each pier at all piers. These sources, stacks, and sinks are an essential part of the model that enables the transport of correct cargo (passengers and/or cargo) from and to the correct pier.

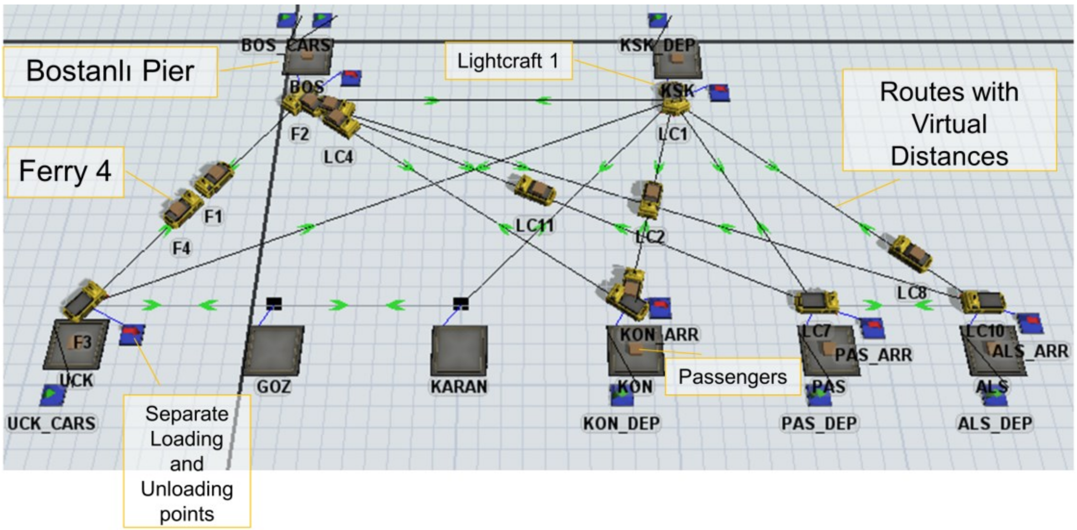


Figure 5.2. 3D representation of the model.

There are two sources and sinks at Bostanlı and Üçkuyular Piers. One is for LCs, and another is for Ro-Ro ferries, while all other piers have one set of sources and sinks. Each box on a source represents the passengers and vehicles to be carried for each segment. In order to successfully complete a segment, passengers or vehicles must be carried via the correct path with the correct ferry and delivered into the correct sink.

In FlexSim, the user can either use coordinate-based distances or virtual distances. The first approach was to use Automated Guided Vehicles (AGV) paths (which use the coordinate system). The second approach was to use Network Nodes (which use defined virtual distances). Models in both methods utilized AGV. The total segment distances that AGVs travelled were the same in both approaches to conduct a fair comparison.

Trials proved that the second approach was significantly more time effective than the first approach. Furthermore, the second approach requires considerably less design complexity and uses less computational power. Using less computational power becomes significantly more critical for conducting several year-long model runs. Therefore, the model in the study was constructed using the virtual distances approach.

Each segment was modelled to create a virtual path between two piers, shown by a direct line with green arrows in the middle in Figure 5.2. However, the path distance is not equal to the direct distance between piers but is instead equal to the minimum segment distance that includes waypoints.

There is a preset schedule for each line that all ferries operated on that line should follow. Therefore, a logic was assembled to manage all ferries and all departures of each segment on each line. A *line logic* for a line chooses the first unreserved departure, reserves, and then assigns it to the next available ferry operating in that line. Simply put, the line logic does not create the passengers or cars on that line. Instead, the line logic assigns the time of departure and the correct passengers and vehicles to the correct ferry. A flowchart of the line logic is given in Figure 5.3.

In the line logic, the number of ships marked available for a line is dynamic. There are two criteria to change the number of ferries operated on a line dynamically:

- The time of day in the simulation, and
- Current status of the ferries assigned to the line.

First, if the simulation time matches a peak hour, the maximum number of available ferries is increased to the maximum number reserved for that line. In contrast, it is decreased to the minimum number when it is off-peak hours.

Second, the current status of the ferry is checked. If it is available for loading, *meaning it has completed its unloading process and is at idle status,* it is added back to the list of available ferries to be assigned on that line. Afterwards, an available ferry gets assigned to load passengers and vehicles.

Ferries in the model are set to depart by the line logic when the simulation time matches the preset departure time. All logic starts with the first departure time set for that line and continuously cycles throughout the day until all departures on that line for that day are exhausted.

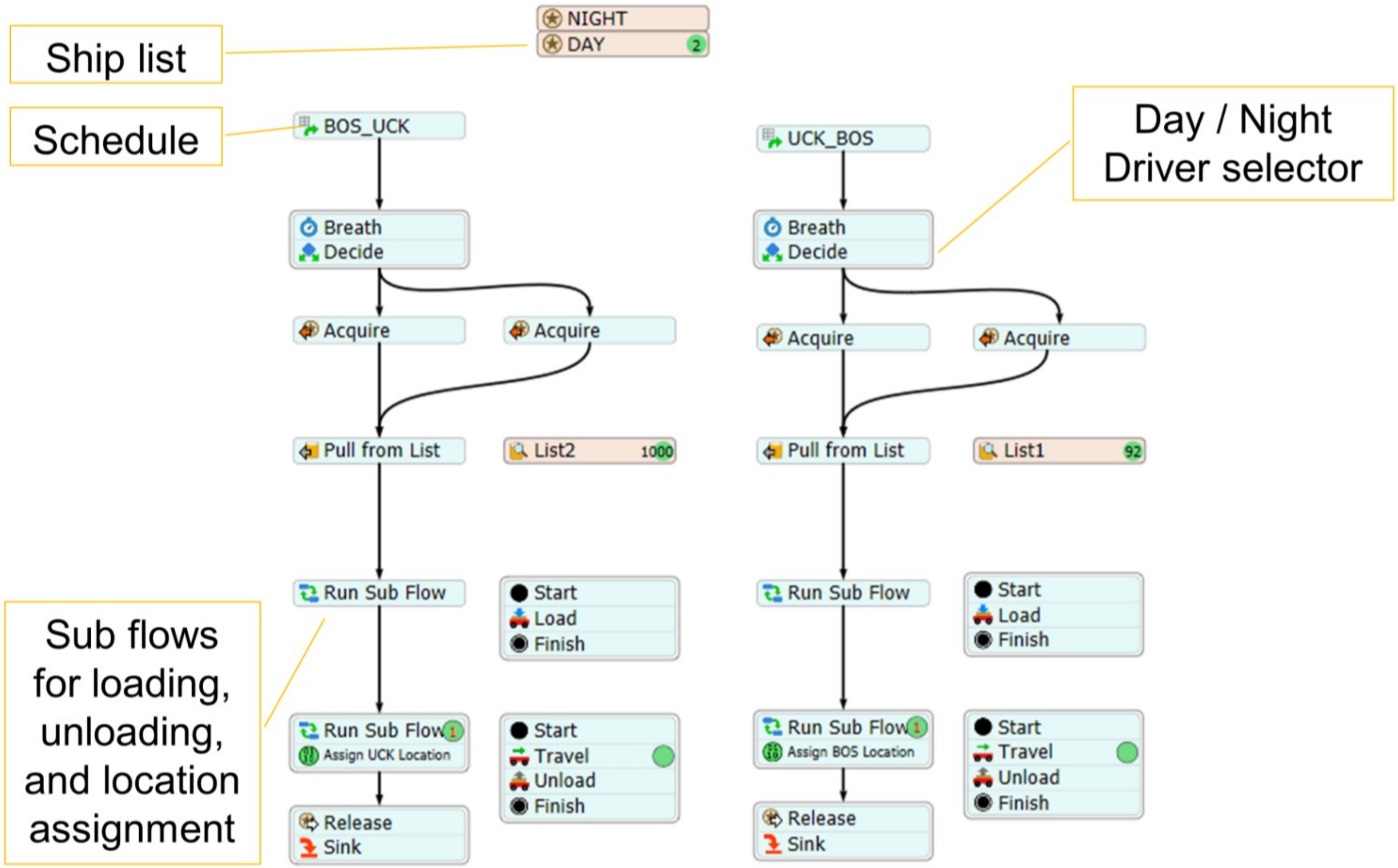


Figure 5.3. The logic that manages the ferries, passengers, and vehicles according to a preset schedule on the Bostanlı - Üçkuyular line. There can be separate logic for different periods to assign a different number of ferries, even on the same line.

All ferries are assigned a location indicator when it reaches a destination pier. This approach was adopted to know where the ferry has been throughout the day to fix design errors or bugs in the custom code. Moreover, this approach enables experimenting with the charging-related variables in an absolute manner.

5.5.2 Weather and sea conditions logic

The model includes a weather and sea conditions logic that adjusts the energy consumption of all ferries. The weather and sea conditions logic use preset weather and sea conditions table to feed a randomized generator. Then the logic assigns the energy consumption rate multiplier for the day in the model, as shown in Figure 5.4. The model generates a new randomized daily energy consumption rate at the end of each day. The new daily energy consumption rate is set at the first second after midnight.

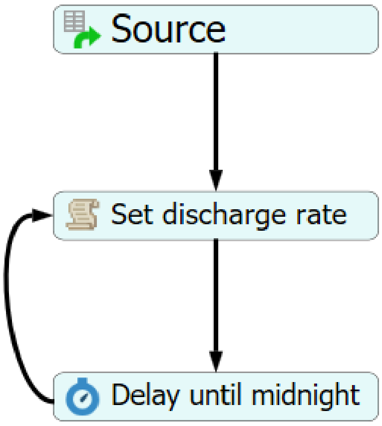


Figure 5.4. Flowchart of the weather and sea conditions logic.

The energy consumption rate is expected to increase as the weather and sea conditions deteriorate. However, it is necessary to determine the numerical values to be used in the model. There are several ways to estimate the effects of weather and sea conditions on ferries' energy consumption. It is possible to calculate and simulate the impact of weather and sea conditions on a ship in the case of in-depth technical data available on the ship's stability. However, the author did not have access to such detailed information and data. Therefore, it was necessary to estimate the effects of weather and sea conditions on fuel consumption.

Several approaches are used to estimate the effects of weather and sea conditions on a ship's fuel/energy consumption in the literature by worldwide research organizations and engine manufacturers. In the literature, it is stated that heavier weather conditions significantly increase the fuel/energy consumption of ships. While the amount of fuel/energy consumption increase due to heavier weather and sea conditions varies significantly in the literature, it has been observed that the consumption rate increase was concentrated between 5% and 15% [81]. An ICE manufacturer recommends a 10% to 25% margin for heavier weather and sea conditions compared to calm [82]. In case of no performance model availability, International Towing Tank Conference (ITTC) Recommended Procedures and Guidelines recommends a 15% to 25% margin for estimating the power requirements for heavier weather and sea conditions [83].

Therefore, it was decided to use a 10% to 20% increase in the daily average fuel consumption due to weather and sea conditions. İzdeniz Superintendent department also confirmed that such fuel consumption cases were plausible, depending on the weather and sea conditions that allow the safe operation of ferries.

Beaufort scales were used for assigning the weather and sea conditions. Three incremental levels of weather and sea conditions were deemed suitable for ferries operated in İzmir.

- Below 3 Beaufort : Calm Conditions
- 3 to 6 Beaufort : Elevated Conditions
- Over 6 Beaufort : Heavy Conditions

As a result, the following rates are appropriate for estimating the fuel consumption rates in heavier weather conditions used in the model:

- Below 3 Beaufort : Calm Conditions, 100% consumption rate
- 3 to 6 Beaufort : Elevated Conditions, 110% consumption rate
- Over 6 Beaufort : Heavy Conditions, 120% consumption rate

The statistical data on wind conditions using the simulated historical climate and weather data for İzmir was gathered [84] and shown in Table 5.6.

Table 5.6. Monthly average weather and sea conditions are grouped using the simulated historical climate and weather data for İzmir [84].

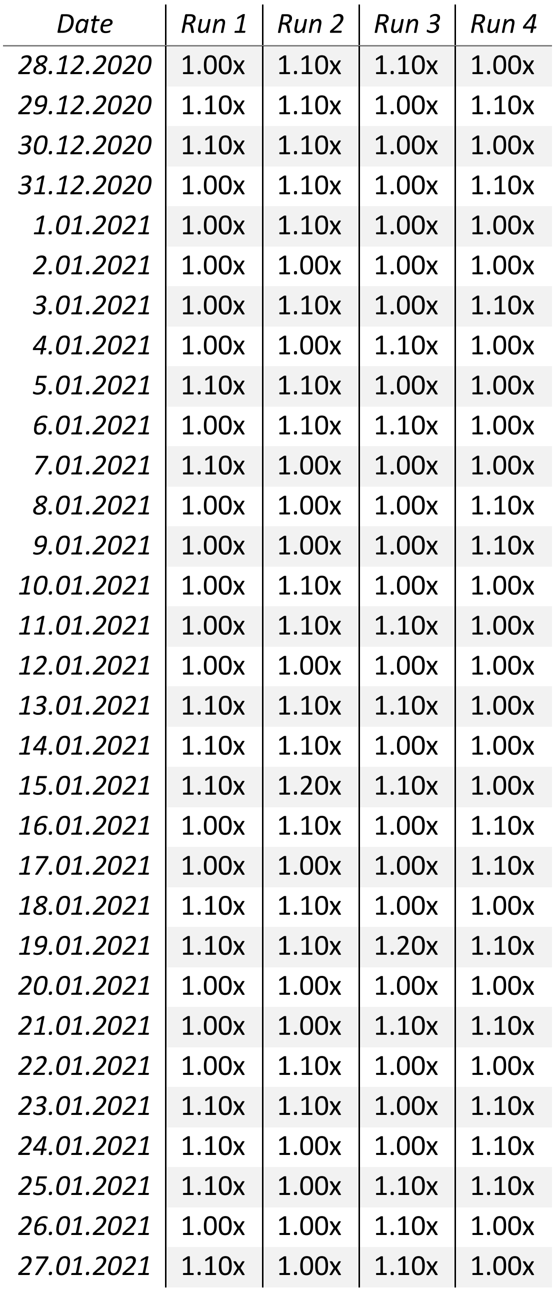
	Calm Conditions			*Elevated Conditions*			*Heavy Conditions*		
	Rate	Chance	Max. Days	Rate	Chance	Max. Days	Rate	Chance	Max. Days
January	1x	0.55	17	1.1x	0.42	13	1.2x	0.03	1
February	1x	0.39	12	1.1x	0.48	15	1.2x	0.03	1
March	1x	0.39	12	1.1x	0.58	18	1.2x	0.03	1
April	1x	0.35	11	1.1x	0.58	18	1.2x	0.03	1
May	1x	0.23	7	1.1x	0.74	23	1.2x	0.03	1
June	1x	0.06	2	1.1x	0.81	25	1.2x	0.10	3
July	1x	0.03	1	1.1x	0.74	23	1.2x	0.23	7
August	1x	0.06	2	1.1x	0.81	25	1.2x	0.13	4
September	1x	0.16	5	1.1x	0.74	23	1.2x	0.06	2
October	1x	0.48	15	1.1x	0.48	15	1.2x	0.03	1
November	1x	0.58	18	1.1x	0.39	12	1.2x	0	0
December	1x	0.55	17	1.1x	0.42	13	1.2x	0.03	1

The “Rate” multiplier affects the fuel consumption of all ferries during the day in the model. If it is set at 1, the fuel consumption rate of the ferries is set to 100%. If it is set at 1.1, the fuel consumption rate of the ferries is set to 110%. If it is set at 1.2, the fuel consumption rate of the ferries is set to 120%.

Depending on the month, there is a daily chance for each weather and sea condition to occur in the weather and sea conditions logic. For example, in İzmir, there is a daily 23% chance for heavy conditions to occur in July. However, there is a 0% chance for heavy conditions to occur in November.

In the logic, the randomized generator may generate calm conditions for all days in July by pure chance, if not limited in any way. Therefore, a monthly limit is introduced to the maximum number of days with each condition to eliminate that issue.

Table 5.7. Different daily consumption rates were generated at four different 744-hour runs of the simulation for the exact dates.



Date	*Run 1*	*Run 2*	*Run 3*	*Run 4*
28.12.2020	1.00x	1.10x	1.10x	1.00x
29.12.2020	1.10x	1.10x	1.00x	1.10x
30.12.2020	1.10x	1.10x	1.00x	1.00x
31.12.2020	1.00x	1.10x	1.00x	1.10x
1.01.2021	1.00x	1.10x	1.00x	1.00x
2.01.2021	1.00x	1.00x	1.00x	1.00x
3.01.2021	1.00x	1.10x	1.00x	1.10x
4.01.2021	1.00x	1.00x	1.10x	1.00x
5.01.2021	1.10x	1.10x	1.00x	1.00x
6.01.2021	1.00x	1.10x	1.10x	1.00x
7.01.2021	1.10x	1.00x	1.00x	1.00x
8.01.2021	1.00x	1.00x	1.00x	1.10x
9.01.2021	1.00x	1.00x	1.00x	1.10x
10.01.2021	1.00x	1.10x	1.00x	1.00x
11.01.2021	1.00x	1.10x	1.10x	1.00x
12.01.2021	1.00x	1.00x	1.00x	1.00x
13.01.2021	1.10x	1.10x	1.10x	1.00x
14.01.2021	1.10x	1.10x	1.00x	1.00x
15.01.2021	1.10x	1.20x	1.10x	1.00x
16.01.2021	1.00x	1.10x	1.00x	1.10x
17.01.2021	1.00x	1.00x	1.00x	1.10x
18.01.2021	1.10x	1.10x	1.00x	1.00x
19.01.2021	1.10x	1.10x	1.20x	1.10x
20.01.2021	1.00x	1.00x	1.00x	1.00x
21.01.2021	1.00x	1.00x	1.10x	1.10x
22.01.2021	1.00x	1.10x	1.00x	1.00x
23.01.2021	1.10x	1.10x	1.00x	1.10x
24.01.2021	1.10x	1.00x	1.00x	1.10x
25.01.2021	1.10x	1.00x	1.10x	1.10x
26.01.2021	1.00x	1.00x	1.10x	1.00x
27.01.2021	1.10x	1.00x	1.10x	1.00x

It is necessary to emphasize that the model's total daily energy consumption depends on the weather and sea conditions, which ferry is operated, and the schedules. As a result, the combined effect of randomized weather and sea conditions and different daily schedules over a week result in a unique yearly energy consumption profile every single time model is run, as Table 5.7 shows.

5.5.3 Discharging, charging, and battery level checking logic

A combined logic manages the model's discharging, charging, and battery level-related events. The first part of the logic is straightforward. If the ferry is in the travelling state, the ferry battery is set to discharge state, as shown in Figure 5.5. As a result, the energy stored in ferry ESS is consumed.

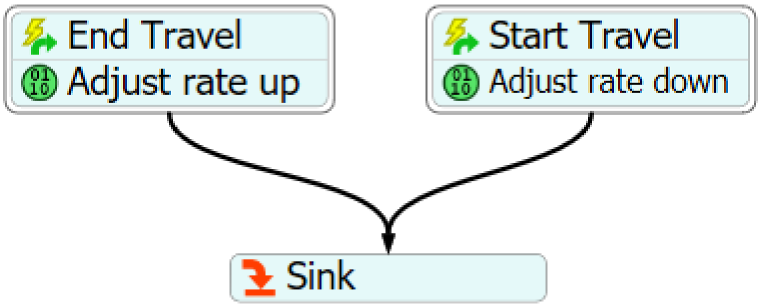


Figure 5.5. Flowchart of the state checking part of the discharging and charging logic.

If the ferry is not in the travelling state, it is set to the charging state if all conditions are met. The requirements are as follows:

- The ferry must complete the “unloading” operation,
- The ferry must be in the “idle” state,
- The ferry must have less than 100% ESS charge level, and
- The ferry must be at a pier with a charging station(s).

In the real world, instantaneously connecting the charging systems to the ferries is impossible. Therefore, a uniformly randomized delay of 30 to 90 seconds for LC and 60 to 180 seconds for Ro-Ro ferries for connecting charging systems at each docking were introduced, which is applied right after the travelling state. For clarification, the ferries in the "unloading" state are not charged.

It is possible to select the piers with charging stations and adjust the rate of charging in the model. The charging rates are assigned to the chosen piers at the beginning of the simulation. The charging rates are also constant and are assigned to ferries on arrival at a pier with charging availability. Ferries are charged either until their ESS level reaches the maximum capacity or until their departure.

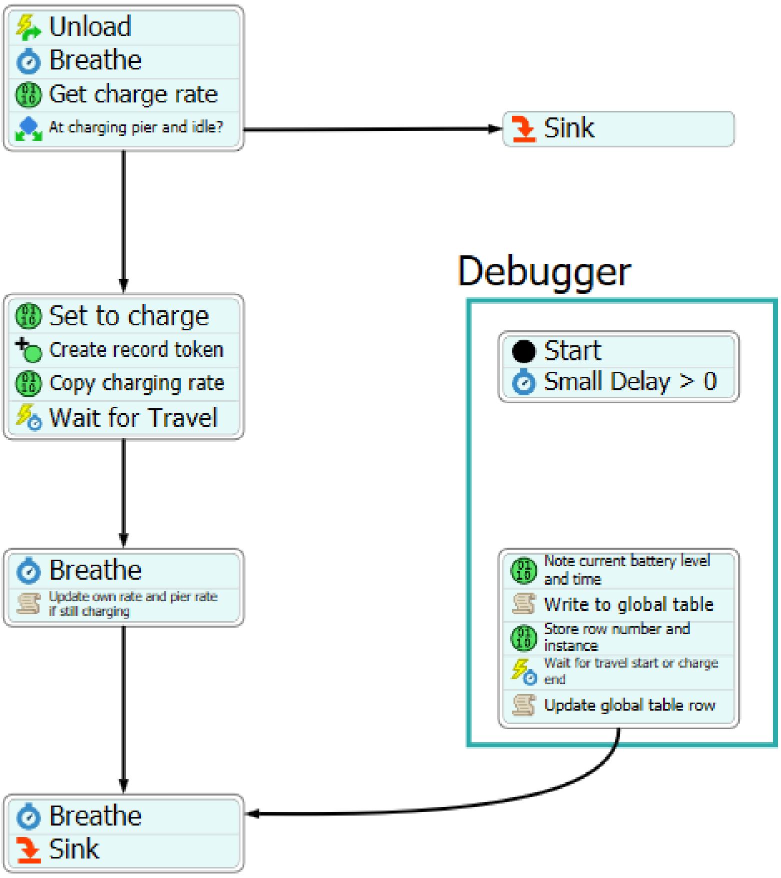


Figure 5.6. Flowchart of the ferry charging logic.

The battery level checking logic constantly checks all ESS charge levels simultaneously. If any ESS onboard a ferry or on a pier is recharged to 100% capacity by the pier charging station and the PV panels, the charge rate is set to 0 kW, as shown in Figure 5.7. This approach eliminates any logic in the model from going beyond 100% capacity for any given ESS at any given time.

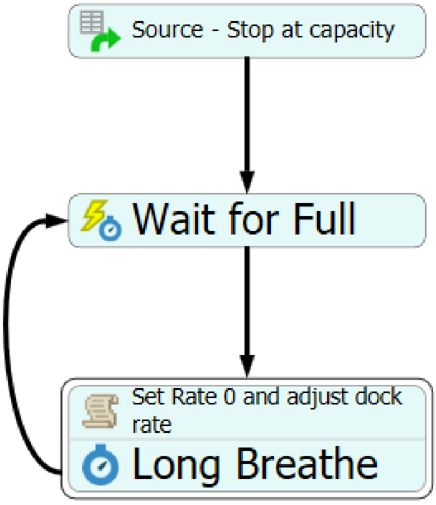
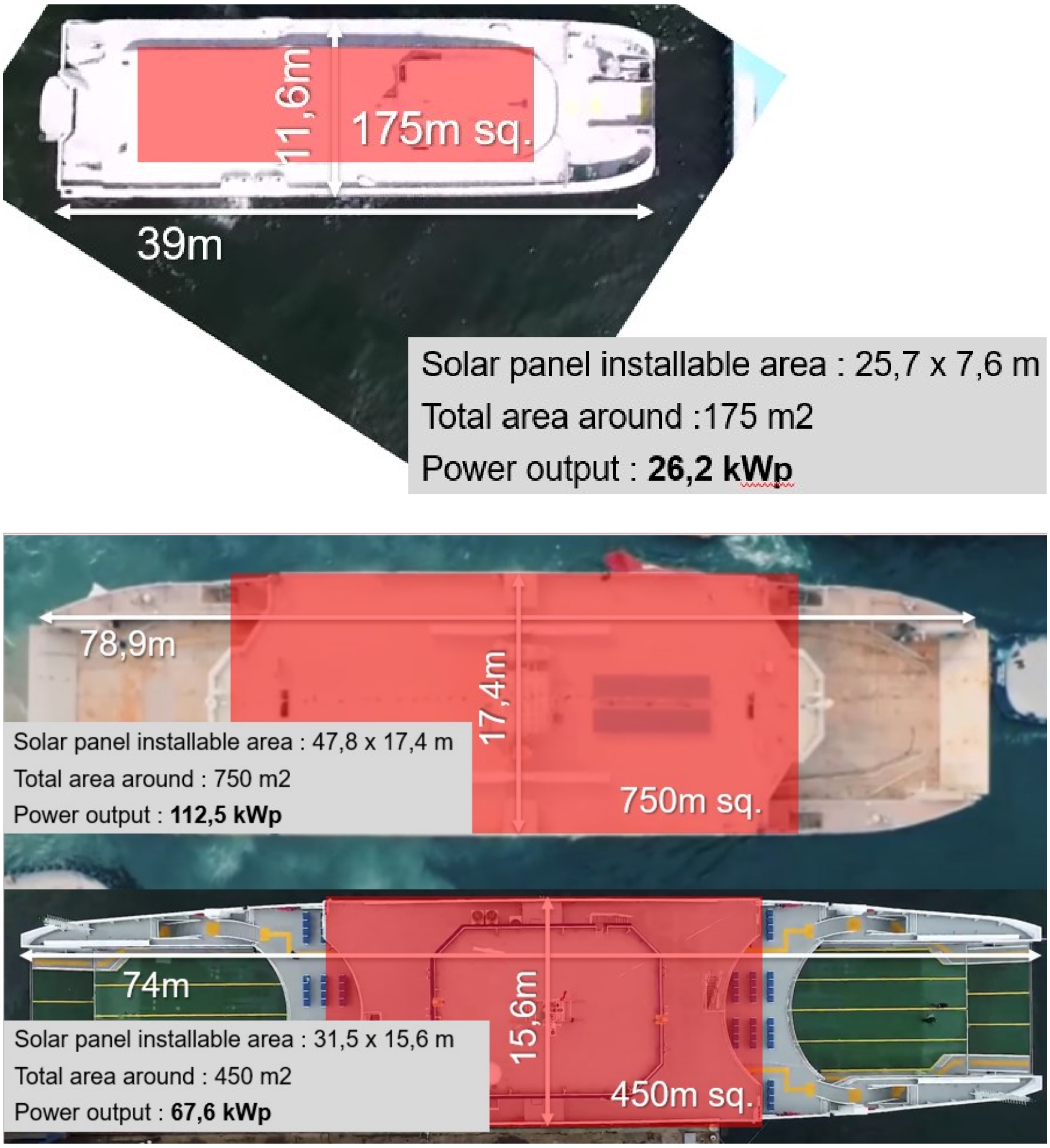


Figure 5.7. The flowchart of battery level checking logic.

5.5.4 Renewable energy logic

A renewable energy logic that also charges ESS batteries during the daytime was integrated into the model. As solar power is used as the source of renewable energy, it was necessary to establish the total PV system power generation rate for each pier and ferry. In order to calculate the hourly power generated by the PV systems, the following areas were deemed to be suitable for PV panel installation:

- 175 m^2 on top of the top deck and hardcover on the semi-open deck of LCs,
- 750 m^2 and 450 m^2 on top of the top deck of the 2015 and 2020 series Ro-Ro ferries, respectively, and
- 2 000 m^2 on top of vehicle waiting areas of Bostanlı and Üçkuyular piers.



Solar panel installable area : 25,7 x 7,6 m
Total area around :175 m2
Power output : **26,2 kWp**

Solar panel installable area : 47,8 x 17,4 m
Total area around : 750 m2
Power output : **112,5 kWp**

Solar panel installable area : 31,5 x 15,6 m
Total area around : 450 m2
Power output : **67,6 kWp**

Figure 5.8. Suitable solar PV panel locations and estimated total PV panel area on ferries.

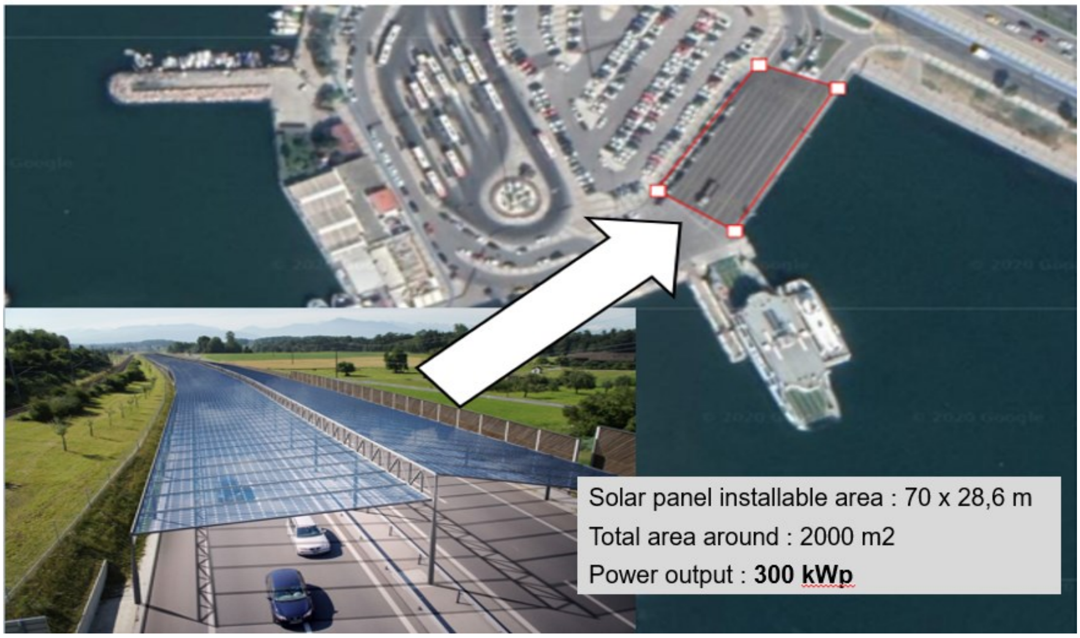


Figure 5.9. Suitable solar PV panel locations and estimated total PV panel area on piers.

The estimated peak power output of panels is shown in Figures 5.8 and 5.9. However, the solar irradiance is not uniform. The hourly, daily and seasonal variances in solar irradiance were considered in the model as an hourly Solar irradiance table for İzmir was used as a reference [64], [65].

The logic uses tabulated power generation values for a one kWp PV system, as shown in Table 3.9. The logic calculates each PV system's total hourly power output values at the first second of each hour. Then, the calculated values are assigned to ferries and piers with PV panels for the hour. If the ESS battery is not charged to its total capacity, the PV system will continue to recharge the ESS.

The PV system works irrespective of the pier chargers. Furthermore, the energy flow is only one directional: from the pier to the ferry. PV systems onboard ferries do not recharge the ESS batteries ashore.

CHAPTER 6

SIMULATION RESULTS

There are several aims of the simulation phase to get the data required for conducting the techno-economic analysis in the study. As a result, models were developed to:

- Estimate the time available for each ferry at each docking,
- Establish energy consumption profiles of ferries,
- Estimate maximum energy consumption of ferries per segment,
- Estimate maximum energy consumption of ferries per segment in simulated weather and sea conditions,
- Estimate the minimum ESS capacities for ferries and piers,
- Estimate the minimum ESS capacities for ferries and piers depending on the charging availability scenarios,
- Estimate the power generated by solar PV panels onboard ferries and piers,
- Estimate the minimum ferry charging power required in all conditions, and
- Estimate the effects of having different ESS capacities on the power requested from the city power grid.

There were four main stages of models selected for development in this study. These stages were created as a result of the step-by-step model development approach. A specialized feature was introduced to the model at each stage. Each main stage is explained in detail in its respective subsection.

6.1 Base model

The base model was formed to estimate the actual annual total, per segment, and per NM energy consumption values of the full-electric ferries to be operated in İzmir. At this stage, the model is barebones and does not incorporate the weather and sea conditions, any charging-related logic, or renewable energy logic.

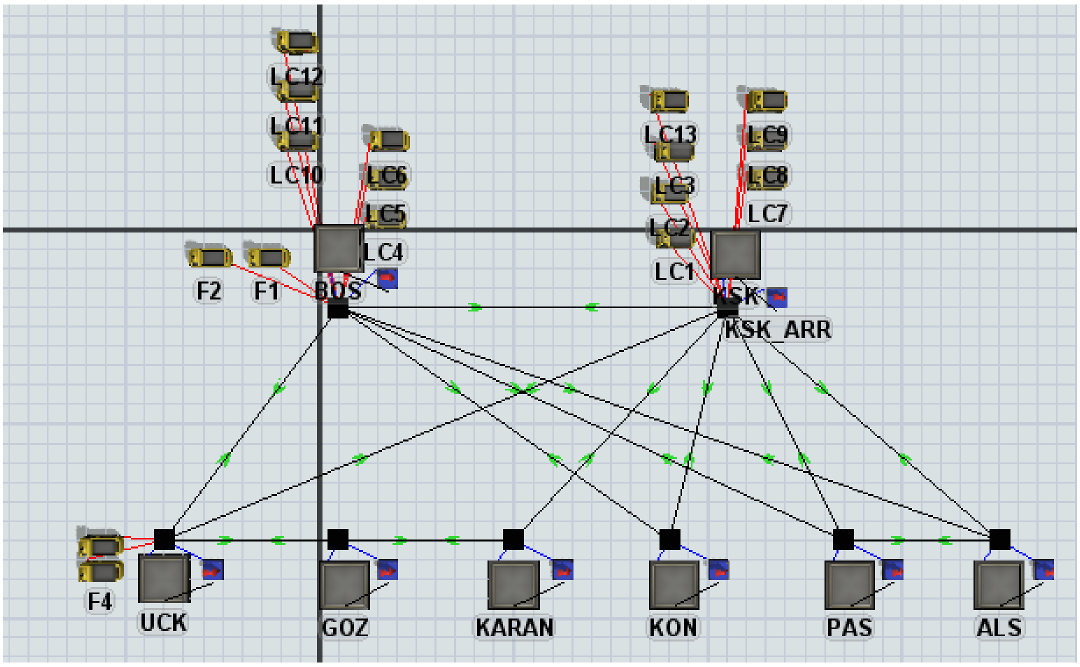


Figure 6.1. Starting positions of each ferry at the beginning of the model.

The base model consists of a complete model that utilizes electric ferries' calculated acceleration, deceleration, and energy consumption data using the values given in Table 4.1.

A total of 777 141 battery level changing events were recorded throughout a single, one-year-long run of the model. As several variables use randomized values in the model, the model was run five times while each event was recorded. The total travel distance, total energy consumption, number of segments, average segment consumption, and average energy consumption per NM for each ferry were calculated using the values averaged from these five runs and given in Table 6.1.

Table 6.1. Calculated annual total travel distance, total energy consumption, the total number of segments, and the energy consumption per segment and NM, using the base model.

	Total Travel Distance (NM)	*Total Energy Consumption (kWh)*	*No. Of Segments*	*Avg. Power Cons. Per Segment (kWh/Segment)*	*Avg. Power Cons. Per Nm (kWh/NM)*
LC1	20 265.90	1 747 209.81	9 426	185.36	86.21
LC2	20 265.90	1 747 209.98	9 426	185.36	86.21
LC3	17 582.71	1 515 880.04	8 178	185.36	86.21
LC4	26 864.21	2 324 591.37	13 106	177.37	86.53
LC5	26 857.35	2 323 988.81	13 102	177.38	86.53
LC6	26 854.21	2 324 591.67	13 106	177.37	86.56
LC7	12 562.81	1 139 871.68	9 918	114.93	90.73
LC8	12 562.81	1 139 871.84	9 918	114.93	90.73
LC9	12 562.81	1 139 871.99	9 918	114.93	90.73
LC10	26 254.66	2 336 756.30	17 467	133.78	89.00
LC11	26 254.66	2 336 756.49	17 467	133.78	89.00
LC12	26 254.66	2 336 756.69	17 467	133.78	89.00
LC13	4 442.23	383 288.03	2 088	183.57	86.28
F1	33 539.75	3 880 033.53	10 925	355.15	115.68
F2	33 536.69	6 106 474.52	10 924	559.00	182.08
F3	33 539.75	3 880 033.39	10 925	355.15	115.68
F4	33 536.68	6 106 473.92	10 924	559.00	182.08
TOTAL	**393 737.79**	**42 769 660.06**	**194 285**		

LC is divided into groups consisting of 3 ferries to be operated on a particular line, as seen from the results. Each ferry in a group has equal or similar total energy consumption values. The reason is the dynamic management of ferries in the model by line logic. LC3 is an exception in the first group as the ferry LC3 is not utilized on weekends. Also, LC13 is the only ferry operated on the Karşıyaka - Üçkuyular - Göztepe - Karantina - Karşıyaka line.

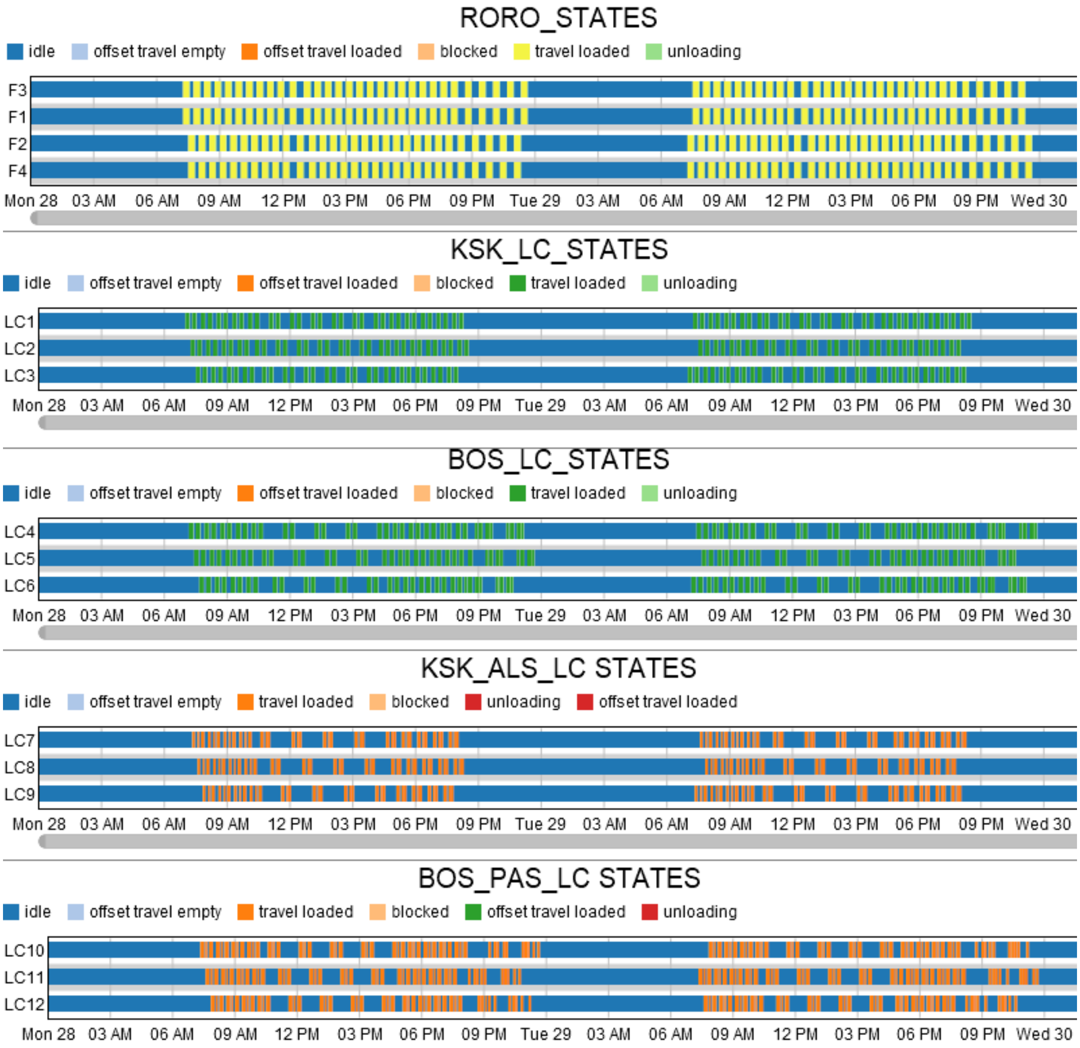


Figure 6.2 States of all ferries in the model. The model was run for 48 hours.

In Figure 6.2, the travel states of Ro-Ro ferries are shown in yellow, the LC1, LC2, LC3, LC4, LC5, and LC6 departing from BOS shown in green, and the rest of the LCs are shown in orange. It was observed that the line logic assigns the ferry that completed its last segment earlier than other ferries to the first segment of a particular line on the next day. In other words, the first ferry on each line is shifted to the next ferry every day. Therefore, the number of ferries operated on a line changes to equalize the daily distance travelled by each ferry, where possible.

The LCs have an annual average energy consumption of 87.98 kWh/NM in the model. The lowest annual average energy consumption is 86.21 kWh/NM, and the highest annual average energy consumption is 90.73 kWh/NM. The difference between the highest and the lowest annual average energy consumption is 4.52 kWh/NM or 5.14% of the average yearly energy consumption.

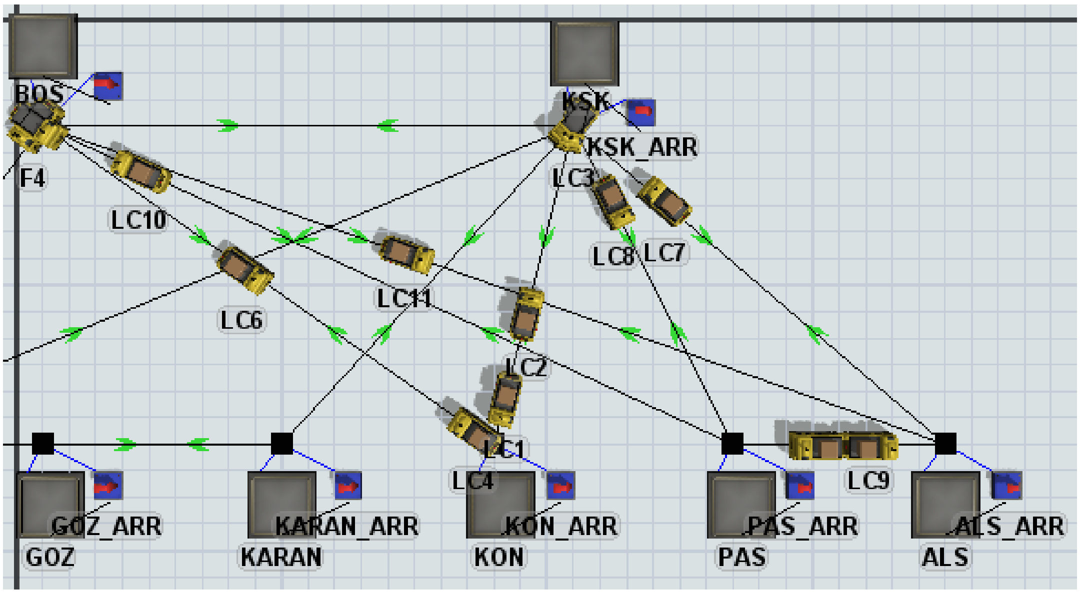


Figure 6.3. The LCs 7 to 12 are directly assigned to lines that include the PAS-ALS or ALS-PAS segment. Distances are not to scale.

It is observed that each group's annual total and average consumption vary while the variables such as the acceleration and deceleration data of LCs are fixed. The differences are due to the short segment distance between the Alsancak and Pasaport piers. The short distance between those piers and the randomized time it takes to unload and load passengers decreases the average speed that ferries can sustain in this particular segment, increasing the average energy consumption compared to other longer segments.

Charging logic is not enabled in this model. However, each ferry's highest energy consumption was recorded to estimate ferry ESS capacities.

There were specific adjustments to the model:

- ESS battery capacities of ferries were set to ten million -virtually infinite- kWh,
- Ferries are able to recharge at Karşıyaka, Bostanlı, and Üçkuyular piers, but the recharge power is one hundred thousand kW *-practically unlimited-*, and
- An ESS battery level entry was recorded at each departure and arrival of each ferry,

Therefore, any ferry that travels and consumes power will decrease its ESS battery levels. The largest difference between an departure and arrival of ferries shall give the highest *-or worst-case scenario-* energy consumption. The maximum energy consumption and, therefore, the energy consumption for the worst-case scenario of each ferry is shown in Table 6.2.

A ferry, its crew, and its passengers onboard can face emergencies. IMO requires a ferry to be full-electric *-i.e., not having fossil-fuel-powered emergency power packs-* the onboard ESS battery needs to maintain all critical systems and emergency equipment (e.g., firefighting) for three hours [9]. As a result, a 30% ESS battery capacity was exclusively reserved for emergencies and therefore included in the minimum ESS battery capacity calculations of ferries.

Table 6.2. The maximum energy consumption of ferries in calm weather and sea conditions.

Ferry & No.	*Max. Energy Consumption*	*ESS Battery Capacity (Including 30% Emergency Reserve)*	*ESS Battery Capacity (Rounded Up)*
LC1, LC2, LC3	371.1 kWh	530.2 kWh	540 kWh
LC4, LC5, LC6	486.7 kWh	695.3 kWh	700 kWh
LC7, LC8, LC9	345.7 kWh	493.9 kWh	500 kWh
LC10, LC11, LC12	576.7 kWh	823.9 kWh	830 kWh
LC13	735.2 kWh	1 050.3 kWh	1 060 kWh
F1, F3	355.7 kWh	508.1 kWh	510 kWh
F2, F4	560.2 kWh	800.4 kWh	810 kWh

There is a significant difference in the maximum consumption values due to the charging availability at only Bostanlı, Karşıyaka, and Üçkuyular piers, and also the total distance of the lines. As shown in Table 6.2, the maximum energy consumption of each ferry varies between 500 kWh and 1 060 kWh.

For the LCs, it was observed that the lowest maximum consumption is 500 kWh and belongs to LC7, LC8, and LC9. The highest maximum consumption is 1 060 kWh and belongs to LC13.

For the Ro-Ro ferries, it was observed that the highest consumption is 810 kWh and belongs to F2 and F4. F2 and F4 are the 2015 Series Ro-Ro ferries. The lowest maximum energy consumption is 510 kWh and belongs to F1 and F3. F1 and F3 are the 2020 series Ro-Ro ferries.

One crucial factor that must be considered when interpreting the calculated maximum energy consumption values in the base model is that the charging power is set to unlimited in this scenario. Therefore, the time the ferry stays at the dock is irrelevant as it is virtually charged instantly. However, as we will see in the following subchapters, the duration of the charging period has significant effects on the maximum energy consumption.

6.2 Weather and sea conditions model

The weather and sea logic defines the daily energy consumption of all ferries. The energy consumption values in the weather and sea conditions enabled model can only increase up to 120% compared to the values in the base model. Therefore, the maximum energy consumption and ESS battery capacity values of all ferries can be calculated by multiplying the maximum energy consumption values in the base model by 1.2, and given in Table 6.3.

Table 6.3. The maximum energy consumption of ferries in heavy weather and sea conditions.

Ferry & No.	*Max. Energy Consumption*	*ESS Battery Capacity (Including 30% Emergency Reserve)*	*ESS Battery Capacity (Rounded Up)*
LC1, LC2, LC3	445.8 kWh	636.8 kWh	640 kWh
LC4, LC5, LC6	584.1 kWh	834.4 kWh	840 kWh
LC7, LC8, LC9	414.9 kWh	592.7 kWh	600 kWh
LC10, LC11, LC12	692.1 kWh	988.8 kWh	990 kWh
LC13	882.3 kWh	1 260.4 kWh	1 270 kWh
F1, F3	426.9 kWh	609.8 kWh	610 kWh
F2, F4	672.3 kWh	960.5 kWh	970 kWh

As a result of rounding up to the nearest ten, the ESS battery capacities for heavy weather and sea conditions have increased by 20% compared to the ESS battery capacities for calm conditions. The increase in the ESS battery capacity of each ferry varies from 19% to 22%.

Table 6.4. Calculated annual total travel distance, total energy consumption, the total number of segments, and the energy consumption per segment and NM, using the weather and sea conditions enabled model.

	Total Travel Distance (NM)	*Total Energy Consumption (kWh)*	*No. of Segments*	*Avg. Energy C. Per Segment (kWh/Segment)*	*Avg. Power C. Per NM (kWh/NM)*
LC1	20 265.90	1 875 835.28	9 426	199.01	92.56
LC2	20 265.90	1 875 679.75	9 426	198.99	92.55
LC3	17 582.71	1 627 570.97	8 178	199.02	92.57
LC4	26 864.21	2 495 351.80	13 106	190.40	92.89
LC5	26 857.35	2 494 750.24	13 102	190.41	92.89
LC6	26 854.21	2 495 452.46	13 106	190.41	92.93
LC7	12 562.81	1 223 855.30	9 918	123.40	97.42
LC8	12 562.81	1 223 710.65	9 918	123.38	97.41
LC9	12 562.81	1 223 869.41	9 918	123.40	97.42
LC10	26 254.66	2 508 537.98	17 467	143.62	95.55
LC11	26 254.66	2 508 743.36	17 467	143.63	95.55
LC12	26 254.66	2 508 556.22	17 467	143.62	95.55
LC13	4 442.23	411 513.25	2 088	197.08	92.64
F1	33 539.75	4 165 369.57	10 925	381.27	124.19
F2	33 536.69	6 555 538.47	10 924	600.10	195.47
F3	33 539.75	4 165 369.43	10 925	381.27	124.19
F4	33 536.68	6 555 537.86	10 924	600.10	195.47
TOTAL	**393 737.79**	**45 915 242.01**	**194 285**		

The calculated annual total travel distance, total energy consumption, the total number of segments, and the average energy consumption per segment and NM are given in Table 6.4.

It was observed that if the weather and sea logic were enabled, the annual total energy consumption and average energy consumption per segment and NM increased by 7.357% compared to the base model. It is also necessary to mention that the average increase ratios remained between 7.346% to 7.369% in each run. Therefore, the weather and sea conditions logic accomplishes the intended effect of modifying energy consumption rates within the predefined limits.

6.3 Charging model

The charging-enabled model was designed to estimate the minimum ESS battery capacities and minimum charging power required to operate the full-electric ferries in İzmir. Therefore, each ferry's per segment maximum energy consumption needed to be calculated in every possible condition.

As the first step, the minimum charging power for each ferry charger was set to 7 500 kW. Afterwards, the ESS battery capacities determined for heavy weather and sea conditions were used.

The most significant aim in this stage of the model is that the ferries must always have more than 30% of their ESS battery capacities, as shown in Figure 6.4. The discharging, charging, and battery level checking logic stopped the simulation as soon as any battery level in the model dropped below 30% of its capacity. An entry is recorded for checking when at which battery and where the event happened. This debugging feature is convenient as it allows iterating ferry ESS battery capacities, charging power of ferry chargers, pier ESS battery capacities, and pier ESS charging power in a fast and robust manner. As a result, more than 100 runs were conducted in order to observe the highest maximum energy consumption values. The findings were consistent with the values determined for the heavy weather and sea conditions.

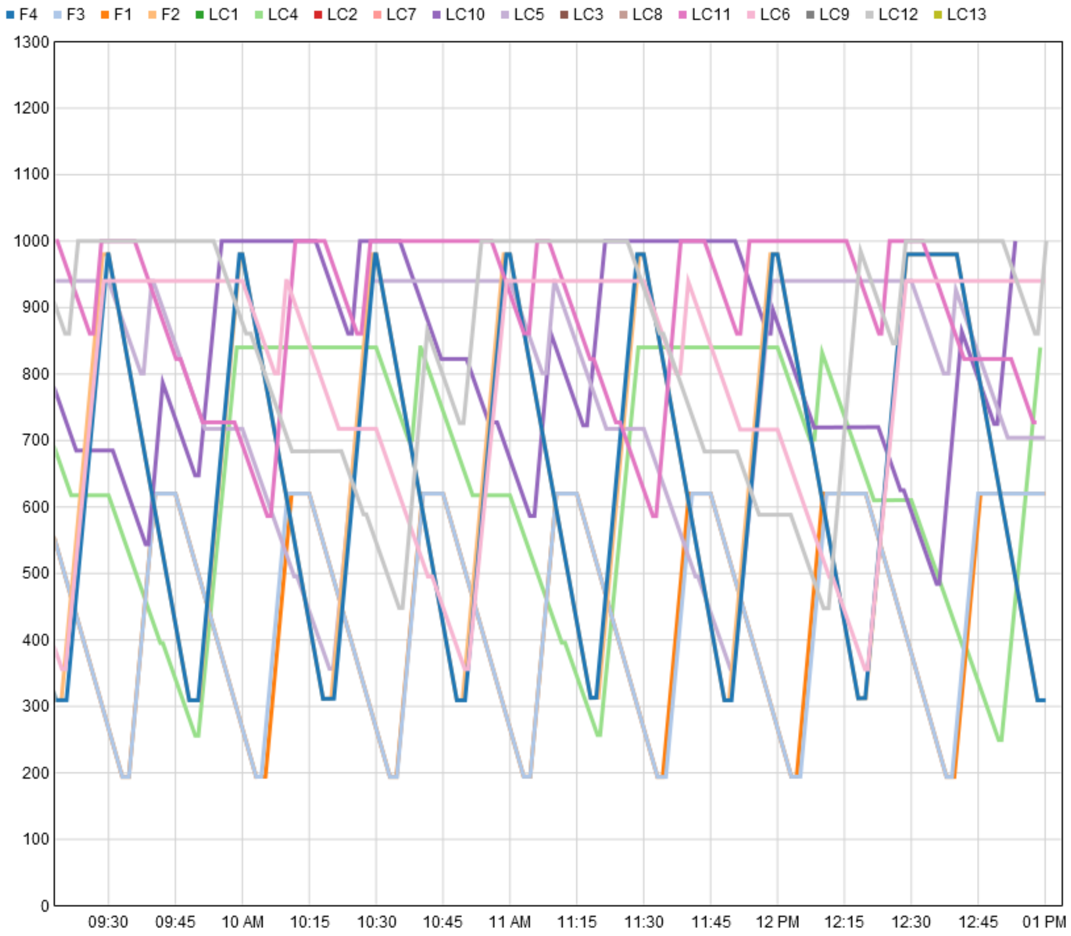


Figure 6.4. The ferry ESS battery levels in heavy weather and sea conditions on the Sunday schedule. The graph is zoomed in and shows a 2.5-hour-long portion. Values in the y- axis show the ESS battery levels and are in kWh.

6.3.1 Scenarios

Four scenarios that can affect ESS battery capacities and all other related variables (i.e., charging rates, pier ESS capacities, ESS battery lifetimes, and costs) were identified and shown in Table 6.5.

Table 6.5. Four scenarios were used for evaluation.

	Minimum ESS Battery Capacities	***Maximum ESS Battery Capacities***
Bostanlı, Karşıyaka and Üçkuyular Ferry Chargers	Scenario 1	Scenario 2
Bostanlı and Karşıyaka Only Ferry Chargers	Scenario 3	Scenario 4

6.3.1.1 Scenario 1

Scenario 1 was designed to calculate the minimum ferry ESS battery capacities and minimum charging power required when charging is enabled. Therefore, the most significant aim of Scenario 1 was to calculate the minimum charging power needed to sustain the ESS batteries without dropping below the critical 30% limit.

There are ferry chargers at Bostanlı, Karşıyaka, and Üçkuyular piers in the scenario. The ferry charging power was set to 10 000 kW at the beginning, and the model ran five times for a year. If there were no critical battery level events recorded, the ferry charging power decreased by 100 kW further, and the model was continuously run for five years in the next step. Until the ferry charging power at Karşıyaka pier was set at 4 000 kW, all runs were completed without any critical battery level event.

The most intriguing finding at this stage of Scenario 1 was that the LCs starting from Bostanlı pier in the morning were *rarely* dropping below the critical 30% ESS battery levels in heavy weather and sea conditions, but *not always*. It was observed that when these ferries, namely the LC4, LC5, and LC6, were operating on the Bostanlı - Karşıyaka - Konak - Karşıyaka -Bostanlı line when the critical battery level events happened.

The reason was investigated, and it was observed that there was not enough time to charge the LC ESS batteries on the first arrival at the Karşıyaka pier. While the ferries started from the Bostanlı pier with 100% ESS battery levels, they could not recharge their ESS battery to 100% capacity at Karşıyaka pier until their departure. Furthermore, the ferries had no charging available on the second arrival at the Karşıyaka pier as well.

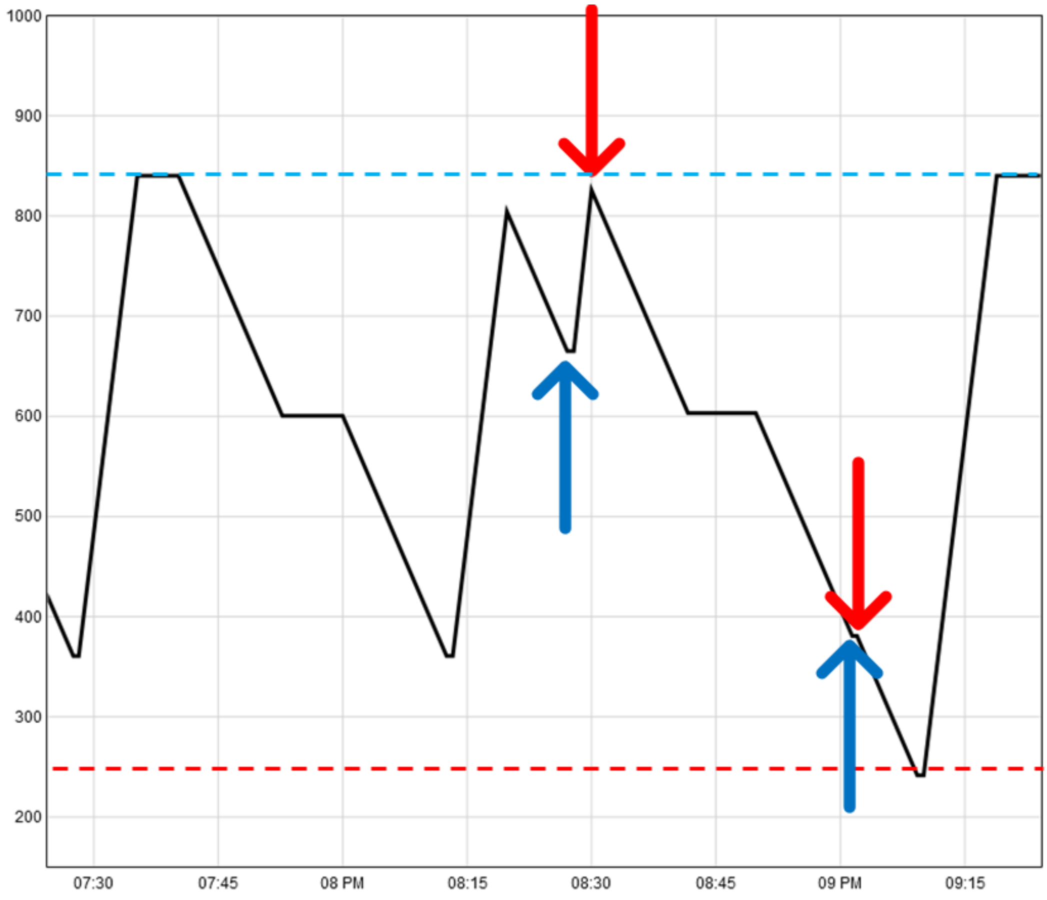


Figure 6.5. The 840 kWh ESS battery level graph of LC6 while operating on the Bostanlı - Karşıyaka - Konak - Karşıyaka - Bostanlı line in heavy weather conditions results in a critical battery level event. Blue arrows show the arrival at Karşıyaka pier, and red arrows show the departure from Karşıyaka pier.

Therefore, it is clear that the battery levels of full-electric ferries in our study significantly decrease when they are equipped with the minimum ESS battery capacities and if they have to skip charging at a pier where charging is available. As a result, ferries operating on the Bostanlı - Karşıyaka - Konak - Karşıyaka - Bostanlı line in heavy weather conditions, such as LC6, were not able reach the Bostanlı pier without going below the critical battery level of 30%, as shown in Figure 6.5.

There are three different ways to mitigate the critical battery level issue. It is possible to either:

- Increase the time that the ferries stay at the Karşıyaka pier, either the first arrival or preferably at the second arrival, by allocating less idle time at Konak pier,
- Increase the ferry charging power at Karşıyaka pier, or
- Increase the ESS battery capacity of LC4, LC 5, and LC6.

As this stage aims to find the minimum ESS battery capacities and charging power, the departure schedules were unchanged. Furthermore, the aim of the study is not to optimize the schedule. If the schedule were to be optimized, the entire schedule would have to be altered.

Moreover, scientific research to optimize the schedule would undoubtedly need to include the data on passenger and vehicle demand per pier *at least* per hour over a yearly period, which the author did not have access to nor could obtain. However, optimizing the schedule by utilizing scientific methods in future studies would be significantly beneficial.

Therefore, in order to find the minimum ESS battery capacities and charging power required for LC4, LC5, and LC6 to complete the segment that results in a critical battery level event, the minimum battery level required was calculated. The minimum battery level required for a five-year-long run was calculated as 281.01 kWh for LC4, LC5, and LC6.

As the minimum 281.01 kWh level is the critical battery level equal to the 30% emergency reserve, the new minimum ESS battery capacity was calculated as 936.7 kWh. Then this value is rounded up to the nearest ten, and the new minimum ESS battery capacity of 940 kWh can be calculated. Furthermore, the new ESS battery capacity of 940 kWh did not result in any critical battery level events, albeit being charged at the minimal charging power of 4 000 kW.

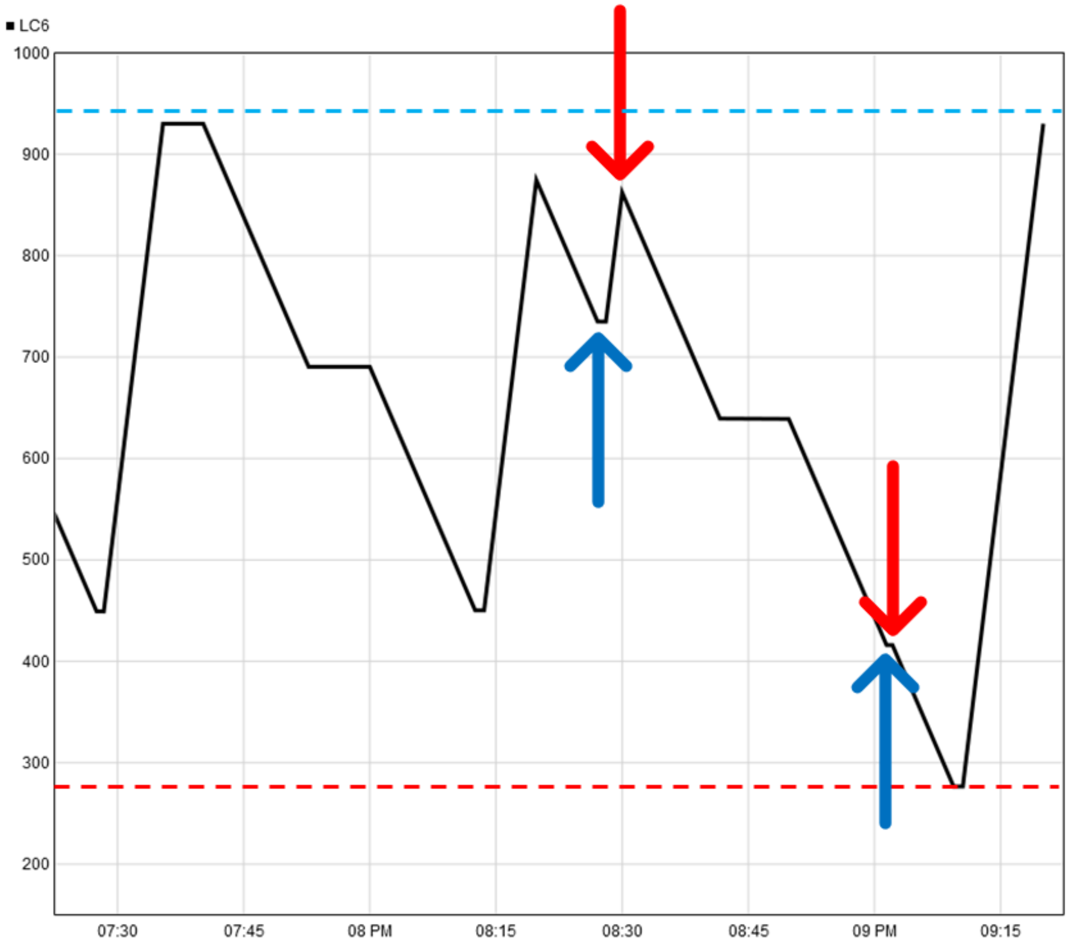


Figure 6.6. A 930 kWh ESS battery level graph of LC6 while operating on the Bostanlı - Karşıyaka - Konak - Karşıyaka - Bostanlı line in heavy weather conditions still results in a critical battery level event, while a 940 kWh ESS battery does not. Blue arrows show the arrival at Karşıyaka pier, and red arrows show the departure from Karşıyaka pier.

As a result of the findings mentioned above, the minimum ESS battery capacities of ferries are calculated and given in Table 6.6.

Table 6.6. The minimum ESS battery capacities of ferries as per Scenario 1.

Ferry & No.	*Max. Energy Consumption*	*ESS Battery Capacity (Including 30% Emergency Reserve)*	*ESS Battery Capacity (Rounded Up)*
LC1, LC2, LC3	445.8 kWh	636.8 kWh	640 kWh
LC4, LC5, LC6	655.7 kWh	936.7 kWh	940 kWh
LC7, LC8, LC9	414.9 kWh	592.7 kWh	600 kWh
LC10, LC11, LC12	694.6 kWh	992.2 kWh	1 000 kWh
LC13	882.3 kWh	1 260.4 kWh	1 270 kWh
F1, F3	428.3 kWh	611.9 kWh	620 kWh
F2, F4	679.2 kWh	970.2 kWh	980 kWh

While the maximum discharge values are required to calculate the ESS capacities, the average discharge and DoD values can be used for the ESS battery lifetime. The maximum discharge values are not used for lifetime calculations because the maximum discharge values are the worst-case energy consumption values and therefore do not represent the randomized conditions throughout a year. Furthermore, the energy consumption -hence the discharge- values in calm weather and sea conditions are even lower than the yearly average discharge values. The charging-enabled model was run for ten years, and the calculated LC ESS battery discharge values are given in Table 6.7.

Table 6.7. The average and maximum discharge and DoD levels when LC ESS battery capacities are set as per Scenario 1.

Ferry & No.	*ESS Battery Capacity*	*Average Discharge*	*Average DoD*	*Maximum Discharge*	*Maximum DoD*
LC1, LC2, LC3	640 kWh	385.8 kWh	60.3%	445.8 kWh	69.7%
LC4, LC5, LC6	940 kWh	371.1 kWh	39.5%	665.7 kWh	70.8%
LC7, LC8, LC9	600 kWh	356.8 kWh	59.5%	414.9 kWh	69.2%
LC10, LC11, LC12	1 000 kWh	347.0 kWh	34.7%	692.1 kWh	69.2%
LC13	1 270 kWh	760.5 kWh	59.9%	882.3 kWh	69.5%
F1, F3	620 kWh	371.0 kWh	59.8%	426.9 kWh	68.9%
F2, F4	980 kWh	538.7 kWh	55.6%	672.3 kWh	68.6%

The battery life of each LC group is calculated and given in Table 6.8, using the number of cycles each ESS completes in a year, the average DoD levels in this scenario, and the DoD and life cycle values given in Figure 3.8.

Table 6.8. Average ESS battery lifetimes of LCs in Scenario 1.

Ferry & No.	*Annual Charge Cycles Per Ferry*	*Average DoD*	*Expected Maximum Cycles*	*Average Battery Lifetime*
LC1, LC2, LC3	4 729	60.3%	10 000	2.22 years
LC4, LC5, LC6	6 570	39.5%	20 000	3.04 years
LC7, LC8, LC9	3 319	59.5%	10 000	3.01 years
LC10, LC11, LC12	7 117	34.7%	20 000	2.82 years
LC13	524	59.9%	10 000	19.08 years
F1, F3	10 955	59.8%	10 000	0.91 years
F2, F4	10 955	55.6%	10 000	0.91 years

In Scenario 1, the calculated average lifetimes of all LC ESS batteries are 4.03 years. If LC13 is excluded, the average lifetime of LC ESS batteries decreases to 2.78 years. The calculated average lifetimes of all Ro-Ro ESS batteries are 0.91 years.

The next step was to find the minimum charging power for each ferry using the ESS battery capacities given in Table 6.8. The calculated minimum charging power and number of ferry chargers that kept the minimum ESS battery levels above 30% are as follows:

- Bostanlı Ro-Ro Chargers : 4 400 kW each, two chargers on the jetty.
- Üçkuyular Ro-Ro Chargers : 4 400 kW each, two chargers on the jetty.
- Bostanlı LC Chargers : 4 100 kW each, three chargers on the pier.
- Karşıyaka LC Chargers : 4 000 kW each, three chargers on the pier.

The number of chargers is equal to the maximum number of ferries that are docked at a pier at any given time. While the ferry ESS battery charging rates are around 4 MW for each charger, the combined maximum load of the chargers on the city's power grid can reach up to 37.8 MW. As a result, the possibility of reducing the maximum combined load of the chargers was investigated.

In order to reduce the maximum power load on the city's power grid, it is possible to install ESS batteries on piers, as well. It was revealed that the capacity of the pier ESS batteries impacts the grid's power load. It was observed that the load on the city's power grid reduced as ESS battery capacity was increased. The pier ESS battery capacity was increased by 500 kWh in each run, and the maximum load on the city's power grid was calculated. Results are shown in Figure 6.7.

The optimal pier ESS battery capacities and pier ESS battery charging power were calculated as follows:

- Bostanlı ESS : 1 500 kWh (750 kWh dedicated capacity for LC ferries, 750 kWh dedicated capacity for Ro-Ro ferries), 8 000 kW pier ESS battery charging power.
- Üçkuyular Ro-Ro ESS : 500 kWh capacity, 3 000 kW pier ESS battery charging power.
- Karşıyaka LC ESS : 1 000 kWh capacity, 5 500 kW pier ESS battery charging power.

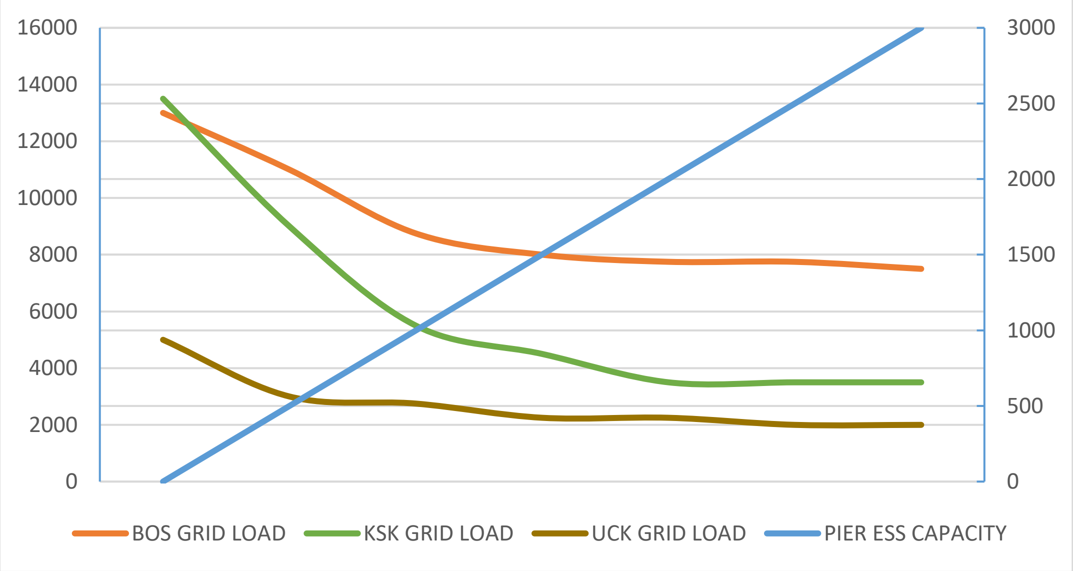


Figure 6.7. The relation between the pier ESS battery capacities (scale on the right, kWh) and the maximum power load on the grid in Scenario 1 (scale on the left, kW).

As a result of installing a total of 3 000 kWh pier ESS batteries, the combined maximum instantaneous load of chargers decreased to 16,5 MW. The maximum load without pier ESS batteries was 37.8 MW. Therefore, a 43.7% decrease in the maximum grid load was observed.

6.3.1.2 Scenario 2

Scenario 2 was designed to observe the effects of installing the highest LC ESS battery capacity in Scenario 1 on all LC ferries. Therefore, all LCs have an ESS battery capacity of 1 270 kWh, and all other values are the same as in Scenario 1, as shown in Table 6.9.

As Ro-Ro ferry ESS battery capacities are kept the same as in Scenario 1, all Ro-Ro ferry-related values in Scenario 1 are also valid in Scenario 2.

The most significant finding of this scenario is that the DoD levels of ESS batteries significantly decrease as the ESS capacity is increased. While increasing the ESS battery capacities of ferries increases the capital costs, it also increases the lifetime of the batteries due to the decreased DoD levels.

Table 6.9. The average and maximum discharge and DoD levels when LC ESS battery capacities are set to 1 270 kWh, as per Scenario 2.

Ferry & No.	*ESS Battery Capacity*	*Average Discharge*	*Average DoD*	*Maximum Discharge*	*Maximum DoD*
LC1, LC2, LC3	1 270 kWh	385.8 kWh	30.4%	445.8 kWh	35.1%
LC4, LC5, LC6	1 270 kWh	371.1 kWh	29.2%	665.7 kWh	52.4%
LC7, LC8, LC9	1 270 kWh	356.8 kWh	28.1%	414.9 kWh	32.7%
LC10, LC11, LC12	1 270 kWh	347.0 kWh	27.3%	692.1 kWh	54.7%
LC13	1 270 kWh	760.5 kWh	59.9%	882.3 kWh	69.5%

The battery life of each LC group is calculated and given in Table 6.10, using the number of cycles each ESS completes in a year, the average DoD levels in this scenario, and the DoD and life cycle values given in Figure 3.8.

Table 6.10. Average ESS battery lifetimes of LCs in Scenario 2.

Ferry & No.	*Annual Charge Cycles Per Ferry*	*Average DoD*	*Expected Maximum Cycles*	*Average Battery Lifetime*
LC1, LC2, LC3	4 729	30.4%	20 000	4.44 years
LC4, LC5, LC6	6 570	29.2%	26 000	3.96 years
LC7, LC8, LC9	3 319	28.1%	26 000	7.83 years
LC10, LC11, LC12	7 117	27.3%	26 000	3.67 years
LC13	524	59.9%	10 000	19.08 years

The benefit of having a 1.270 kWh ESS battery capacity on all LCs is significant. The average lifetimes of the LC ESS batteries in Scenario 2 are 6.06 years, which is 50,40% longer compared to Scenario 1. If LC13 is excluded, the average lifetime of LC ESS batteries decreases to 4.98 years.

When LC13 is excluded, the difference in average lifetimes of the rest of the LCs ESS batteries in Scenario 2 is 79.13% longer compared to Scenario 1. Therefore, increasing the ESS battery capacity of all LCs by a total of 5 700 kWh (59.8%) compared to Scenario 1 can result in a 50.4% longer average lifetime of LC ferry ESS batteries.

Moreover, there is also the operational benefit of having 13 identical ferries to operate. While breakdowns and service interrupting events are highly unlikely today, no system is immune to errors, and emergencies can happen. Therefore, having the ability to assign any ferry to any line at any given time is quite significant for the operator.

Since the energy consumption of ferries is the same as in Scenario 1, the ferry charging rates are the same. As a result, the pier ESS battery capacities and pier ESS battery charging power are also the same.

It is possible to reduce the ferry ESS battery charging power by using larger LC ESS battery capacities. The calculated minimum charging power and number of ferry chargers that kept the minimum ESS battery levels above 30% are as follows:

- Bostanlı LC Chargers : 3 700 kW each, three chargers on the pier.
- Karşıyaka LC Chargers : 1 800 kW each, three chargers on the pier.

There can be significant reductions in charging power required by installing 1 270 kWh ESS batteries onboard LCs. Compared to Scenario 1, the LC ESS battery charging power required decreased by 400 kW (9.76%) at Bostanlı pier while 2 200 kW (55%) at Karşıyaka pier in Scenario 2.

However, decreasing the charging power also nullifies the benefit of having a longer ESS battery lifetime by having 1 270 kWh ESS batteries onboard LCs. Reducing the charging power to these values increases DoD up to 70%, which is the critical battery level. Therefore, the reduced ferry ESS charging power rates will not be included in the techno-economic analysis.

The optimal pier ESS battery capacities and pier ESS battery charging power were the same as in Scenario 1 and calculated as follows:

- Bostanlı ESS : 1 500 kWh (750 kWh dedicated capacity for LC ferries, 750 kWh dedicated capacity for Ro-Ro ferries), 8 000 kW pier ESS battery charging power.
- Üçkuyular Ro-Ro ESS : 500 kWh capacity, 3 000 kW pier ESS battery charging power.
- Karşıyaka LC ESS : 1 000 kWh capacity, 5 500 kW pier ESS battery charging power.

6.3.1.3 Scenario 3

The main difference between Scenario 3 and Scenario 1 is that no Ro-Ro ferry charging is available at Üçkuyular pier. This scenario is designed to find the minimum Ro-Ro ferry ESS battery capacities if there is no charging availability in the Üçkuyular pier.

As a result of no charging availability at Üçkuyular pier, The Ro-Ro ferry ESS battery capacities and Ro-Ro ferry ESS battery charging power are expected to increase, as shown in Table 6.11 and Figure 6.8. Moreover, all Ro-Ro ferry-related values are also expected to change accordingly. All values related to LCs remain identical to Scenario 1; therefore, any values associated with LCs are excluded.

In the model, the charging power of the Üçkuyular Ro-Ro ferry charger was set to zero, the charging power of the Bostanlı Ro-Ro ferry charger was set to 10 000 kW, and the maximum discharge of Ro-Ro ferries was calculated. The minimum Ro-Ro ferry ESS battery capacities were calculated as follows:

Table 6.11. Calculated maximum discharge and Ro-Ro ferry ESS battery capacities, as per Scenario 3.

Ferry & No.	*Max. Energy Consumption*	*ESS Battery Capacity (Including 30% Emergency Reserve)*	*ESS Battery Capacity*
F1, F3	868.5 kWh	1 240.7 kWh	1 250 kWh
F2, F4	1 380.8 kWh	1 972.6 kWh	1 980 kWh

When compared to the Ro-Ro ESS battery capacities calculated in Scenario 1, it is observed that the computed minimum Ro-Ro ESS battery capacities in Scenario 3 is doubled, as shown in Table 6.12. The ESS battery capacities of F1 and F2 (2020 Series Ro-Ro ferries) increased from 620 kWh to 1 250 kWh (a 101.61% increase), while F3 and F4 (2015 Series Ro-Ro ferries) increased from 980 kWh to 1 980 kWh (a 102.02% increase).

Table 6.12. The average and maximum discharge and DoD levels when ferry ESS battery capacities are set as per Scenario 3.

Ferry & No.	*ESS Battery Capacity*	*Average Discharge*	*Average DoD*	*Maximum Discharge*	*Maximum DoD*
F1, F3	1 250 kWh	762.2 kWh	61.0%	868.5 kWh	69.5%
F2, F4	1 980 kWh	1 200.2 kWh	60.6%	1 380.8 kWh	69.7%

The battery life of each LC group is calculated and given in Table 6.13, using the number of cycles each ESS completes in a year, the average DoD levels in this scenario, and the DoD and life cycle values given in Figure 3.8.

Table 6.13. Average ESS battery lifetimes of ferries in Scenario 3.

Ferry & No.	*Annual Charge Cycles Per Ferry*	*Average DoD*	*Expected Maximum Cycles*	*Average Battery Lifetime*
F1, F3	5 477	61.0%	10 000	1.83 years
F2, F4	5 477	60.6%	10 000	1.83 years

In Scenario 3, the calculated average lifetimes of all Ro-Ro ferry ESS batteries are 1.83 years. Therefore, increasing the total ESS capacity of Ro-Ro ferries by 3 260 kWh (or by101.87%) can result in a 100.02% longer average lifetime of Ro-Ro ferry ESS batteries.

As mentioned above, the Bostanlı pier Ro-Ro ferry charging power was set to 10 000 kW for trial purposes. However, this value is not the minimum required charging power to sustain ESS battery capacities above the 30% critical battery level. To find the minimum required charging power in Scenario 3, the model ran for a year for five times. If no critical battery level events were recorded, the Ro-Ro ferry charging power decreased by 100 kW in the next step.

As a result, the minimum required charging powers were calculated as follows:

- Bostanlı Ro-Ro Chargers : 8 500 kW each, two chargers on the jetty.
- Üçkuyular Ro-Ro Chargers : N/A
- Bostanlı LC Chargers : 4 100 kW each, three chargers on the pier.
- Karşıyaka LC Chargers : 4 000 kW each, three chargers on the pier.

The optimal pier ESS battery capacities and pier ESS battery charging power were calculated as follows:

- Bostanlı ESS : 1 800 kWh (900 kWh dedicated capacity for LC ferries, 900 kWh dedicated capacity for Ro-Ro ferries), 9 500 kW pier ESS battery charging power.
- Üçkuyular Ro-Ro ESS : N/A
- Karşıyaka LC ESS : 1 000 kWh capacity, 5 500 kW pier ESS battery charging power.

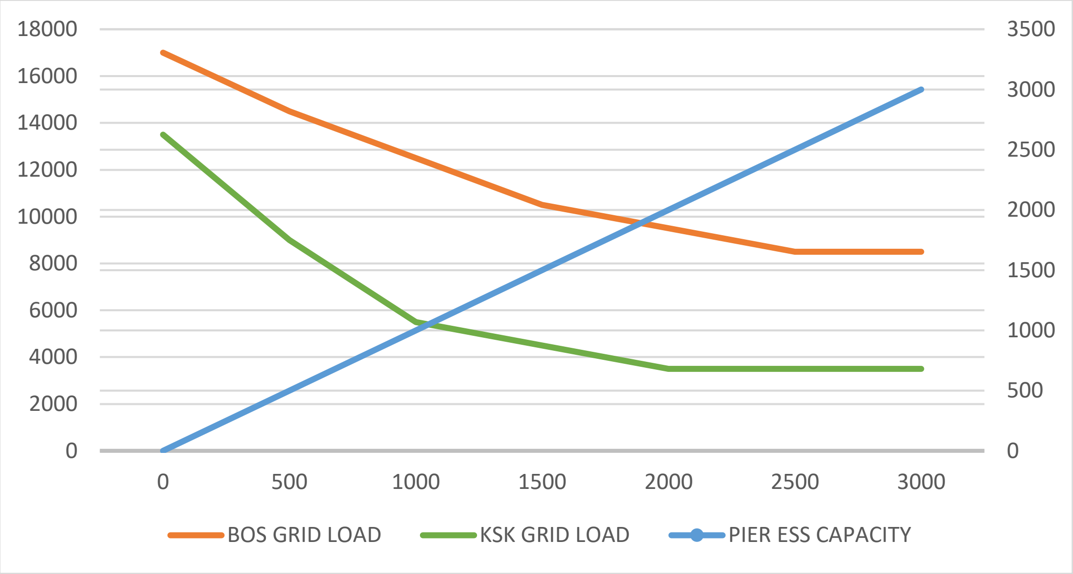


Figure 6.8. The relation between the pier ESS battery capacities (scale on the right, kWh) and the maximum power load on the grid in Scenario 3 (scale on the left, kW).

As a result of installing a total of 2 800 kWh pier ESS batteries, the combined maximum instantaneous load of chargers decreased to 15 MW. The maximum load without pier ESS batteries was 30.5 MW. Therefore, a 50.8% decrease in the maximum grid load was observed.

6.3.1.4 Scenario 4

Scenario 4 was designed to find the effects of having charging availability only at Bostanlı and Karşıyaka piers and maximum ESS battery capacities on all ferries and all charging piers on costs. Therefore, Scenario 4 is a mix of Scenarios 2 and 3.

The highest ESS battery capacities in Scenarios 2 and 3 are as follows:

- All LCs have an ESS battery capacity of 1 270 kWh,
- F1 and F3 have 1 250 kWh, and
- F2 and F4 have 1 980 kWh.

As a result of having the same ESS battery capacities and consumption profiles, the lifetimes of LC and Ro-Ro ferry ESS batteries are equal to the values in Scenarios 2 and 3, respectively.

In Scenario 4, the ferry charging powers are as follows:

- Bostanlı Ro-Ro Chargers : 8 500 kW each, two chargers on the jetty.
- Üçkuyular Ro-Ro Chargers : N/A
- Bostanlı LC Chargers : 4 100 kW each, three chargers on the pier.
- Karşıyaka LC Chargers : 4 000 kW each, three chargers on the pier.

The optimal pier ESS battery capacities and pier ESS battery charging power were calculated as follows:

- Bostanlı ESS : 1 800 kWh (900 kWh dedicated capacity for LC ferries, 900 kWh dedicated capacity for Ro-Ro ferries), 9 500 kW pier ESS battery charging power.
- Üçkuyular Ro-Ro ESS : N/A
- Karşıyaka LC ESS : 1 000 kWh capacity, 5 500 kW pier ESS battery charging power.

As the pier ESS battery capacities and charging power are the same as in Scenario 3, the combined maximum instantaneous load of chargers on the city grid is identical, which is 15 MW.

6.4 REPP model

The REPP model integrates the renewable energy logic into the model. The logic works independently from the charging logic, except for the battery capacity component. Therefore, the logic will recharge ESS batteries up to 100% capacity and will stop there.

In this stage of the model, all ferries, Bostanlı, and Üçkuyular piers have REPP, which utilizes solar power. The peak power generation capacity of the REPPs is as follows:

LCs	: 26.2 kWp each
2015 Series Ro-Ro	: 112.5 kWp each
2020 Series Ro-Ro	: 67.6 kWp each
Bostanlı and Üçkuyular piers	: 300.0 kWp each

The logic uses the annual hourly average power output values per month for one kWp REPP, as shown in Figure 3.8, and scales it according to the capacity of REPPs given above.

In order to calculate the actual power output of REPPs, the model was run for a year three times with REPP logic enabled and with REPP logic disabled. The total power consumption difference between the runs was averaged and given in Table 6.14.

Calculations show that it is possible to produce combined energy of 1 926 349 kWh annually with such REPPs [65]. However, a total of 1 762 367 kWh was stored, as shown in Table 6.14. The difference of 163 982 kWh of energy produced is due to the lack of storage capacity. This means that while the REPP produced the energy, ESS batteries were already charged to 100% capacity and could not store the energy produced.

It is necessary to mention that while renewable energy is a sustainable and greener way to charge the ESS batteries, the 1 762 367 kWh annual energy stored only constitutes 3.84% of the total energy consumed, which is 45 915 242.01 kWh. The city grid provided the rest of the energy required to charge the ferry fleet, which is 44 152 875.01 kWh, or 96.16% of the total energy consumed.

Table 6.14. The average REPP energy stored is calculated by comparing the average total energy consumption with and without REPP.

	Peak Power (kWp)	*Avg. Cons. W/O REPP*	*Avg. Cons. W/ REPP*	*Avg. REPP Energy Stored*	
LC1	26.2	1 876 105	1 840 362	35 743	kWh
LC2	26.2	1 876 177	1 840 424	35 752	kWh
LC3	26.2	1 628 243	1 592 375	35 869	kWh
LC4	26.2	2 495 050	2 459 947	35 103	kWh
LC5	26.2	2 494 681	2 459 551	35 130	kWh
LC6	26.2	2 495 217	2 460 134	35 083	kWh
LC7	26.2	1 224 285	1 188 587	35 698	kWh
LC8	26.2	1 224 352	1 188 645	35 707	kWh
LC9	26.2	1 224 370	1 188 610	35 760	kWh
LC10	26.2	2 508 520	2 472 834	35 686	kWh
LC11	26.2	2 508 544	2 472 790	35 755	kWh
LC12	26.2	2 508 631	2 472 864	35 766	kWh
LC13	26.2	411 689	376 180	35 509	kWh
F1	67.6	4 165 258	4 073 470	91 789	kWh
F2	112.5	6 555 132	6 402 388	152 745	kWh
F3	67.6	4 165 258	4 073 469	91 789	kWh
F4	112.5	6 555 132	6 402 387	152 745	kWh
BOS	300.0	11 983 832	11 578 463	405 369	kWh
UCK	300.0	11 983 832	11 578 463	405 369	kWh
TOTAL	**1 300.8**			**1 762 367**	**kWh**

CHAPTER 7

TECHNO-ECONOMIC ANALYSIS

There are complex relations between many values that affect the amount of investment necessary to achieve the aim of operating full-electric ferries in İzmir. Moreover, the values and relations show differences between scenarios investigated through the model development.

The main decision factor for forming the scenarios was ESS battery capacities and charging availability rather than costs. However, when considering final designs, it is necessary to take economic attributes -or *costs*- of all variables in different scenarios over the service period of ferries. Therefore, the Total Cost has been selected as a decision factor for finalizing ferry ESS, REPP, and charger designs.

It is possible to calculate the Total Cost using Equation 2:

$$Total\ Cost = \sum Capital\ Cost + \sum Annual\ Operating\ Costs \tag{2}$$

The Capital Cost can be calculated using Equation 3:

$$\begin{aligned}&\sum Capital\ Cost = \sum Ferry\ ESS\ Battery\ Costs + \sum Pier\ ESS\ Battery\ Costs + \\ &\sum Ferry\ Charger\ Installation\ Costs + \sum REPP\ Installation\ Costs + \\ &\sum Ferry\ Electric\ Drive\ Retrofit\ Costs\end{aligned} \tag{3}$$

The Annual Operating Cost can be calculated using Equation 4:

$$\begin{aligned}&Annual\ Operating\ Cost = \sum Ferry\ ESS\ Battery\ Renewal\ Costs + \\ &\sum Pier\ ESS\ Battery\ Renewal\ Costs + \sum Annual\ Energy\ Costs + \\ &\sum Annual\ Service\ Costs\end{aligned} \tag{4}$$

Using the equations above, the preliminary calculation for predicting the capital cost suggests that the ESS battery capacities shall have the most significant effect on capital costs compared to the other factors.

In order to conduct the techno-economic analysis of operating full-electric ferries in İzmir, the Capital Cost and Annual Operating Costs must be known for the two final designs. The operational life of ferries and REPPs is estimated as 25 years for the calculations in the study.

7.1 Designs for calculations

There are two different designs created for conducting the techno-economic analysis in this study, namely Design No. 1 and Design No 2. Preliminary calculations suggested that the total ESS battery capacities of ferries and piers should be the major factor that directly affects the results of the techno-economic analysis. Therefore, two distinct designs were created on opposite extremes of total ESS battery capacities, and shown in Table 7.1.

The Design No. 1 was based on the total ESS battery capacities in the Scenario 1, which is the minimum capacities that ferries that required to safely sustain all trips on their assigned lines.

The Design No. 2 was based on the total ESS battery capacities in the Scenario 4, which is the maximum capacities that enable ferries to be assigned on all available lines.

It was expected that the Design No. 1 should have the lowest capital costs for ferry ESS batteries, as per having the minimum ESS battery capacities. Design No. 2 was expected to have the highest capital costs as per having the maximum ESS battery capacities.

Table 7.1. There are two designs for techno-economic evaluation.

Design No.	*ESS Battery Capacities*	*Ferry Chargers*	*REPP*
1	Minimum capacities (Scenario 1 Values)	Bostanlı, Karşıyaka, and Üçkuyular	All ferries and piers with ferry chargers
2	Maximum capacities (Scenario 4 Values)	Bostanlı and Karşıyaka	

It was observed that while the above expectations are valid, the difference between the Designs No. 1 & 2 proved to be less than the values expected within the preliminary calculations. It was aimed to explain the reason by providing the results of cost and benefit calculations, assumptions, and limitations of this study, in the following subchapters.

7.2 Capital costs

The Capital Cost is the initial sum that is required to be invested. It can be calculated using Equation 3 if ESS Battery Costs, Ferry Charger Installation Costs, REPP Installation Costs, and Ferry Electric Drive Retrofit Costs are known.

7.2.1 Limitations on forecasting future battery prices

It is necessary to mention that the calculations related to ESS batteries in this study do not include any capacity degradation mechanisms other than degradation due to cycling. As the lifetime of batteries lengthens, mechanisms such as calendar aging, graphite, NMC fracturing, electrolyte oxidation, and lithium metal deposition will have more pronounced effects on SOH and ESS battery capacity fading, especially the older the battery gets.

The expected lifetime of NMC batteries is six years *(depending on several operational conditions such as temperature, SOC, charging rate(s), discharging* *rate(s), etc.)*, and it is significantly shorter than LTO or LFP batteries [85]. Therefore, as the calculated ESS battery lifetimes in Design No. 1 and 2 are generally within the typical lifetime ranges of NMC batteries, the rest of the degradation mechanisms were ignored to reduce the complexity required for ESS battery capacity calculations.

If such battery capacity degradation mechanisms did not exist, it would be greatly advantageous to install the largest ESS capacity that can be installed onboard a ferry to have a battery life equal to the service lifetime of the ferry, as the initial installation costs would be the only costs associated with ESS battery costs. However, due to the stated reasons above, it is not possible.

LTO and LFP batteries have longer cycle lifetimes than NMC. However, the per kWh cost of LTO batteries is significantly higher than NMC batteries. In contrast, LFP batteries require 30% larger space due to lower energy density and are less safe than NMC batteries [85], [86]. Therefore, LTO and NMC batteries are significantly better candidates for maritime applications than LFP.

If the per kWh price of NMC and LTO is directly compared, NMC batteries cost significantly less than LTO batteries. However, the significantly higher cycle lifetimes of LTO batteries can make up for the higher per kWh cost and are stated to equalize the total costs when DoD levels and cycle times are considered [87]. Therefore, the costs of choosing NMC or LTO technology would be virtually equal.

Therefore it could be stated that the LTO batteries are better and safer alternatives to the NMC batteries [86], [87]. It is also necessary to mention that the LTO batteries can sustain faster charging rates than the stated rates in this study with less performance degradation compared to NMC batteries [88]. Therefore, as per kWh prices reduce, LTO batteries are more likely to be utilized in fast-charging ferries than NMC batteries. However, currently, there are no price predictions for LTO batteries found in the literature or other sources, except for the prices of 1 050 USD per kWh in 2016 and 480 USD per kWh by 2030 [89]. The data found is not enough to iterate any future prices. On the contrary, there is enough data on NMC battery per kWh prices in the literature and other sources.

As a result, the per kWh price of NMC batteries was chosen as the basis for the calculations in this study.

7.2.2 ESS battery costs

The ESS battery cost component of the Capital Cost can be calculated by multiplying the cost per kWh ESS battery capacity and the total ESS battery capacities in each design. The price per kWh ESS battery capacity can be estimated using the literature or quoting manufacturers.

In order to quote a price per kWh ESS battery capacity, the Author of this study tried to reach the ESS producers AKASOL, Corvus, Echandia, Leclanché, Saft, Siemens, SPBES, Spear, and XALT via email, personal communication, and social networks. Corvus was the only producer in the study that allowed the author to use an estimated price per kWh capacity.

Corvus kindly informed the author that the average per kWh ESS battery capacity should be taken as 620 USD in calculations as of May 2022 [90]. Literature suggests that the per kWh ESS battery capacity prices would be an estimated average of 492 EUR per kWh capacity as of 2022 [9]. 492 EUR would be equal to 527 USD, in May 2022. The difference between these prices is 93 USD per kWh, on average. However, the prices stated in the literature might not include the cost of Battery Management Systems and other systems.

There are many reasons behind such a difference between prices stated above. It could be argued that the following reasons are also thought to be affecting the prices:

- Economic effects of the Global Covid-19 Pandemic (2019 - Ongoing),
- Globally increasing demand for battery-powered vehicles, vessels, and aircraft while limited lithium production growth,
- Geographical and temporal dimensions of the competitive market,
- Political relations and rather *tensions* that affect energy and commodity-related prices,
- Other costs *(such as globally increasing semiconductors and electronic component production, shipping, handling, and labor costs)*, and
- Globally fluctuating inflation levels.

As a result, it could be argued that the actual cost per kWh ESS battery capacity depends on variables such as the year the ESS battery will be installed, market conditions at the time, chosen producer(s), and product line(s) and what is included in the cost analysis.

Only one ESS battery manufacturer quoted the cost per kWh ESS battery capacity for a single year in this study, while the e-Ferry analysis based the cost per kWh ESS battery capacity values from different manufacturers and years.

Therefore, the best approach was to take the estimated average price per kWh ESS capacity from the literature for 2022. However, there was no price per kWh ESS capacity mentioned for 2022.

As this value was not provided directly, a curve fitting was applied using the values given in the e-Ferry study, and given in Figure 7.1. The curve fitting equation is calculated as $y = 1335.3e^{-0,111x}$ ($R^2 = 0.9885$), where x is the years after 2012 and y is the price per kWh ESS capacity in EUR. Using this equation, it was also possible to estimate the other future prices per kWh ESS capacity.

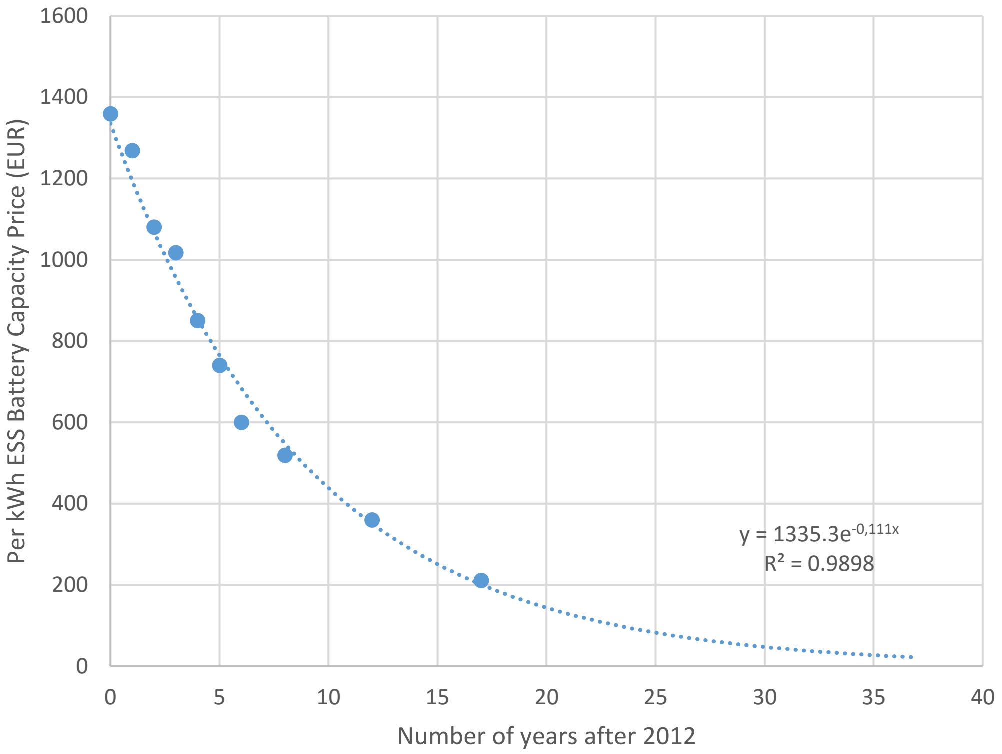


Figure 7.1. Estimated per kWh battery capacity prices from 2012. Values are in EUR.

As a result, the calculated cost per kWh ESS battery capacity in 2022 would be 491.72 EUR which can be converted to 526.44 USD as shown in Figure 7.2, using the 1.070 609 28 EUR to USD parity in May 2022.

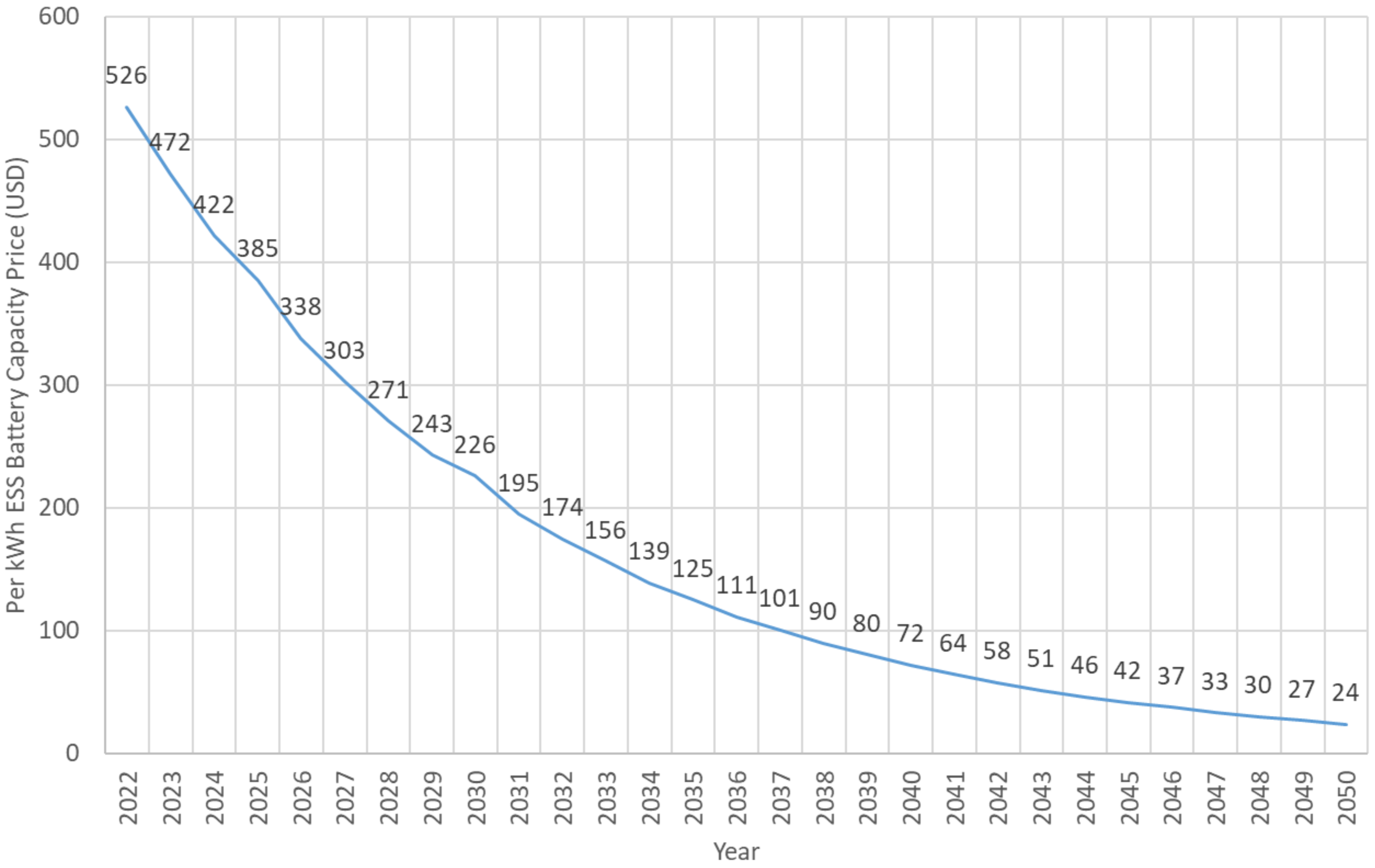


Figure 7.2. Estimated per kWh battery capacity prices from 2022. Values are in USD.

In Design No. 1, the total ferry ESS battery capacity and pier ESS battery capacities are 14 010 kWh and 3 000 kWh, respectively. As a result, the total ESS battery cost is 8 954 744.4 USD.

In Design No. 2, the total ferry ESS battery capacity and pier ESS battery capacities are 22 970 kWh and 2 800 kWh, respectively. As a result, the total ESS battery cost is 13 566 359.8 USD.

The difference between Design No. 1 and 2 ESS battery cost is 4 611 615.4 USD.

7.2.3 Ferry charger installation costs

The author tried to contact several ferry charger manufacturers, namely Stemmann-Technik, Wabtec, and Wärtsilä. Stemmann-Technik replied, however, that they were not able to quote a price for any chargers stating that the prices were quoted for very individual specifications of an operator. In contrast, several technical details were shared with Stemmann-Technik, resulting in no further communication.

The literature on ferry charger prices is quite rare. In the e-ferry project, the average cost of installing a ferry charger is around 1 million USD [9]. The value is taken as is in the calculations.

In Design No. 1, the total number of ferry chargers is ten. As a result, the total ferry charger installation cost is 10 million USD.

In Design No. 2, the total number of ferry chargers is eight. As a result, the total ferry charger installation cost is 8 million USD.

The difference between Design No. 1 and 2 ferry charger costs is 2 million USD.

7.2.4 REPP installation costs

The REPP installation costs include many variables, such as land value, project size, design costs, certification and permit costs, and taxes. However, in our study, it is also possible to estimate the REPP installation costs by using average installation costs per kWp for 1 MWp REPP and by scaling the average cost accordingly.

An average capital cost of 1 MWp REPP in Türkiye costs around 1.1 million USD, excluding taxes and land costs [91]. Therefore, the study's average cost per kWp for REPP is 1 100 USD.

In Design No. 1, the total peak power of REPP is 1 300.8 kWp. As a result, the total REPP installation cost is 1 430 880 USD.

In Design No. 2, the total peak power of REPP is 1 000.8 kWp. As a result, the total REPP installation cost is 1 100 880 USD.

The difference between Designs No. 1 and 2 REPP installation costs is 330 thousand USD.

7.2.5 Ferry electric drive retrofit costs

The cost of retrofit of existing LC and Ro-Ro ferries into electric drive includes the following:

- Project design, audits, and certification,
- Removal of all ICE, including generators,
- Removal of fossil fuel-related pumps and control systems,
- Installing electric motors and drive systems,
- Installing a new reduction gearbox and adjustment of related systems,
- Recalibration or retrofit of all monitoring and control systems, and
- Vetting and certification.

The power output of electric motors at service speeds shall be matched to the ICE removed from the ferries. As the RPM range of the propeller shaft needs to remain within a different range to keep the speed of the ferries the same after the retrofit, the reduction gearbox also needs to be changed due to the higher working RPM range of the electric motors compared to ICE.

The total cost of retrofitting all LC and Ro-Ro ferries with electric drive systems is estimated to be 17 million USD for Designs No. 1 and 2.

7.2.6 Results

The total capital cost of Design No. 1 is calculated as 37 385 624.4 USD, whereas the total capital cost of Design No. 2 is calculated as 39 667 238.8 USD. The sums and components of the capital costs are visualized in Figure 7.3.

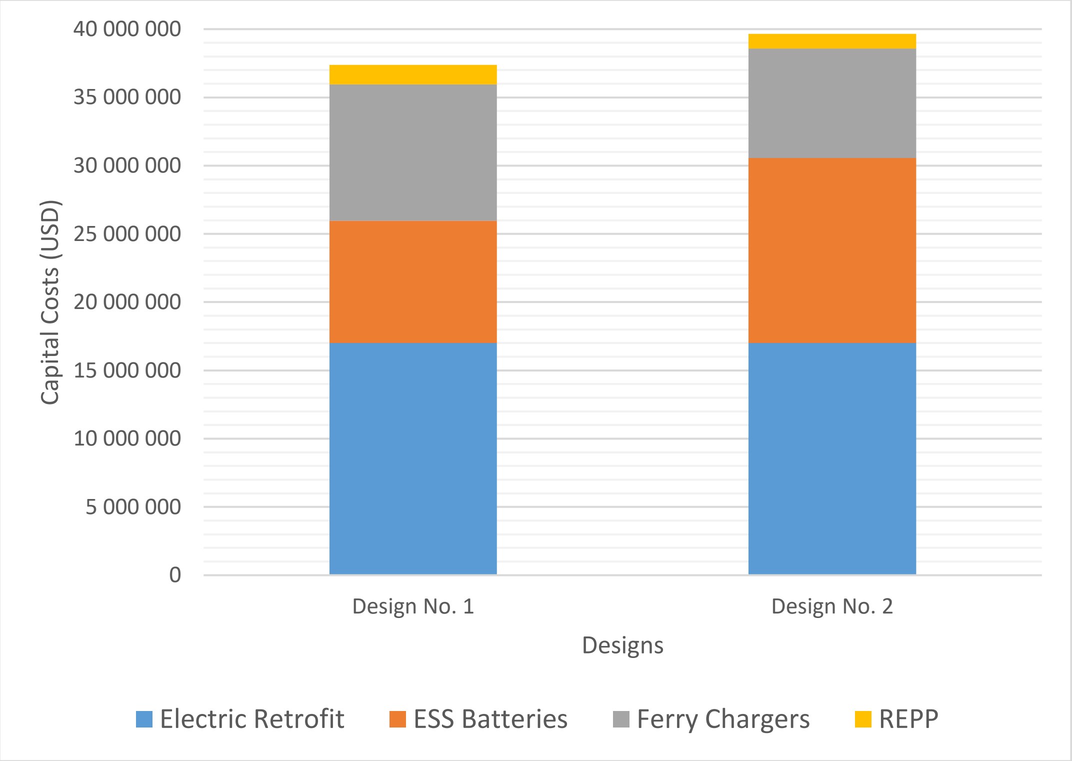


Figure 7.3. Total capital costs of Design No 1 and 2.

Therefore, it is evident that choosing opposite extremes of ESS battery capacities for design purposes results in the largest difference in initial ESS battery costs. It also changes the number of ferry chargers, total REPP capacity, and the difference between capital costs.

Design No. 1 has the lowest ESS battery capacities and costs while having more ferry chargers and a larger REPP capacity, which increases costs. On the other hand, Design No. 2 has the highest ESS battery capacities and costs while having fewer ferry chargers and a smaller REPP capacity, which decreases costs.

Therefore, it could be stated that the cost difference between designs diminished as ESS battery-related factors were included in the calculations. More specifically, the difference between the total ESS battery costs of different designs was 4 611 615.4 USD, whereas the difference between the total capital costs of different designs was 2 281 614.40 USD.

7.3 Annual operating costs

The annual operating costs are the yearly costs necessary to operate full-electric ferries. The annual operating costs include the ESS battery renewal costs, the cost of average annual energy consumption of all ferries minus the average energy produced by REPP, annual average service costs for electric drive systems of full-electric ferries, annual service costs for all REPP systems, annual service costs ferry ESS batteries, and yearly service costs all ferry chargers.

However, annual costs are not static. Between 2022 and 2047, the ESS battery capacity needed to be renewed, the per kWh price of ESS battery capacity, total energy produced by REPP, the per liter price of Ultra Low Sulphur Marine Diesel, and the per kWh price of electricity estimated to have different characteristics for Design No. 1 and 2. Therefore, all values need to be adjusted for each year to calculate the annual operating costs over the 25-year operational period.

It should be noted that all indemnity insurance, crew wages, and other related expenses are excluded from the study as no data was found from the literature that predicts the prices for the next 25 years.

7.3.1 ESS battery renewal costs

There are different total annual capacities of ESS batteries needed to be renewed in each design due to the difference in estimated average lifetimes of ESS batteries. For example, the average ESS battery life of Ro-Ro ferries in Design No. 1 is 0.91 years, while the average ESS battery life of Ro-Ro ferries in Design No. 2 is 1.83 years.

There are slight differences even inside the groups of ferries due to the differences in the total number of battery cycles of individual ferries. The average ESS battery lifetime of all ferries is calculated and given in Table 7.2.

Table 7.2. The average ESS lifetime of all ferries.

Ferry	*Number of Annual Charge Cycles*		*DoD (%)*		*Battery Life (Years)*	
	Design #1	Design #2	Design #1	Design #2	Design #1	Design #2
F1	10 955	5 477	59.9%	61.0%	0.91 y	1,83 y
F2	10 955	5 477	59.6%	60.6%	0.91 y	1,83 y
F3	10 955	5 477	59.9%	61.0%	0.91 y	1,83 y
F4	10 955	5 477	59.6%	60.6%	0.91 y	1,83 y
LC1	4 729		60.8%	30.6%	2.11 y	4.23 y
LC2	4 729		60.8%	30.6%	2.11 y	4.23 y
LC3	4 104		60.9%	30.7%	2.44 y	4.87 y
LC4	6 571		39.7%	29.4%	3.04 y	3.96 y
LC5	6 569		39.7%	29.4%	3.04 y	3.96 y
LC6	6 570		39.7%	29.4%	3.04 y	3.96 y
LC7	3 319		60.4%	28.6%	3.01 y	7.83 y
LC8	3 319		60.5%	28.6%	3.01 y	7.83 y
LC9	3 318		60.5%	28.6%	3.01 y	7.84 y
LC10	7 108		35.3%	27.8%	2.81 y	3.66 y
LC11	7 117		35.0%	27.5%	2.81 y	3.65 y
LC12	7 044		35.3%	27.8%	2.84 y	3.69 y
LC13	524		60.9%	60.9%	19.08 y	19.08 y

As a result of average ESS lifetime differences between designs, the amount of ESS batteries to be renewed changes significantly. In the study, all pier and ferry batteries were renewed in the 24-year period after the initial year was calculated using the

ESS battery lifetimes and the ESS battery capacities of ferries for each design. The ESS batteries were used up to their estimated lifetimes and renewed immediately. The total amount of ESS batteries renewed is then summed annually and given in Figure 7.4.

The number of times batteries are renewed is not the same in each design. The number of times ESS batteries were replaced throughout the 24-year period is as follows:

- F1, F2, F3, F4 : 27 times in Design 1, 13 times in Design 2.
- LC1, LC2 : 11 times in Design 1, 5 times in Design 2.
- LC3 : 10 times in Design 1, 5 times in Design 2.
- LC4, LC5, LC6 : 8 times in Design 1, 6 times in Design 2.
- LC8, LC8, LC9 : 8 times in Design 1, 3 times in Design 2.
- LC10, LC11, LC12 : 8 times in Design 1, 6 times in Design 2.
- LC13 : Once in Design 1 and 2.

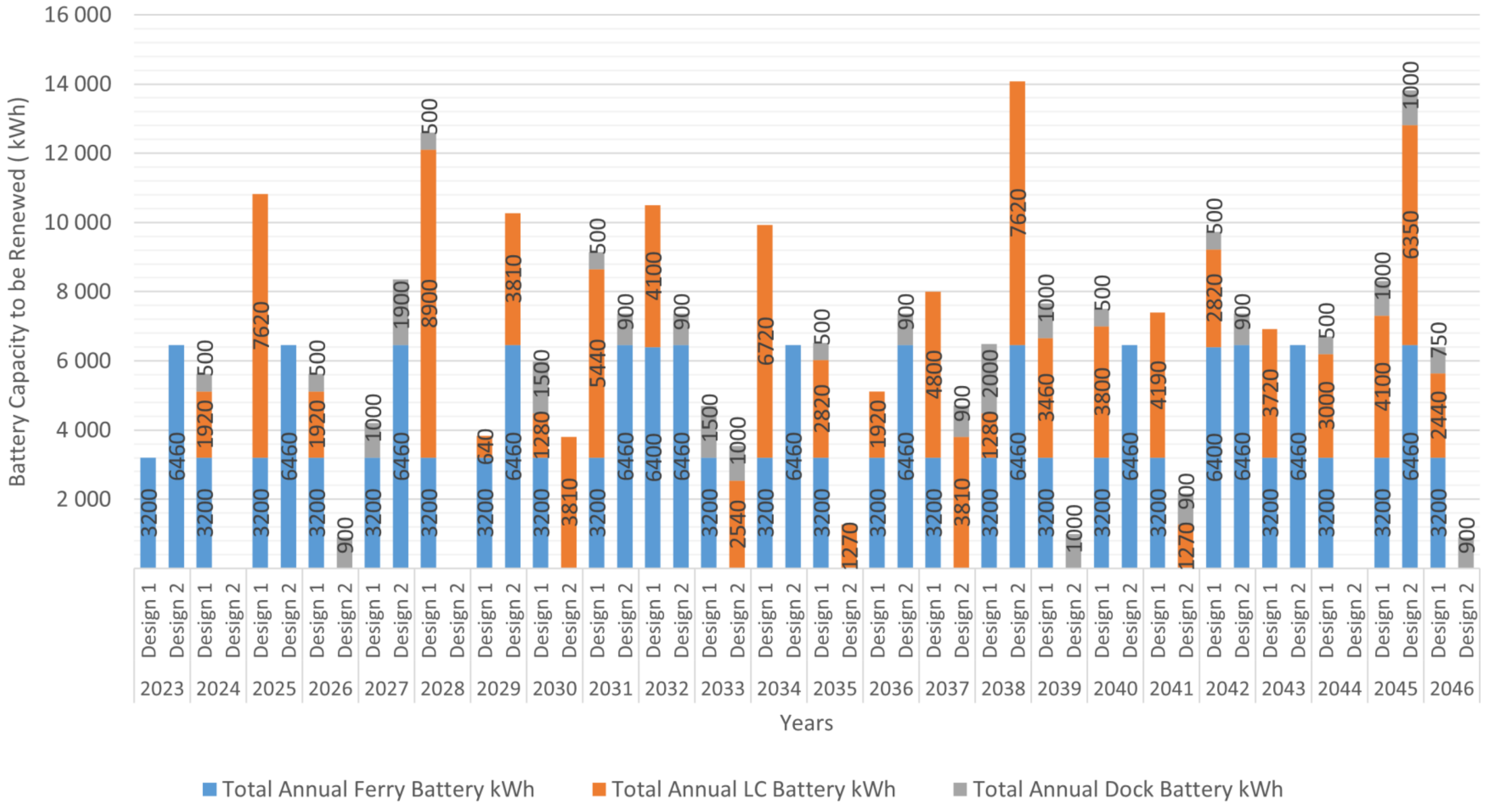


Figure 7.4. The total ESS battery capacities needed to be renewed annually after the first year.

In order to calculate the annual costs of renewing ESS batteries, the battery prices for each year must be calculated accordingly using the curve fitting equation $y = 1335.3e^{-0,111x}$ ($R^2 = 0.9885$), where y is the price per kWh battery capacity in EUR and x is the years since 2012. Then the EUR values are converted to USD using the 1.070 609 28 EUR to USD parity in May 2022. The calculated per kWh ESS battery capacity prices are given in Figure 7.2.

It is possible to calculate the annual ESS battery costs simply by multiplying the amount of ESS battery to be renewed in kWh and the price per kWh ESS battery capacity for the particular year. The annual ESS battery costs given in Table 7.3 and visualized in Figure 7.5. All values are calculated between 2023 and 2046, as 2022 is taken as the year ESS batteries were first installed.

Table 7.3. Annual ESS Battery Costs and differences between Design No. 1 and 2.

Year	*Annual ESS Battery Cost Design No. 1 (USD)*	*Annual ESS Battery Cost Design No. 2 (USD)*	*Yearly Cost Difference Between Designs (USD)*
2023	1 745 919	3 897 646	- 2 151 727
2024	4 055 600	421 580	3 634 020
2025	3 782 664	6 116 976	- 2 334 312
2026	2 238 354	1 626 357	611 997
2027	2 028 827	2 501 211	- 472 384
2028	3 275 591	270 710	3 004 881
2029	1 054 143	4 782 504	- 3 728 362
2030	2 027 415	799 226	1 228 189
2031	2 036 980	1 855 872	181 108
2032	1 601 084	1 744 100	- 143 016
2033	1 046 674	1 074 794	- 28 120
2034	1 702 584	1 516 190	186 394
2035	463 203	112 671	350 532
2036	1 070 514	1 384 323	- 313 810
2037	987 696	957 522	30 174
2038	627 362	970 704	- 343 342
2039	508 785	80 250	428 535
2040	703 996	865 298	- 61 303
2041	699 138	471 870	227 268
2042	398 682	477 263	- 8 581
2043	654 326	644 054	10 272
2044	308 267	141 251	167 016
2045	249 545	666 845	- 417 300
2046	391 727	81 267	310 461
Total	***33 659 076***	***33 460 484***	***198 592***

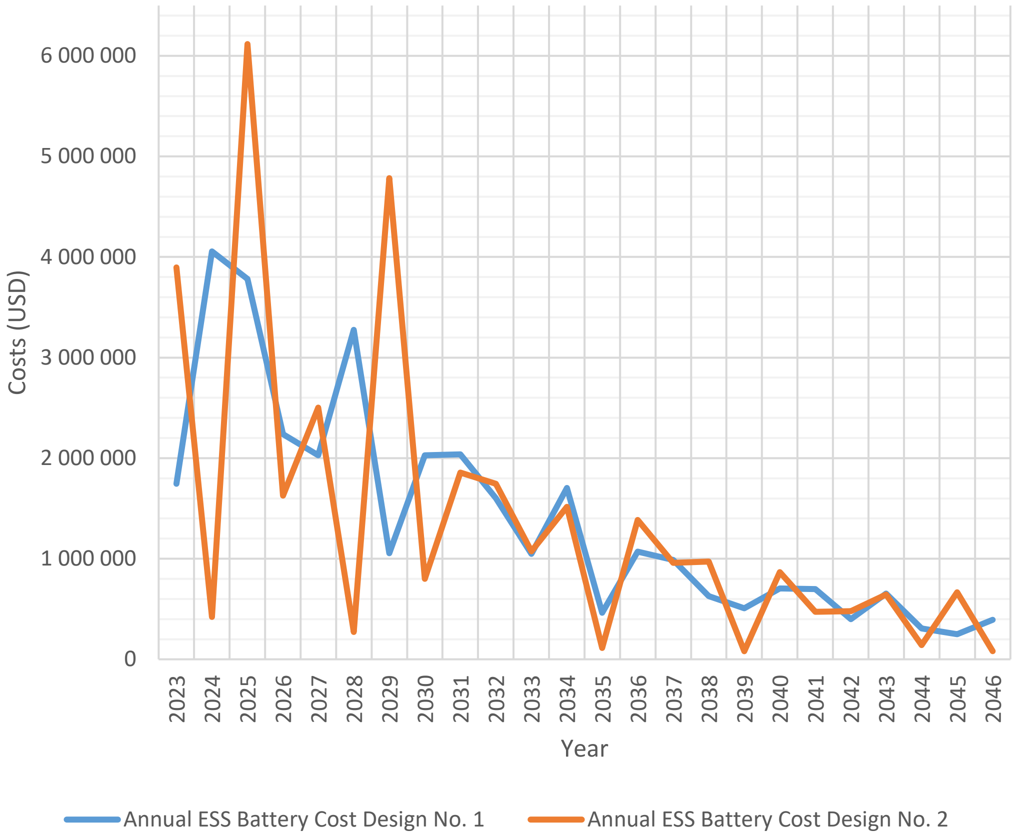


Figure 7.5. Annual ESS Battery Costs of Design No. 1 and 2.

The most significant finding is that there is virtually no difference in total ESS battery renewal costs between Design No. 1 and 2 after 24 years, as shown in Table 7.3. The difference in total ESS battery renewal costs is 198 592 USD, which is 0.59% of the total ESS battery renewal costs of Design No. 1.

7.3.2 Annual energy costs

The annual energy costs are the total cost of fuel or electric energy required to operate ferries. The study takes the literature's 2022 market prices of fuel and electricity in Türkiye and the predicted international prices of fuel and electricity for the 2023-2047 period.

The author of this study acknowledges that any attempt to predict energy prices over timescales such as 25 years can result in values significantly different from the actual market prices in the future. The reason is that energy is a finite and strategic source. Furthermore, the volatility of the markets and magnitudes of other factors affect energy prices. However, several studies try to forecast energy prices for the long term, including oil and electricity.

7.3.2.1 Fossil Fuel (ICE) ferries

The LC and Ro-Ro ferries that İzdeniz currently operates are fossil fuel powered and have ICE that runs on Ultra Low Sulphur Diesel (ULSD) *-a.k.a. Euro Diesel, which will be called as fuel for simplicity, unless necessary-*. The annual fuel consumption can be calculated using the yearly fuel price for a particular year and the total fuel consumption of ferries. The total fuel consumption can be calculated by simply multiplying the distances each ferry travels annually in NM and fuel consumption per NM.

Annually, the LC ferries travel a total of 259 585 NM, the 2015 series Ro-Ro ferries travel a total of 67 080 NM, and the 2020 series Ro-Ro ferries travel a total of 67 073 NM.

On average, LCs consume 19 liters of fuel per NM, 2015 series Ro-Ro ferries consume 40 liters of fuel per NM, and 2020 series Ro-Ro ferries consume 24 liters of fuel per NM. Therefore, it could be stated that:

- LC ferries consume 4 932 113 liters of fuel,
- 2015 series Ro-Ro ferries consume 1 609 908 liters of fuel, and
- 2020 series Ro-Ro ferries consume 2 682 935 liters of fuel annually.

Therefore, the annual average fuel consumption of ferries operated by İzdeniz is calculated as 9 224 956 liters and is taken as is for all years in the annual energy cost calculations. This value is consistent with the yearly fuel tendered by İzdeniz, which is quoted at 10 million liters for 2021 and 2022 [92], [93].

It is not suitable to take the market prices directly in the annual energy cost calculations, as several taxes are applied to market prices of fuel in Türkiye. The tax mainly consists of Value Added Tax (VAT) and Special Consumption Tax / Excise Duty (SCT). In theory, the SCT is deducted from prices when İzdeniz buys fuel, as companies operating Turkish flag vessels are exempt from SCT when purchasing fuel for their Turkish flag vessels. The most recent SCT is 1.794 5 TL at the time of writing [94]. As a result, SCT is excluded from all calculations in the study.

İzdeniz tenders the amount equal to annual fuel consumption for a lump sum with a particular discount. For example, the per liter market fuel price was 6.26 TL, and İzdeniz tendered it for 2.38 TL for a year on 25.11.2020. Similarly, the per liter market price of fuel was 7.94 TL, and İzdeniz tendered it for 6.16 TL for a year on 15.11.2021 [95]. Therefore, while İzdeniz further decreases the annual per liter cost of fuel they buy, it is impossible to estimate the result of each year's tender and the yearly per liter fuel cost for that year.

As a result, the per liter fuel price is taken from the May 2022 market price, which was 24.27 TL as of 27.05.2022. Then, the SCT tax is removed from the market price, and we get 22.475 5 TL per liter fuel cost. As the TL/USD parity on 27.05.2022 was 16.401 9 [96], the per liter fuel price can be converted to 1.370 298 563 USD.

As a result, the annual fuel cost of ferries for 2022 can be calculated as follows:

- LC ferries consume 6 758 468.01 USD worth of fuel,
- 2015 series Ro-Ro ferries consume 2 206 054.62 USD worth of fuel, and
- 2020 series Ro-Ro ferries consume 3 676 421.70 USD worth of fuel.

Therefore, the total fuel cost of ferries in 2022 can be calculated as 12 640 944.33 USD.

In order to calculate annual fuel costs of the future, the average ULSD prices for each year must be known. However, it was not possible to find any forecasts for ULSD until the 2050s. Therefore, it was decided to use oil price forecasts to estimate the ULSD prices between 2022 and 2046. These future fuel prices were predicted based on the values in the study "EU28 fuel prices for 2015, 2030, and 2050" [97]. Appendix I of the EU study includes the Background Report's forecast on oil prices per MWh. The forecasted oil prices per MWh are as follows:

- 35.68 EUR for 2015,
- 75.98 EUR for 2030, and
- 93.48 EUR for 2050.

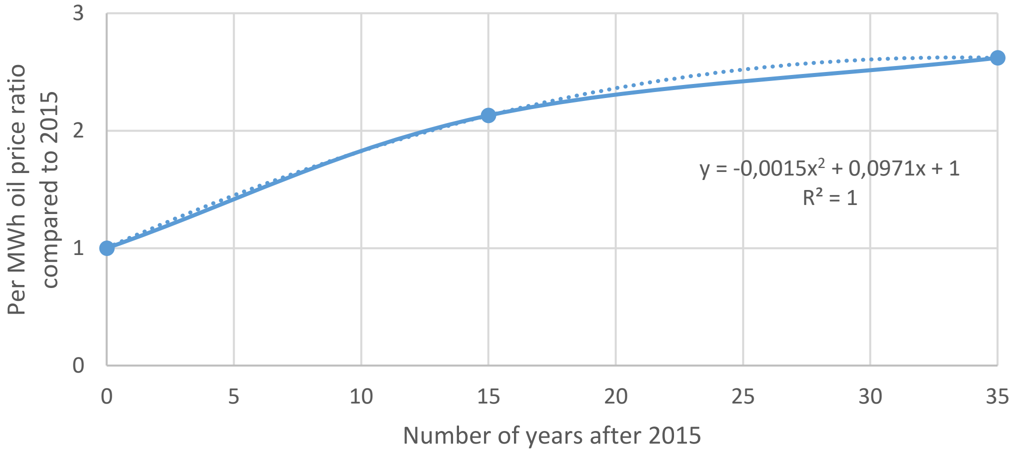


Figure 7.6. Forecasted oil prices per MWh, compared to 2015 values.

It is possible to calculate the average oil prices for each year based on the forecasted prices using the equation $y = -0.0015x^2 + 0.0971x + 1$ ($R^2 = 1$), where y is the ratio of oil price compared to the 2015 oil price and x the years since 2015, as shown in Figure 7.6. Therefore, curve fitting was applied to calculate the forecasted oil prices between 2015 and 2050, and given in Figure 7.7.

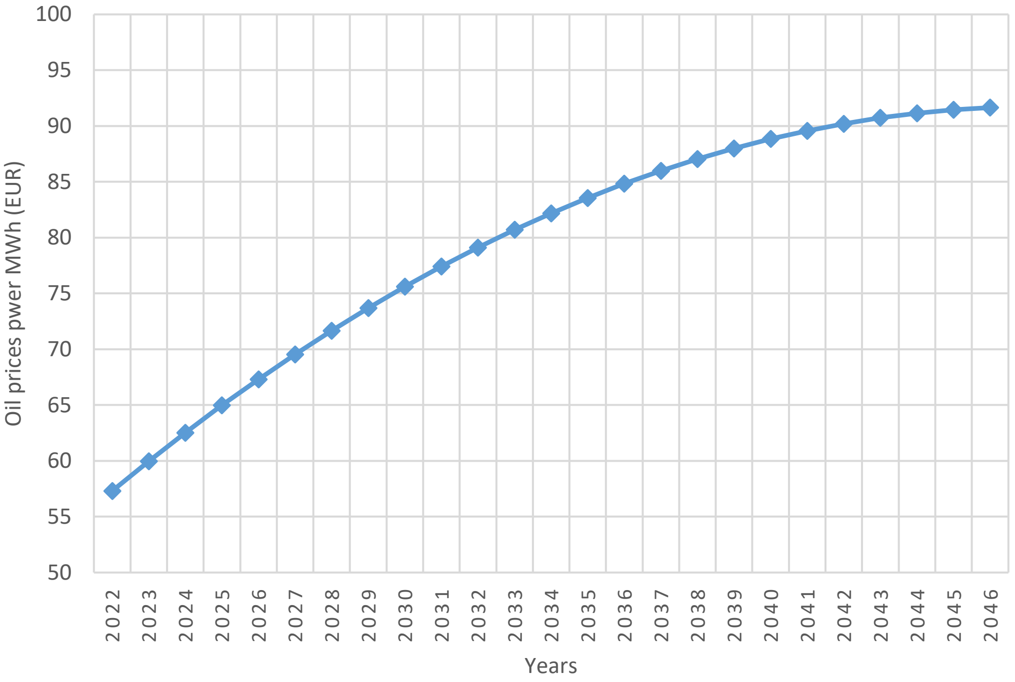


Figure 7.7. Calculated per MWh oil prices between 2022 and 2046.

However, calculating the oil prices for the 2022 - 2046 period is sufficient for this study. Therefore, a new basis of oil prices for 2022 was taken as the ratio of “1”. The future fuel prices can be calculated by simply multiplying the 2022 base price by the ratio calculated for each year. The yearly oil prices until 2046 were adjusted accordingly. It is also possible to calculate the annual fuel cost for each year simply by multiplying that year's fuel price with the yearly total fuel consumption, as given in Table 7.4.

The total fuel cost of operating ICE ferries in İzmir for a 25-year period between 2022 and 2046 is estimated to be 437 852 657.22 USD.

Table 7.4. Annual total fuel costs per year.

Year	*Per Liter Fuel Price Ratio (Compared to 2022 prices)*	*Calculated Per Liter Fuel Price (USD)*	*Annual Total Fuel Cost (USD)*
2022	1.000	1.370	12 640 944.33
2023	1.046	1.434	13 228 053.32
2024	1.091	1.495	13 791 552.02
2025	1.134	1.554	14 331 440.44
2026	1.175	1.610	14 847 718.58
2027	1.214	1.663	15 340 386.44
2028	1.251	1.714	15 809 444.02
2029	1.286	1.762	16 254 891.31
2030	1.319	1.808	16 676 728.33
2031	1.351	1.851	17 074 955.07
2032	1.380	1.892	17 449 571.52
2033	1.408	1.930	17 800 577.70
2034	1.434	1.965	18 127 973.59
2035	1.458	1.998	18 431 759.20
2036	1.480	2.028	18 711 934.53
2037	1.501	2.056	18 968 499.59
2038	1.519	2.081	19 201 454.36
2039	1.536	2.104	19 410 798.85
2040	1.550	2.124	19 596 533.05
2041	1.563	2.142	19 758 656.98
2042	1.574	2.157	19 897 170.63
2043	1.583	2.169	20 012 074.00
2044	1.590	2.179	20 103 367.08
2045	1.596	2.187	20 171 049.89
2046	1.599	2.191	20 215 122.41
TOTAL			***437 852 657.22***

7.3.2.2 Full-electric ferries

The annual energy costs of full-electric ferries are the electric energy drawn from the grid. In order to calculate the yearly cost of electricity, the price per kWh of electricity for each year and annual total energy consumption must be known.

Literature suggests that until 2050 electric prices are forecasted to stay relatively similar to today's prices [98] or decrease significantly [99]. It was decided to take today's electric price per kWh for all future electric prices and related calculations in this study. Therefore, the annual cost of electricity in 2022 shall be equal to all other years' yearly electricity costs in the study.

The final price per kWh of electricity was 2.730 318 TL for medium voltage and industrial uses in Türkiye as of 01.06.2022 [100]. This price includes active energy costs, distribution costs, energy fund contribution margin (0.7%), municipality consumption tax (5%), and VAT (18%). The TL/USD parity on 27.05.2022 was 16.401 9 [96]. Therefore, the price of the kWh of electricity can be converted to 0.168 330 332 9 USD.

The annual electricity consumption of all ferries is 45 915 242.01 kWh. However, depending on the design, the yearly REPP energy output must be deducted from the annual electricity consumption. As a result, for the year 2022, the total electric energy purchased in Design No. 1 is 44 152 874.92 kWh, whereas the total electric energy purchased in Design No. 2 is 44 558 244.18 kWh.

Therefore, the annual electricity cost in 2022 can be calculated as 7 432 268.14 USD for Design No. 1 and 7 500 504.08 USD for Design No. 2.

However, the REPP output over the years is not expected to be constant. Yearly performance degradation of 0.8% is taken for calculations, as stated as the average annual performance degradation for a worst-case scenario in the literature [101]. As a result, the total energy produced by REPPs will decrease yearly. Therefore, the annual electricity costs between 2023 and 2046 must be adjusted accordingly.

Table 7.5. Comparison of yearly REPP energy output (USD) of designs.

Year	*Design No. 1 Output (USD)*	*Design No. 2 Output (USD)*
2022	296 659.84	228 423.90
2023	294 286.56	226 596.51
2024	291 913.28	224 769.11
2025	289 540 00	222 941.72
2026	287 166.72	221 114.33
2027	284 793.44	219 286.94
2028	282 420.17	217 459.55
2029	280 046.89	215 632.16
2030	277 673.61	213 804.77
2031	275 300.33	211 977.38
2032	272 927.05	210 149.98
2033	270 553.77	208 322.59
2034	268 180.49	206 495.20
2035	265 807.21	204 667.81
2036	263 433.94	202 840.42
2037	261 060.66	201 013.03
2038	258 687.38	199 185.64
2039	256 314.10	197 358.25
2040	253 940.82	195 530.86
2041	251 567.54	193 703.46
2042	249 194.26	191 876.07
2043	246 820.98	190 048.68
2044	244 447.71	188 221.29
2045	242 074.43	186 393.90
2046	239 701.15	184 566.51
TOTAL	***6 704 512.33***	***5 162 380.06***

Table 7.6. Annual and total electricity consumption and costs of Design No. 1 and 2, compared.

	Consumption (MWh)		*Cost (USD)*	
Year	Design No. 1	Design No. 2	Design No. 1	Design No. 2
2022	44 164.63	44 569.99	7 432 268.14	7 500 504.08
2023	44 178.72	44 580.85	7 434 641.41	7 502 331.47
2024	44 192.82	44 591.71	7 437 014.69	7 504 158.86
2025	44 206.92	44 602.56	7 439 387.97	7 505 986.25
2026	44 221.02	44 613.42	7 441 761.25	7 507 813.64
2027	44 235.12	44 624.27	7 444 134.53	7 509 641.03
2028	44 249.22	44 635.13	7 446 507.81	7 511 468.42
2029	44 263.32	44 645.99	7 448 881.09	7 513 295.81
2030	44 277.42	44 656.84	7 451 254.37	7 515 123.21
2031	44 291.52	44 667.70	7 453 627.64	7 516 950.60
2032	44 305.61	44 678.55	7 456 000.92	7 518 777.99
2033	44 319.71	44 689.41	7 458 374.20	7 520 605.38
2034	44 333.81	44 700.27	7 460 747.48	7 522 432.77
2035	44 347.91	44 711.12	7 463 120.76	7 524 260.16
2036	44 362.01	44 721.98	7 465 494.04	7 526 087.55
2037	44 376.11	44 732.83	7 467 867.32	7 527 914.94
2038	44 390.21	44 743.69	7 470 240.59	7 529 742.34
2039	44 404.31	44 754.55	7 472 613.87	7 531 569.73
2040	44 418.41	44 765.40	7 474 987.15	7 533 397.12
2041	44 432.50	44 776.26	7 477 360.43	7 535 224.51
2042	44 446.60	44 787.11	7 479 733.71	7 537 051.90
2043	44 460.70	44 797.97	7 482 106.99	7 538 879.29
2044	44 474.80	44 808.83	7 484 480.27	7 540 706.68
2045	44 488.90	44 819.68	7 486 853.55	7 542 534.07
2046	44 503 00	44 830.54	7 489 226.82	7 544 361.46
TOTAL	***1 108 345.31***	***1 117 506.65***	***186 518 687.0***	***188 060 819.27***

It is possible to calculate the annual electricity cost between 2023 and 2046, as shown in Table 7.6. The total electricity cost of operating full-electric ferries in İzmir for a 25-year period between 2022 and 2046 is estimated to be 186 518 687 00 USD for Design No. 1 and 188 060 819.27 USD for Design No. 2.

7.3.3 Annual service costs

There are other operational costs of operating ferries than fuel or energy costs. Only the service and related certification costs related to the full-electric drive, propulsion and control systems, ESS batteries, REPPs onboard and ashore, and ferry chargers are required to keep them operational. The best estimates of average annual service costs were provided by İzdeniz and given below:

- Full-electric drive systems : 10 000 USD per ferry
- Ferry ESS batteries : 20 000 USD per ferry
- Pier ESS batteries : 15 000 USD for all pier batteries
- Ferry chargers : 35 000 USD for all chargers
- REPPs onboard and ashore : 10 000 USD per MWp capacity
- ICE ferries service costs : 22 600 USD per ferry

7.3.4 Results

The annual operating costs of operating ferries and piers through a 25-year service period between 2022 and 2046 were calculated for ICE ferries and full-electric ferries in Designs No. 1 and 2, and given in Table 7.7.

Table 7.7. Total annual operating costs of ICE ferries and full-electric ferries. All values are in USD.

Year	*ICE (USD)*	*Design No. 1 (USD)*	*Design No. 2 (USD)*
2022	13 025 144.33	8 005 268.14	8 061 505.08
2023	13 612 253.32	8 007 641.41	8 063 332.47
2024	14 175 752.02	8 010 014.69	8 065 159.86
2025	14 715 640.44	8 012 387.97	8 066 987.25
2026	15 231 918.58	8 014 761.25	8 068 814.64
2027	15 724 586.44	8 017 134.53	8 070 642.03
2028	16 193 644.02	8 019 507.81	8 072 469.42
2029	16 639 091.31	8 021 881.09	8 074 296.81
2030	17 060 928.33	8 024 254.37	8 076 124.21
2031	17 459 155.07	8 026 627.64	8 077 951.60
2032	17 833 771.52	8 029 000.92	8 079 778.99
2033	18 184 777.70	8 031 374.20	8 081 606.38
2034	18 512 173.59	8 033 747.48	8 083 433.77
2035	18 815 959.20	8 036 120.76	8 085 261.16
2036	19 096 134.53	8 038 494.04	8 087 088.55
2037	19 352 699.59	8 040 867.32	8 088 915.94
2038	19 585 654.36	8 043 240.59	8 090 743.34
2039	19 794 998.85	8 045 613.87	8 092 570.73
2040	19 980 733.05	8 047 987.15	8 094 398.12
2041	20 142 856.98	8 050 360.43	8 096 225.51
2042	20 281 370.63	8 052 733.71	8 098 052.90
2043	20 396 274 00	8 055 106.99	8 099 880.29
2044	20 487 567.08	8 057 480.27	8 101 707.68
2045	20 555 249.89	8 059 853.55	8 103 535.07
2046	20 599 322.41	8 062 226.82	8 105 362.46
TOTAL	***447 457 657.22***	***200 843 687 00***	***202 085 844.27***

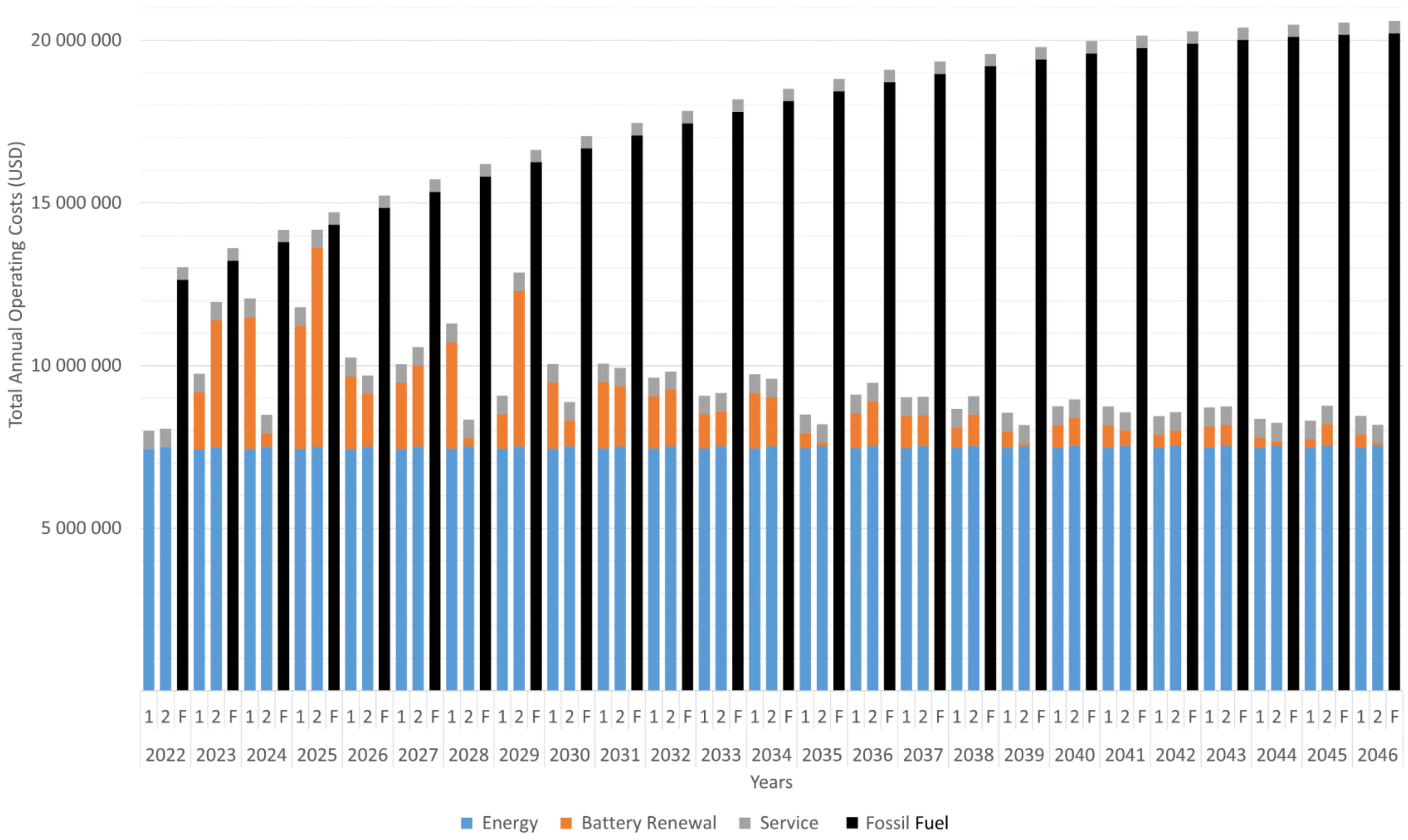


Figure 7.8. Total annual operating costs of Design No. 1, 2, and fossil fuel powered ICE ferries, categorized.

7.4 Total costs

The total cost of operating ferries and piers through a 25-year service period between 2022 and 2046 was calculated for ICE ferries and full-electric ferries in Designs No. 1 and 2 using the values given in respective subsections. The annual total costs were summed up cumulatively, given in Table 7.8, and visualized in Figure 7.9.

Table 7.8. Cumulative total costs of ICE ferries and full-electric ferries in Designs No. 1 and 2. All values are in USD.

Year	*ICE (USD)*	*Design No. 1 (USD)*	*Design No. 2 (USD)*
2022	13 025 144.33	45 390 892.54	47 728 743.88
2023	26 637 397.65	55 144 452.95	59 689 722.54
2024	40 813 149.67	67 210 067.24	68 176 462.40
2025	55 528 790.11	79 005 119.21	82 360 425.65
2026	70 760 708.68	89 258 234.86	92 055 597.50
2027	86 485 295.12	99 304 196.39	102 627 450.13
2028	102 678 939.14	110 599 295.20	110 970 629.55
2029	119 318 030.45	119 675 318.89	123 827 430.47
2030	136 378 958.78	129 726 987.85	132 702 780.47
2031	153 838 113.85	139 790 595.90	142 636 604.27
2032	171 671 885.37	149 246 270.62	152 460 483.26
2033	189 856 663.06	158 324 318.82	161 616 883.24
2034	208 368 836.65	167 921 550.30	171 216 507.01
2035	227 184 795.85	176 420 874.06	179 414 439.17
2036	246 280 930.39	185 418 601.70	188 885 850.92
2037	265 633 629.97	194 447 164.61	197 932 288.47
2038	285 219 284.33	203 117 767.61	206 993 735.80
2039	305 014 283.17	211 591 916.48	215 166 556.53
2040	324 995 016.23	220 343 899.43	224 126 252.95
2041	345 137 873.21	229 029 197.86	232 694 348.46
2042	365 419 243.84	237 480 613.57	241 269 664.16
2043	385 815 517.84	246 138 686.96	250 013 598.85
2044	406 303 084.92	254 366 404.23	258 256 557.23
2045	426 858 334.80	262 634 073.17	267 026 937.71
2046	447 457 657.22	270 982 418 00	275 213 566.67

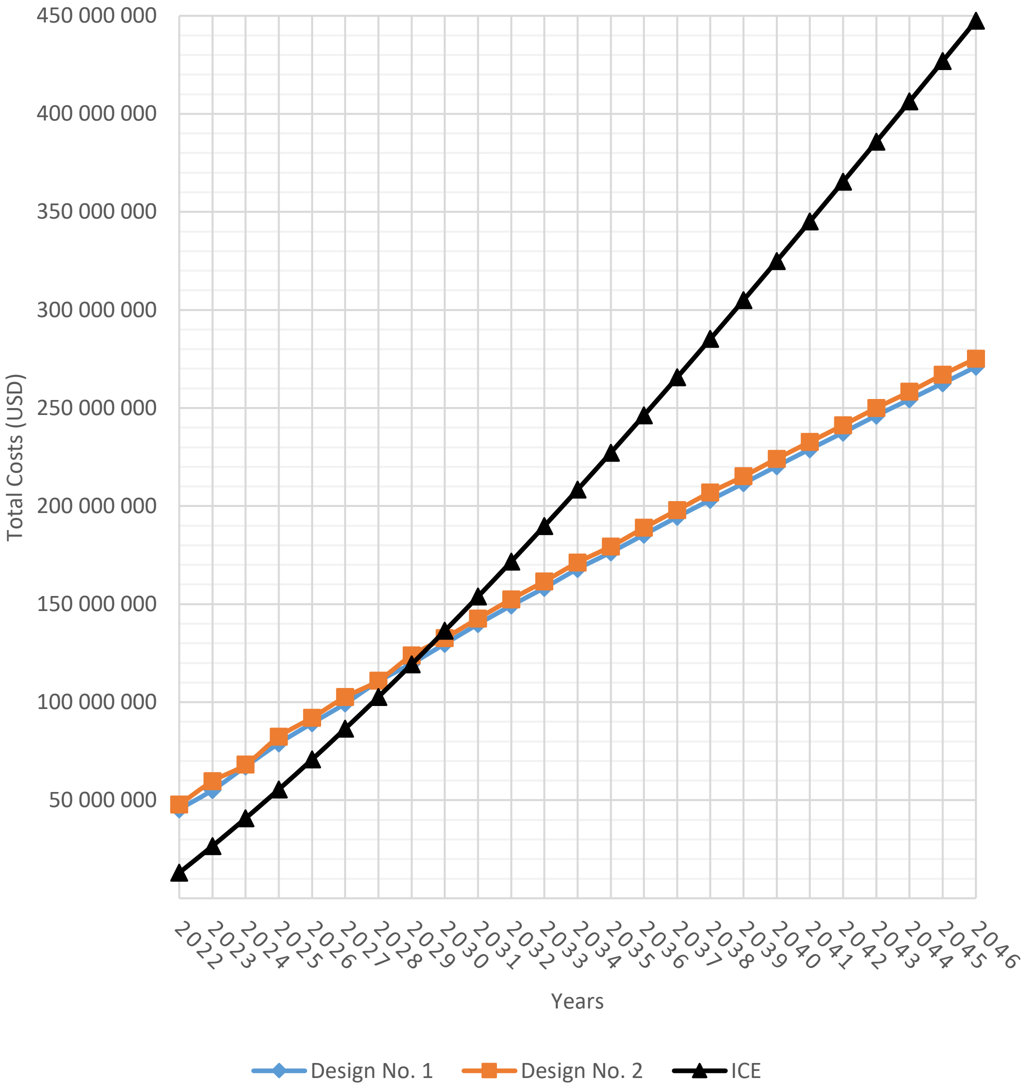


Figure 7.9. The total cost comparison of ICE ferries and full-electric ferries.

The total cost of Design No. 1 is calculated as 270 982 418.00 USD, and the total cost of Design No. 2 is calculated as 275 213 566.67 USD over the 25-year period.

Figure 7.9 shows the trend of cumulative total costs over the years. It can be observed that the total cost of operating ICE ferries has an increasingly increasing trend and surpasses the total cost of operating full-electric ferries in 8 years.

Before reaching the break-even points mentioned above, operating ICE ferries is the more cost-effective solution. However, full-electric ferries become the more cost-effective solution after that break-even point, and the difference between the total cost of operating ICE ferries and full-electric ferries is saved. The total amount saved by choosing Design No. 1 is 176 475 239.22 USD, and 172 244 090.55 USD by choosing Design No. 2.

The calculations above do not include the annual discount rate, which is crucial for making investments across multiple years. The discount rate is the rate of return used to discount future cash flows back to their present value [102]. It should be mentioned that the higher the discount rate implies, the lower the present value of a future cash flow. The discount rate is calculated by subtracting the inflation rate from the interest rate.

The highest discount rate of USD was 3% in the last decade [103] and is taken as the basis for this study. The future costs are discounted back to present values with an annual discount rate of 3% by dividing the calculated added annual cost by $(1+0.03)^y$, where y is the number of years after 2022.

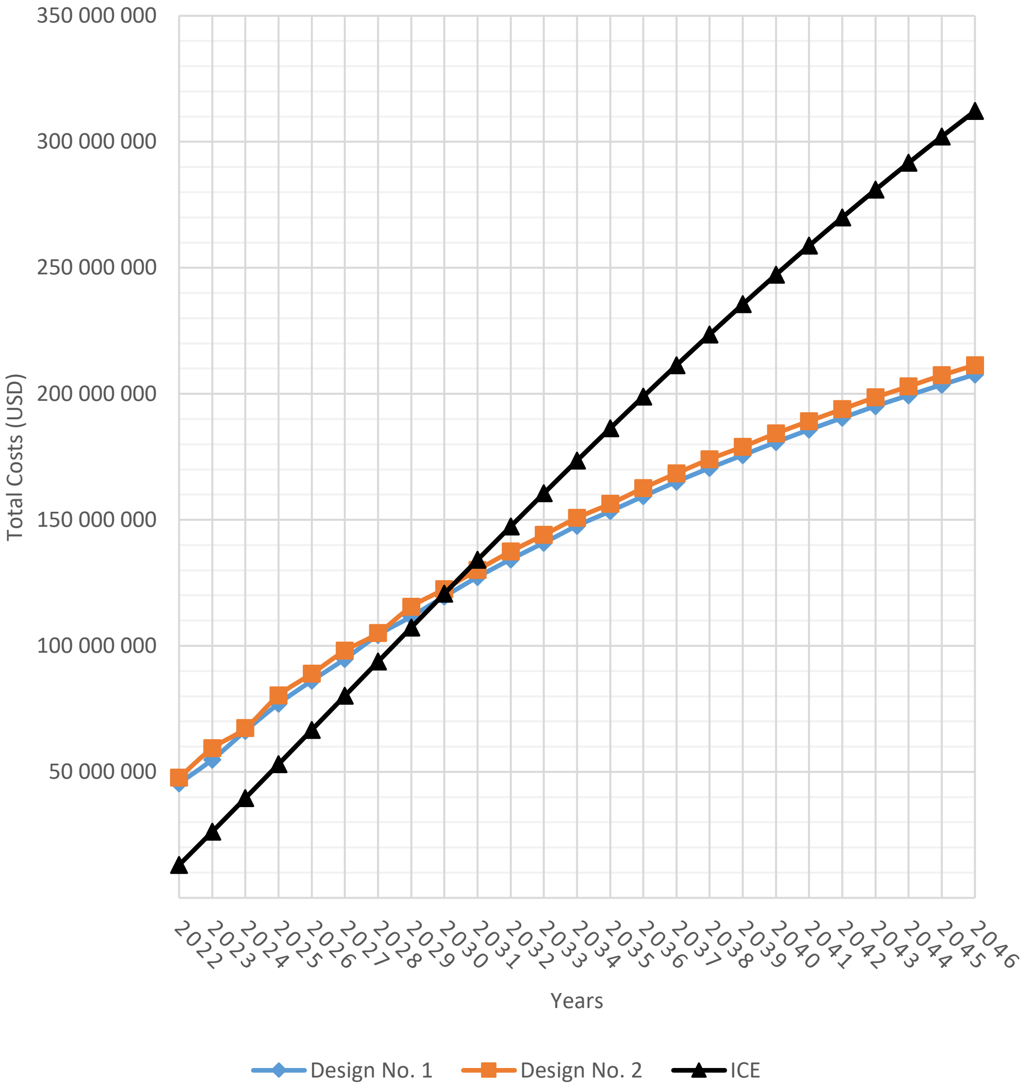


Figure 7.10. The NPV of the total cost of ICE ferries surpasses full-electric ferries between 8 to 9 years, depending on the design choice.

The Net Present Value (NPV) of future costs is lower in the present value method. Therefore, the NPV difference between the total cost of ICE ferries and full-electric ferries diminishes further into the future. As a result, the calculated break-even point is pushed to a further date. The break-even point calculated by the NPV method is about 8 years for Design No. 1, and 9 years for Design No. 2. The NPV of the total amount saved by choosing Design No. 1 is 104 503 116.60 USD, and 100 811 643.00 USD by choosing Design No. 2 over ICE ferries, as shown in Figure 7.10.

7.4.1 Achieving ESS battery lifetimes over ten years

An industry trend often promotes ESS batteries to have lifetimes over ten years can be achieved by installing ESS batteries with different chemistry such as LTO or LFP, adjusting the installed capacity and, therefore, the DoD, or adjusting the schedules, sailing, and charging times.

In this study, it is possible to renew all ESS batteries in a 10-year interval by adjusting the size of the ESS capacities of ferries, as given in Table 7.9. Such a design will be labelled as Design No. 3 to avoid confusion. It should be noted that ESS capacities given in Table 7.9 do not include any additional emergency reserve on top, as the DoD percentages of ESS batteries are already shallow enough.

Table 7.9. ESS battery capacities, average DoD percentages, and average lifetimes of ESS batteries with at least 10-year expected renewal times of Design No. 3.

Ferry	*ESS Battery Capacity (kWh)*	*Average DoD (%)*	*Average Lifetime (years)*
F1, F3	7 430	5	10.04
F2, F4	11 690	5	10.04
LC1, LC2, LC3	2 600	15	12.22
LC4, LC5, LC6	3 740	10	11.42
LC7, LC8, LC9	1 820	20	11.15
LC10, LC11, LC12	3 540	10	10.65
LC13	1 290	60	19.08

It is possible that some of the ESS batteries for Design No. 3 cannot be installed completely. The ferry hull may not be able to store the amount of ESS batteries that can be physically installed. There might be a need to place ESS units on the deck if enough deck space is available.

The calculated ESS battery renewal cost of Design No. 3 would be 21 681 067.60 USD. This is 11 072 039.00 USD less than the ESS battery renewal cost of Design No. 1 and 11 779 416.00 USD less than the ESS battery renewal cost of Design No. 2.

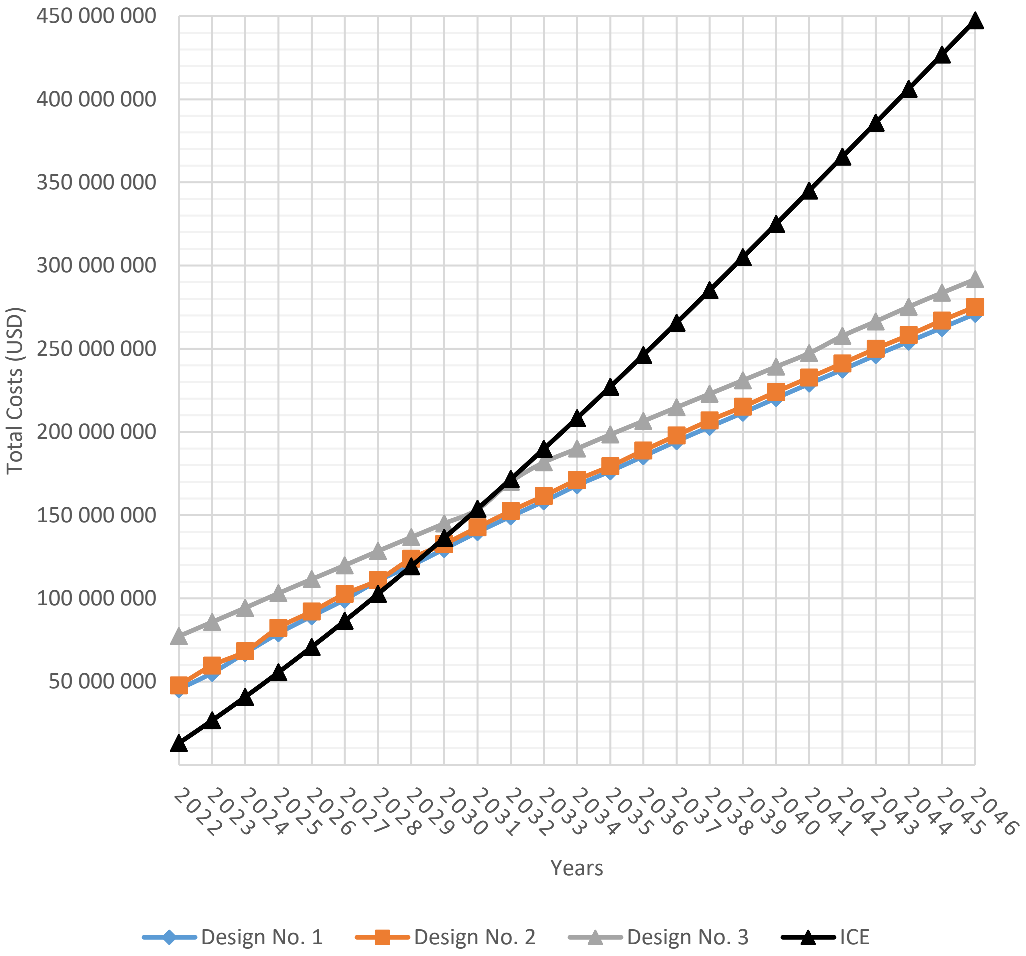


Figure 7.11. The total cost of Design No 3. is higher than other designs at all times.

The economic gains of Design No. 3 would have been quite significant due to having a significantly lower ESS battery renewal cost over the 24-year period. However, the capital cost of Design No. 3 would be extremely high due to the 74 590 kWh total ESS battery capacity needed to be installed. As a result, the capital cost of Design No. 3 in 2022 is calculated as 40 793 836 USD. This is 31 839 091.20 USD more than (or 4.56 times) the capital cost of Design No. 1 and 29 557 476.80 USD more than (or 3.01 times) the capital cost of Design No. 2. Therefore, the total cost of Design No. 3 would be significantly higher than other designs, as shown in Figure 7.11, and therefore was excluded from the analysis.

7.5 Environmental costs and benefits

This study will calculate the environmental costs of operating full-electric ferries and ICE ferries as the total CO_2 equivalent footprint. The benefits of operating full-electric ferries will be calculated in the same manner. Then the costs will be subtracted from the benefits to calculate the total lifetime benefits. The CO_2 footprint of the ESS batteries, REPPs, electric production, consumption, and avoided ULSD consumption are included in the calculations.

There are several types of NMC batteries that can be manufactured with different chemistries, such as NMC111, NMC532, NMC622, and NMC811. The NMC111 would have equal 1:1:1 ratios of nickel (N), manganese (M), and cobalt (C) inside the cathode of the battery. The other NMC batteries would have the N, M, and C ratios indicated by the numbers.

Although the chemistry of the cathode NMC batteries can be different, it is stated that the environmental impact of the different chemistries of NMC batteries is not significantly different [104]. It is also stated that the maximum CO_2 footprint of NMC batteries is 135 kg CO_2 equivalent per kWh capacity produced today [104]. Therefore, the total CO_2 footprint of the NMC batteries required for ESS capacities calculated for each design over the operational period between 2022 and 2046 in this study would be as follows:

- Design No. 1 : 25 325 metric tons CO_2 eq.
- Design No. 2 : 26 440 metric tons CO_2 eq.

The REPPs in this study would also have PV panels with a CO_2 footprint of 72 grams CO_2 equivalent per kWh of electric energy produced by the REPP [51]. Therefore, the total CO_2 footprint of the energy produced by the REPPs calculated for each design over the operational period between 2022 and 2046 in this study would be as follows:

- Design No. 1 : 2 868 metric tons CO_2 eq.
- Design No. 2 : 2 208 metric tons CO_2 eq.

The electric energy bought from Türkiye's energy grid has an average CO_2 eq. footprint of 484 kg per MWh of electricity delivered [106]. However, the electricity produced by the REPP would decrease the amount bought from the grid and, therefore, the total CO_2 footprint. The calculated total CO_2 eq footprint of the energy bought from Türkiye's electric grid for each design over the operational period between 2022 and 2046 in this study would be as follows:

- Design No. 1 : 536 439 metric tons CO_2 eq.
- Design No. 2 : 540 873 metric tons CO_2 eq.

The most significant benefit of full-electric ferries over ICE ferries is that they have zero CO_2 or other GHG emissions during their regular operation and, therefore, no CO_2 footprint. In this study, the total ULSD consumption of ICE ferries over the operational period between 2022 and 2046 is 230 623 900 liters. It is stated that 2.64 kg CO_2 would be emitted by burning 1 liter of ULSD [105]. However, these direct emissions are avoided due to the usage of full-electric ferries. The amount of direct emissions reduced is calculated as 608 847.10 metric tons.

There are also emissions related with the "Well-to-Tank" transfer of ULSD. It is stated that the delivery of diesel on the complete pathway from the crude oil well to the ULSD tanks of ferries results in GHG emissions of 14.0 grams CO_2 eq./MJ [107]. However, again, such indirect emissions are avoided due to the usage of full-electric ferries. The amount of indirect emissions reduced is calculated as 123 629.64 metric tons.

Therefore, a calculated total CO_2 footprint of 732 476.74 metric tons is avoided due to the zero-emission drive systems of full-electric ferries.

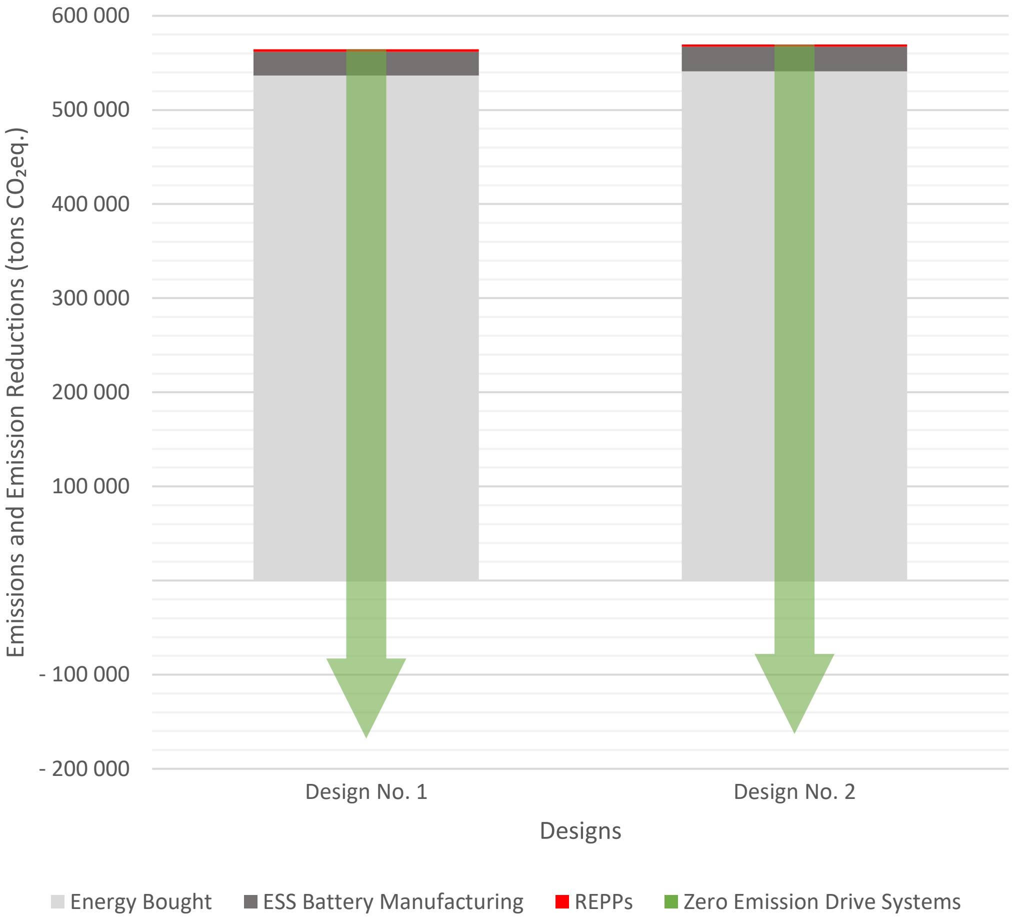


Figure 7.12. The CO_2eq. footprint changes due to using full-electric ferries in İzmir for 25 years.

As a result of all emissions and emission reductions, it is observed that both designs have lower than zero CO_2 eq. total emissions, as shown in Figure 7.12. The CO_2 eq. total emissions of Design No. 1 are calculated as -167 845.23 metric tons and the CO_2 eq. total emissions of Design No. 2 are calculated as -162 955.66 tons.

Today, CO_2 abatement prices vary between 2 USD to more than 260 USD per metric ton of abated CO_2 [108]. IMF estimates that the CO_2 abatement price per metric ton was 6 USD in 2022 and should be 75 USD by 2030 to reach national and global emission targets [109], [110].

It is stated that the total CO_2 emissions of Türkiye are expected to decrease by 29% compared to business-as-usual levels in 2030 by pricing the recommended CO_2 abatement price of 75 USD per metric ton [110]. The IMF recommended price is also expected to vary depending on the progress of countries and the year; however, the IMF recommended price of 75 USD is taken as an average price for the calculations.

As a result, the evaluated total environmental benefit of using full-electric ferries instead of ICE ferries in İzmir over the operational period between 2022 and 2046 due to the significantly lowered total CO_2 footprint is calculated as 12 588 392.53 USD for Design No. 1 and 12 221 674.66 USD for Design No. 2.

If these benefits are considered as the internalized economic benefits of full-electric ferries -as a result of probable carbon tax market and/or governmental policies to be implemented in the near future-, the total economic and environmental benefits of Design No. 1 increases to 189 063 631.75 USD and the total economic and environmental benefits of Design No. 2 increases to 184 465 765.21 USD.

CHAPTER 8

CONCLUSIONS

The analysis of a total of 242 electric ships worldwide shows that there are only 55 full-electric ferries among electric ships, which is only 22.6% of all electric ships. Moreover, only 37 full-electric ferries are operational today, and the rest is new building vessels. It is also observed that there is a significant correlation between the ESS capacity and the GT or passenger capacity of full-electric ferries.

The ESS battery system manufacturers of 98% of electric ships -238 out of 242- in the list were identified. It was observed that 80.49% of the total ESS battery capacity of all ships in the study is manufactured by a single manufacturer, which is 240 592 kWh out of 298 901 kWh. As a result, it could be argued that this manufacturer is far more successful compared to other manufacturers worldwide. However, as this manufacturer has expertise in Li-NMC batteries, time will show how LTO and other batteries will change the balance.

There the data on ferry chargers was quite limited. It is sufficient to state that the average charging rate of full-electric ferries is 2 218 kW, and the average time for charging is 10.3 minutes. However, virtually all ferry chargers' maximum sustained charging rates are stated to go beyond 10 MW. These values might create a general idea about the charging conditions of full-electric ferries. The most significant limitation of full-electric ferry charging could be stated as the time available for charging rather than the charging rate.

The required charging rates to recharge the energy needed can increase significantly due to short periods of charging availability at piers. However, the NMC and other promising battery chemistry technologies -such as LTO- are developing rapidly, increasing their overall reliability, safety, energy density, and charging rates in every generation.

Simulation results show that it is technically possible to convert existing ICE ferries to full-electric ferries and complete almost all scheduled trips with the converted full-electric ferries. The ESS batteries have significantly lower energy density than diesel, no matter the battery's chemistry. However, ICE engines have considerably lower energy conversion efficiency than electric propulsion systems, with a maximum of 35% and a minimum of 90%, respectively. Therefore, while ESS batteries require more room to store the same amount of energy, less energy per NM is needed to be stored onboard due to the higher efficiency of electric propulsion systems.

The ESS battery capacities stated in Designs No. 1 and 2 are enough to complete all trips throughout the year in all weather and sea conditions. However, it is assessed that the 1 270 kWh LC ESS battery capacities of Design No. 2 would provide the operator, İzdeniz, the significant flexibility to interchange any LC ferry on any lines should operational conditions arise.

Electric motors and drive systems increase onboard energy efficiency significantly while reducing operating costs and producing zero emissions. Moreover, the energy efficiency of full-electric ferries can be further increased by installing solar PV REPPs onboard ships.

The capital costs required to convert ICE ferries to full electric ferries, install ESS batteries onboard, and install chargers on piers are today's most significant deterrents to full-electric ferry adoption. However, when the total costs are considered, calculations show that full-electric ferries can become the more cost-effective solution in under eight years for both designs in our study. Even when the NPV method was used for evaluation, the break-even period was pushed back a few months and still under eight years for Design No. 1 and under nine years for Design No. 2.

The CO_2 and other GHG emissions from ICE ferries are significant. In the 25-year period between 2022 and 2047, it is estimated that more than six hundred thousand tons of CO_2 will be emitted into the atmosphere, not including the emissions of HSCs and any increases in the fleet size. The levelized abatement cost of such emissions is estimated to be around 43 million USD.

The total number of passengers and vehicles transported has been increasing, as İzdeniz yearly statistics show, and the demand for seaway passenger and vehicle transportation services is expected to increase by 2,3 fold, as stated in the İzmir Metropolitan Municipality Transport Master Plan for 2030 [111]. It is possible to meet this demand by increasing the trip frequency for each pier by operating more ferries, higher-capacity ferries, or similar solutions. Therefore, it is clear that the actual total CO_2 emissions would be much higher than the estimated six hundred thousand tons if a fossil fuel-powered fleet were still operated instead of a full-electric fleet.

Today, companies often externalize the environmental costs of operating ICE ferries and offload them to society due to the absence of a functioning carbon market. These externalized costs could be paid in terms of changed land use, increased healthcare costs, reduced welfare, damaged ecosystem health, and reduced ecosystem services. However, it is possible to turn most of those costs into externalized costs by adopting full-electric ferries. If these externalized costs are considered as the internalized economic benefits of full-electric ferries in a functioning carbon market, the total economic benefits of both designs in the study increase to over 215 million USD.

As a result of all findings in the study, it is clear that Design No. 1 is the most cost-effective solution for full-electric ferries to be operated in İzmir.

Figure 8.1. Artist’s rendition of how a full-electric ferry fleet in İzmir in the future might look.

The social aspects of full-electric ferries were not evaluated in this study. Such an evaluation would be highly hypothetical due to the lack of any electric ferries operating in Türkiye. However, it is thought that an electric ferry operating in İzmir, which might look like the ferries in Figure 8.1, would be the first electric vehicle citizens will experience in their life. Therefore, it could be argued that electric ferries would be beneficial for increasing social awareness on the carbon footprint of transportation and adopting sustainable mobility to mitigate problems related to GHG emissions of urban public transportation.

8.1 Hypothesis testing

Four hypotheses of the study were tested against the results of the study. It was observed that all hypotheses were assessed to be valid:

- T1: Operating full-electric ferries in İzmir is helpful for Türkiye to reach the Paris Agreement goals by 2050. Full-electric ferries are zero-emission ships, which mitigate significantly more than the GHG emissions required to build and operate them. Moreover, while the emission reduction target is set by 2050, even adopting full-electric ferries today would be economically feasible.
- T2: It is technologically possible to convert existing ferries to full-electric ferries that can operate in İzmir without decreasing the frequency of trips. The technical specifications of ESS batteries, full-electric drive systems, and charging systems are compatible with the existing ferries in İzmir. However, while the frequency of trips is not decreased, certain restrictions were applied to the schedule.
- T3: The economic costs and benefits of using full-electric ferries in İzmir can reach the break-even point in 10 years. The calculated break-even point is around eight years in simple analysis, or 8 to 9 years, with the NPV method applied. The total benefit of choosing Design No. 1 is 176 475 239.22 USD, and 172 244 090.55 USD for choosing Design No. 2.
- T4: The sum of economic and environmental costs and benefits of using full-electric ferries in İzmir can reach the break-even point in 10 years. If environmental costs and benefits are internalized with a carbon market or a similar mechanism, the total benefits of full-electric ferries increase significantly. When economically evaluated, the total economic and environmental benefits of Design No. 1 increase to 189 063 631.75 USD, and the total economic and environmental benefits of Design No. 2 increase to 184 465 765.21 USD.

8.2 Contribution to literature

The literature on full-electric ferries' environmental and techno-economic analysis is severely limited. As a result, an analysis of existing electric ship designs was carried out, and a simulation was developed to conduct an environmental and techno-economic analysis of full-electric ferries that can be operated in Türkiye.

It was necessary to create a table with information on the technical, energy storage, and navigational aspects of all 242 electric ships worldwide in this study, as no such list was found to exist. The table is given in Appendix A.

The data in the table and other related sources were analyzed in great detail in this study. The correlations between technical aspects of electric ships, the big picture of hybrid and full-electric ships, and the historical trend of electric ship development in the world were shown clearly.

Creating such a table and publishing it for free in an open-access manner is vital for scientific work and progress. It enables replicability and testing of the analyses and information given in this study. It is also possible to utilize this data as a foundation for further studies, as there is still much information to extract.

In Türkiye, there are no up-to-date scientific studies found in the literature that presents a holistic approach to;

- Identify the technical limitations, challenges, and opportunities of introducing ESS battery systems on ferries and charging systems on shores,
- Evaluate the economic and environmental costs and benefits of switching to full-electric ferries, and
- Explore the usage of renewable energy sources in the urban seaway passenger and vehicle transportation sector.

This study aims to fill this gap in the literature using precise primary and secondary data, and scientific methods.

As a result of the review of large-scale and internationally funded studies and logical analysis, it has been understood that a simulation-based scientific approach that uses weather, sea, and solar input data is required for the best planning and operation of full-electric ships suitable for Türkiye’s conditions. Therefore, the methodology of the study was shaped around this simulation-based approach.

The simulation-based approach enabled creation and monitoring of unique and complex data on energy consumption profiles of full-electric ferries that can be operated in İzmir. A ferry service model was created with 17 ferries operating on 10 lines between 8 piers for a year, resulting in over 750 000 battery level-related events and around 200 000 departure records. Logics with custom coding were developed from scratch to reflect real-life conditions affecting ferries' energy consumption, such as the weather and sea states and the duration of charging. As a result, it was possible to determine the ESS battery capacities of full-electric ferries and piers with charging stations. Moreover, different scenarios on ferry charger numbers and full-electric ferries' ESS battery capacities were evaluated to estimate the costs and benefits of different configurations.

The use of renewable solar energy was an integrated part of the model. It enabled ferries and piers to utilize the freely available solar energy with PV power plants built on top of them. The use of yearly solar irradiation data with an hourly resolution resulted in realistic power production and consumption data, which was essential for accurate cost and benefit analysis.

Therefore, this study shall provide important high-precision data and information on full-electric ferries to the literature, which would be significantly helpful for decision and policy-making and future scientific and technical studies.

8.3 Contribution for policymakers

The policy and decision makers on modernizing maritime transportation systems shall take the findings of scientific studies into account to achieve the net-zero emission target of the Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC), to which Türkiye is a party.

The Ministry Of Transport and Infrastructure of Türkiye prepared the 2053 Transportation and Logistics Master Plan as a result of the 11th Development Plan (2019-2023) and the 2020 Presidential Annual Program [5]. The 2053 Transportation and Logistics Master Plan focuses on solving economic, efficiency, and environmental issues. There is a strong emphasis on the determination of Türkiye in the context of solving environmental problems created by the transportation sector by guiding the sector and taking necessary legislative and executive steps.

There are six goals within the 2053 Transportation and Logistics Master Plan that prioritize social sustainability, efficiency, environmental awareness, emissions, costs, global and local competitiveness, and legislative matters. Goals 2 to 6 directly take matters related to maritime transportation into account [5].

The 2053 Transportation and Logistics Master Plan's goals are clear and encompass the same aims as this dissertation. They are created to take responsibility on the way to reaching the Paris Agreement’s 2100 global warming goal. This study evaluated the economic and environmental costs and benefits of using electric ships in Türkiye. As a result, electric ships are thought to be significantly helpful on the way to reaching the sustainability, efficiency, environmental and economic targets adopted in the 2053 Transportation and Logistics Master Plan.

In the maritime sector, it is necessary to utilize full-electric ships to reach the net-zero emission target of the Paris Agreement. Ferries used for seaway public transportation services are no exception, and the costs and benefits of switching to full-electric ferries must be evaluated scientifically.

It could be stated that operating full-electric ferries is incredibly beneficial, especially in achieving the UN's sustainable development goals as well as Türkiye's 2053 Transportation and Logistic Master Plan goals, due to all the economic, environmental, and social benefits stated in this study. Specifically, by operating a 17-ship full-electric ferry fleet in İzmir, it is possible to avoid using over 230 million liters of diesel and reduce CO_2 emissions by over 160 thousand metric tons in the next 25 years. By scaling the benefits to national size, it is clear that the total economic and environmental benefits will heavily outweigh the economic costs. While it is expected that the capital costs will be higher today than in the future, the cost of delaying feasible and readily available solutions will have a higher cost for future generations. Therefore, it could be stated that full-electric ferries will be a sustainable step toward even safer and more efficient shipping in a better and cleaner future.

For Türkiye, as a signatory of the Paris Agreement and a country with goals of a better and cleaner future, full-electric ferries are a beneficial and essential future opportunity that needs to be mastered now.

8.4 Recommendations for further research

Due to limited data, it was not possible to evaluate LTO battery costs in the study. As more data becomes available, evaluating LTO battery lifetimes and total costs on full-electric ferries would be incredibly beneficial.

Due to the sheer amount of articles and papers on the electric ship subject, it was possible to evaluate a fraction of the articles and papers available. Therefore, a comprehensive analysis of the articles and papers could provide insight into more cutting-edge developments in the field.

It is necessary to monitor national and international policies adopted relevant to electric ships. Future problems need to be assessed proactively, and scientific studies can provide better solutions and insight today. Providing valid data and scientific analysis of such data is crucial to relevant parties, especially policymakers.

There were no social aspects of electric ferries evaluated in this study besides environmental concerns. Social studies on the effects of electric ferries on passenger mindset and travel habits might uncover important data to be evaluated.

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APPENDICES

A. All electric ships

There are a total of 242 electric ships identified in the study. The Ship Name, Ship Type, Built Year, Length Overall (LOA), Width (W), Draught (D), Gross Ton (GT), ESS Battery Capacity (ESS), Car Capacity (CAR), Passenger Capacity (PAX), Per Trip Distance (PTD), Total Trip Distance (TTD), Type of Propulsion System (T), and ESS Battery Manufacturer (MANU.) is listed below. If there is no data found, the cell is left blank.

Please note that all ship dimensions are in meters, all ESS battery capacities are in kWh, and all distances are in NM.

Please also note that some ships have no data on several aspects. The related cell is left blank if no data was found on a specific aspect.

There are various abbreviations used in the list due to space limitations:

- Bulk Carrier : Bulk
- Container Vessel : Conta.
- Cruise Ship : Cruise
- Fishing Ship : Fishing
- Full-electric Propulsion : F
- Hybrid Propulsion : H
- Newbuilt : N
- Offshore Service Vessel : OSV
- Research Vessel : RV
- Rotterdam Waterbus Project : R. W. P.

NO	SHIP NAME	TYPE	YEAR	LOA	W	D	GT	ESS	CAR	PAX	PTD	TTD	T	MANU.
1	YARA BIRKELAND	Conta.	2020	80.0	14.8	6.0	3 000	6 800			7.0		F	Leclanché
2	AMPERE	Ferry	2014	76.4	20.8	3.7	1 598	1 090	120	350	3.0	101.0	F	Corvus
3	FOLGEFONN	Ferry	2014	76.5	15.0	4.8	1 182	1 000	76	199	1.9	119.1	F	Corvus
4	FÖRI	Ferry	2017	18.0	6.0	1.0		57		75	0.0		F	Corvus
5	GLOPPEFJORD	Ferry	2017	106.0	17.2	3.8	2 697	1 080	120	349	1.1	77.8	F	Siemens
6	KOMMANDØREN	Ferry	2018	87.5	20.8	4.3	2 641	2 938	120	350	6.8		F	Corvus
7	VESTRÅTT	Ferry	2018	66.4	14.5	5.5	2 159	1 137	50	195	3.1	110.9	F	Corvus
8	AUSTRÅTT	Ferry	2018	66.4	14.5	5.5	2 159	1 137	50	195	3.1	110.9	F	Corvus
9	ELLEN	Ferry	2019	59.4	13.4	2.5	996	4 300	31	198	3.2	31.9	F	Leclanché
10	NESVIK	Ferry	2019	82.4	17.5	4.2	2 840	1 582	80	300	2.7	129.9	F	Corvus
11	HERJÓLFUR IV	Ferry	2019	71.8	15.5	2.9	3 270	2 983	75	550	8.1	72.9	F	Corvus
12	FEDJEBJØRN	Ferry	2019	67.0	15.0	5.0	2 297	1 356	50	145	4.3	43.2	F	Corvus
13	BØMLAFJORD	Ferry	2019	67.0	15.0	4.5	2 297	1 356	50	145	3.2		F	Corvus
14	HJELLESTAD	Ferry	2019	43.2	11.7	2.5	623	1 243	16	80	5.4		F	Corvus
15	TIDEFJORD	Ferry	2019	113.9	16.8	3.1	2 979	1 808	120	350	2.7	35.1	F	Corvus
16	MS PRINSEN	Ferry	2019	49.8	12.1	3.5	1 125	2 034		600	3.8	60.5	F	Corvus
17	MS DRONNINGEN	Ferry	2019	49.8	12.1	3.5	1 125	2 034		600	3.8	60.5	F	Corvus
18	MS KONGEN	Ferry	2019	49.8	12.1	3.5	1 125	2 034		600	3.8	60.5	F	Corvus
19	SKOPPHORN	Ferry	2019	111.0	17.0	3.6	3 000	1 808	120	394	2.0	58.0	F	Corvus
20	ROVDEHORN	Ferry	2019	111.0	17.0	3.6	3 000	1 808	120	394	2.0	58.0	F	Corvus
21	YTTERØYNINGEN	Ferry	2019	49.8	13.7	3.4	632	1 989	49	160			F	Corvus
22	MS BRIM	Ferry	2019	24.0	11.0	1.2	264	790		146	10.0	100.0	F	Corvus
23	MOLDEFJORD	Ferry	2020	122.7	16.7	5.0	2 971	1 582	128	390	6.2		F	Corvus
24	KORSFJORD	Ferry	2020	122.7	16.7	4.8	2 971	1 582	125	390	3.9	116.1	F	Corvus
25	ROMSDALSFJORD	Ferry	2020	122.7	16.7	4.8	2 971	1 582	125	390	2.9	133.4	F	Corvus
26	LEIKANGER	Ferry	2020	84.2			2 476	1 582	80	300	2.7		F	Corvus
27	MATRE	Ferry	2020	66.5	14.2	3.8	2 167	1 582	50	199	4.1	102.5	F	Corvus
28	UTNEFJORD	Ferry	2020	74.4	14.2	3.5	1 989	1 356	60	199	3.0	108.7	F	Corvus
29	STANGVIKFJORD	Ferry	2020	67.0	15.0	4.5	2 297	1 130	50	149	3.3	29.6	F	Corvus
30	SMØLA	Ferry	2020	67.0	15.0	4.5	2 297	1 356	50	195	3.3	29.6	F	Corvus
31	MØRINGEN	Ferry	2020	67.0	15.0	4.5	2 297	1 356	50	195	3.3	29.6	F	Corvus
32	BRYGGEN	Ferry	2020	23.3	5.6	1.9	101	183		80	3.5	31.5	F	Echandia
33	HOLMEN	Ferry	2020	23.3	5.6	1.9	101	183		80	3.5	31.5	F	Echandia
34	NYHAVN	Ferry	2020	23.3	5.6	1.9	101	183		80	3.5	31.5	F	Echandia
35	CHRISTIANSHAVN	Ferry	2020	23.3	5.6	1.9	101	183		80	3.5	31.5	F	Echandia
36	REFSHALEØEN	Ferry	2020	23.3	5.6	1.9	101	183		80	3.5	31.5	F	Echandia
37	SYDHAVN	Ferry	2020	23.3	5.6	1.9	101	183		80	3.5	31.5	F	Echandia
38	TYCHO BRAHE	Ferry	2021	111.2	28.2	5.5	11 148	6 345	240	1 250	2.2	99.4	F	Corvus
39	MV MARILYN BELL I	Ferry	2021	29.3	11.5		270	226	15	200	0.1	5.8	F	Corvus
40	GROTTE	Ferry	2021	49.9	13.4	2.3	925	1 107	35	396	1.9	64.3	F	Corvus
41	AMHERST ISLANDER II	Ferry	2021	71.7	20.2	2.7	1 230	1 900	42	300	1.9	62.7	F	Leclanché
42	WOLFE ISLANDER IV	Ferry	2021	99.0	20.0	2.7	1 754	4600	80	399	2.7	108.0	F	Leclanché
43	TOMREFJORD	Ferry	2021	108.8	17.7	5.5	2 850	2 016	120	399	6.8	202.5	F	Unknown
44	MALMEFJORD	Ferry	2021	108.8	17.7	5.5	2 850	2 016	120	399	6.8	168.8	F	Unknown
45	IKA RERE	Ferry	2021	18.5	7.0	1.2		525		130	4.9	77.8	F	Unknown
46	Bastø Electric	Ferry	2021	144.0	20.0	4.0	7 911	4 000	200	600	5.7	147.4	F	Siemens
47	RANDSFJORDFERJA ELROND	Ferry	2022	33.7	11.6		288	678	16	65			F	Corvus
48	MS MEDSTRAUM	Ferry	2022	30.0	9.0		260	1524		150			F	Corvus

NO	SHIP NAME	TYPE	YEAR	LOA	W	D	GT	ESS	CAR	PAX	PTD	TTD	T	MANU.
49	RYFYLKEFERJEN	Ferry	2022	45.4	11.9		720	4 001	27	99			F	Corvus
50	HELLA	Ferry	2022	84.2	16.8	4.1	2 755	1 582	80	300	2.7		F	Corvus
51	R. W. P.	Ferry	N					183		80			F	Echandia
52	R. W. P.	Ferry	N					183		80			F	Echandia
53	R. W. P.	Ferry	N					183		80			F	Echandia
54	SANDØY	Ferry	N	42.0	11.0	4.4	498	1 356	16	98			F	Corvus
55	DRAGSVIK	Ferry	N	84.2			2 755	1 582	80	300	2.7		F	Corvus
56	VESTREFJORD	Ferry	N	108.8	17.7	5.5	2 850	2 016	120	399			F	Unknown
57	ASTRID HELENE	Fishing	2017	13.9	7.6			340					F	Corvus
58	GUANGZHOU	Tanker	2017	70.5	13.9	4.5		2 400					F	Unknown
59	Project e5	Tanker	N	62.0	10.3	4.2	499	3 500					F	Corvus
60	PELIKAN 2	Tug	2020	12.0	6.0			554					F	Corvus
61	GISAS POWER	Tug	2020	18.7	6.7	3.5		1424					F	Corvus
62	HANNAH KRISTINA	Bulk	2017	100.9	18.7	6.3	5 932	994					H	Corvus
63	HAGLAND CAPTAIN	Bulk	2019	89.9	14.4	6.2	3 984	994					H	Corvus
64	STAR LAGUNA	Bulk	2019	204.0	32.2	12.7	37 447	67					H	Corvus
65	NOR VIKING	Bulk	2021	120.0	17.0	5.1	8 300	1 469					H	Corvus
66	SC CONNECTOR	Cargo	2020	154.5	22.7	6.7	12 251	339					H	Corvus
67	MAERSK CAPE TOWN	Conta.	2019	249.0	37.4	13.5	50 869	610					H	Corvus
68	MS STENA JUTLANDICA	Cruise	2018	184.0	28.0	6.0	29 691	1 017	550	1.5k	51.3		H	Corvus
69	MS CRUISE ROMA	Cruise	2019	287.0	30.4	7.2	63 742	5 469					H	Corvus
70	MS CRUISE BARCELONA	Cruise	2019	224.9	30.4	7.2	54 310	5 469					H	Corvus
71	MS FRIDTJOF NANSEN	Cruise	2019	140.0	23.6	5.3	20 000	1 356					H	Corvus
72	AIDAperla	Cruise	2020	300.0	37.7	8.3	125 572	10k					H	Corvus
73	HAVILA CASTOR	Cruise	2020	124.1	22.0	4.6	15 471	6 102					H	Corvus
74	HAVILA CAPELLA	Cruise	2020	124.1	22.0	4.6	15 471	6 102					H	Corvus
75	HAVILA POLLUX	Cruise	2020	124.1	22.0	4.6	15 471	6 102					H	Corvus
76	HAVILA POLARIS	Cruise	2020	124.1	22.0	4.6	15 471	6 102					H	Corvus
77	LE COMMANDANT CHARCOT	Cruise	2021	150.0	28.0	10.0	30 956	4 520					H	Corvus
78	AURORA BOTNIA	Cruise	2021	150.0	26.0	6.1	24 300	2 200					H	Leclanché
79	HYSEAS III	Cruise	2021	39.9	10.0	4.0		700			4.0		H	Leclanché
80	MV SCHLESWIG-HOLSTEIN	Ferry	2014	142.0	25.4	5.8	15 187	2 700			10.8		H	Corvus
81	MV PRINSESSE BENEDIKTE	Ferry	2015	142.0	25.4	5.8	14 621	1 600			10.8		H	Corvus
82	MV PRINS RICHARD	Ferry	2015	142.0	25.4	5.8	14 621	1 600			10.8		H	Corvus
83	MV BERLIN	Ferry	2015	169.5	25.4	5.5	22 319	1 500			25.4		H	Corvus
84	FANNEFJORD	Ferry	2015	122.6	16.7	5.2	2 971	410			6.2		H	Corvus
85	MV COPENHAGEN	Ferry	2016	169.5	25.4	5.5	22 319	1500			25.4		H	Corvus
86	SEASPAN RELIANT	Ferry	2017	148.9	26.0	4.3	4 810	545					H	Corvus
87	ÆRØXPRESSEN	Ferry	2018	49.3	12.2	2.2	479	316					H	Corvus
88	VICTORIA OF WIGHT	Ferry	2018	89.7	22.0	2.6	8 041	818			5.4		H	Corvus
89	DAME VERA LYNN	Ferry	2018	62.3	18.8	1.8	1 750	181					H	Corvus

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90	SULØY	Ferry	2018	134.0	21.0	7.1	2 641	2 938					H	Corvus
91	HADARØY	Ferry	2018	111.0	17.4	5.5	2 641	2 938					H	Corvus
92	HUSAVIK	Ferry	2018	66.4	14.4	3.8	2 159	1 590			3.7		H	Corvus
93	BEN WOOLLACOTT	Ferry	2018	62.3	18.8	1.8	1 750	181			0.3		H	Corvus
94	FINNØY	Ferry	2019	108.0	15.0	5.2	1 935	1 568			1.7		H	Corvus
95	KINSARVIK	Ferry	2019	44.0	11.0	3.0	453	746			7.0		H	Corvus
96	ENHYDRA	Ferry	2019	39.0	9.1	2.0	93	158					H	Corvus
97	ARLAU	Ferry	2019	30.0	9.6	1.6	200	700					H	Corvus
98	ISLAND DISCOVERY	Ferry	2019	81.0	17.0	5.7	2 277	813			4.3		H	Corvus
99	BARMEN	Ferry	2019	27.0	9.7	2.6	146	156			0.9		H	Corvus
100	NORANGSFJORD	Ferry	2019	113.9	16.7	3.1	2 979	2 712			1.7		H	Corvus
101	FESTØYA	Ferry	2019	114.4	17.7	4.3	2 427	1 130			2.4		H	Corvus
102	HEILHORN	Ferry	2019	84.4	14.2	4.0	3 100	1 536			3.0		H	Corvus
103	TELLUS	Ferry	2019	99.7	18.2	2.1	979	948					H	Corvus
104	HUFTARØY	Ferry	2019	134.0	21.0	7.1	7 294	1 017			11.9		H	Corvus
105	SAMNØY	Ferry	2019	134.0	21.0	7.1	7 294	1 017			11.9		H	Corvus
106	GISKØY	Ferry	2019	134.0	21.0	7.1	2 641	2 938					H	Corvus
107	LYSØY	Ferry	2019	129.0	2.7	7.3	6 800	1 017			11.9		H	Corvus
108	SEASPAN TRADER	Ferry	2020	149.0	26.0	3.8	4 857	2 034					H	Corvus
109	STOKKAFJORD	Ferry	2020	80.5	14.5	5.6	2 700	2 034			9.4		H	Corvus
110	ALCATRAZ FLYER	Ferry	2020	40.0	10.0	1.5	97	1 446					H	Corvus
111	TÖLL	Ferry	2020	113.9	16.7	4.0	4 987	678			3.8		H	Corvus
112	MS ANNABELLE	Ferry	2020	135.0	12.0	2.0	3 600	67					H	Corvus
113	MS ANNIKA	Ferry	2020	135.0	12.0	1.6	3 600	67					H	Corvus
114	FODNES	Ferry	2020	114.4	17.7	4.3	2 427	1 130			1.6		H	Corvus
115	MANNHELLER	Ferry	2020	114.4	17.7	4.3	2 427	1 130			1.6		H	Corvus
116	SOLAVÅGEN	Ferry	2020	114.4	17.7	4.3	2 427	1 130			2.4		H	Corvus
117	ECO VALENCIA	Ferry	2020	238.0	34.0	6.0	67 311	5 100					H	Leclanché
118	FOLKESTAD	Ferry	2021	87.6	16.4	3.9	1 910	2 712					H	Corvus
119	ECO BARCELONA	Ferry	2021	238.0	34.0	6.0	67 311	5 100					H	Leclanché
120	ECO LIVORNO	Ferry	2021	238.0	34.0	6.0	64 575	5 100					H	Leclanché
121	ECO SAVONA	Ferry	2021	238.0	34.0	6.0	67 311	5 100					H	Leclanché
122	ECO CATANIA	Ferry	2021	238.0	34.0	6.0	67 311	5 100					H	Leclanché
123	MS JUNGFRAU	Ferry	2021	48.0	10.5			338		700			H	Leclanché
124	MS JUNGFRAU-II	Ferry	N					1 200					H	Leclanché
125	MS JUNGFRAU-III	Ferry	N					1 400					H	Leclanché
126	ISLAND AURORA	Ferry	N	81.0	17.0	5.7	2 277	813			7.6		H	Corvus
127	KAROLINE	Fishing	2015	11.0	4.2		95	195					H	Corvus
128	ANGELSEN SENIOR	Fishing	2018	21.0	9.0		310	271					H	Corvus
129	NORWEGIAN GANNET	Fishing	2018	94.0	18.0	7.5	5 943	305					H	Corvus
130	ORTZE	Fishing	2019	20.0	6.0	2.8		203					H	Corvus
131	SENJA	Fishing	2019	80.4	16.7		4 171	316					H	Corvus
132	GEIR	Fishing	2019	61.7	13.5		2 508	248					H	Corvus
133	ATLANTIC	Fishing	2019	62.8	14.0	5.9	2 925	203					H	Corvus
134	TRONDSKJÆR	Fishing	2019	39.7	9.8	5.1	499	254					H	Corvus
135	STØTTFJORD	Fishing	2019	39.7	9.8	5.1	499	254			9.2		H	Corvus
136	BJØRØYVÆR	Fishing	2019	19.0	12.0	4.3	205	180					H	Corvus
137	EDEL	Fishing	2019	13.5	8.0			244					H	AKASOL
138	FRØY STADT	Fishing	2020	24.0	11.0			180					H	Corvus
139	HARALD MARTIN	Fishing	2020	86.0	19.0		5 300	678					H	Corvus

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140	MULTI ENERGY	Fishing	2020	27.0	11.5		340	271					H	Corvus
141	SKROVA	Fishing	2020	63.9	14.0	5.3	1 920	226					H	Corvus
142	BJØRG PAULINE	Fishing	2020	86.0	19.0		5 300	678					H	Corvus
143	CAPE ARKONA	Fishing	2020	66.9	15.0			361					H	Corvus
144	KONGSFJORD	Fishing	2020	80.4	16.7		4 171	316					H	Corvus
145	HORDAGUT	Fishing	2020	84.0	18.0	8.1	4 800	994					H	Corvus
146	LIBAS	Fishing	2020	86.1	17.8		4 000	508					H	Corvus
147	EL-VINE	Fishing	2020	10.7	5.0			330					H	Corvus
148	EL-IDA	Fishing	2020	10.7	5.0			330					H	Corvus
149	FRØY FENRIS	Fishing	2020	14.9	10.6			180					H	Corvus
150	FRØY SKULD	Fishing	2020	19.9	10.6			180					H	Corvus
151	FRØY HILD	Fishing	2021	20.0	12.0		299	181					H	Corvus
152	SUNNY LADY	Fishing	2021	86.5	17.8	9.3	4 800	1 017					H	Corvus
153	SELVÅG SENIOR	Fishing	2021	79.9	16.2	8.5	4 050	1 017					H	Corvus
154	GITTE HENNING	Fishing	2021	87.6	20.0		4 750	1 130					H	Corvus
155	MULTI POWER	Fishing	2021	27.0	11.5		315	271					H	Corvus
156	FÆRØYSUND	Fishing	2021	77.0	17.8		2 990	621					H	Corvus
157	MULTI EXPLORER	Fishing	2022	27.0	11.5			361					H	Corvus
158	AKRABERG	Fishing	2022	85.9	14.0		2 968	316					H	Corvus
159	EDDA FERD	OSV	2013	92.2	20.6		4 870	272					H	Corvus
160	VIKING LADY	OSV	2013	92.2	21.0		6 111	500					H	Corvus
161	BHAGWAN DRYDEN	OSV	2014	56.8	16.0	6.3	1 475	130					H	Corvus
162	NORMAND SUN	OSV	2017	94.7	21.0	7.0	4 797	497					H	Corvus
163	VIKING PRINCESS	OSV	2017	89.6	21.0	8.0	5 381	511					H	Corvus
164	SKANDI FLORA	OSV	2018	94.9	20.0	6.6	4 469	621					H	Corvus
165	FAR SEARCHER	OSV	2018	93.0	21.0	6.6	4 755	497					H	Corvus
166	SKANDI MONGSTAD	OSV	2018	96.9	21.0	7.0	4 859	621					H	Corvus
167	SEVEN VIKING	OSV	2018	106.5	24.5	8.0	11 363	1 356					H	Corvus
168	JUANITA	OSV	2018	88.9	20.0		3 601	678					H	Corvus
169	HAVILA CHARISMA	OSV	2018	92.8	19.6	6.6	4 327	625					H	Corvus
170	HAVILA FORESIGHT	OSV	2018	93.6	19.7	6.4	4 309	625					H	Corvus
171	SJOBORG	OSV	2018	86.0	19.6	6.6	4 000	568					H	Corvus
172	SEACOR MAYA	OSV	2018	87.8	18.8	5.9	3 601	497					H	Corvus
173	NORMAND NALEY	OSV	2019	85.0	20.0	8.6	4 258	904					H	Corvus
174	ACTA CENTAURUS	OSV	2019	93.4	18.0		6 078	497					H	Corvus
175	BAILEY TIDE	OSV	2019	87.0	19.3	7.4	3 601	746					H	Corvus
176	OCEAN ART	OSV	2019	90.4	20.0		4 800	746					H	Corvus
177	HARVEY CHAMPION	OSV	2019	89.0	19.5	5.9	3 912	745					H	Corvus
178	NKT VICTORIA	OSV	2019	140.0	29.6	8.0	16 171	180					H	Corvus
179	SEACOR AZTECA	OSV	2019	87.0	89.2	7.4	3 601	497					H	Corvus
180	REM HRIST	OSV	2019	88.8	19.0	8.0	4 157	621					H	Corvus
181	REM EIR	OSV	2019	92.5	20.0		5 380	621					H	Corvus
182	SEACOR AMAZON	OSV	2019	87.7	18.0	6.5	4 125	452					H	Corvus
183	REM MIST	OSV	2019	88.8	19.0	8.0	4 176	621					H	Corvus
184	SEACOR MURRAY	OSV	2019	85.7	18.0	6.5	4 125	452					H	Corvus
185	NORTH BARENTS	OSV	2019	92.6	19.2	8.5	4 508	621					H	Corvus
186	ISLAND CLIPPER	OSV	2019	97.0	20.0	8.2	5 086	873					H	Corvus

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187	TROMS ARCTURUS	OSV	2019	94.7	21.0	8.5	4 969	621					H	Corvus
188	STRIL BARENTS	OSV	2019	94.1	20.0		5 937	745					H	Corvus
189	NORMAND FALNES	OSV	2020	80.0	20.0		4 500	904					H	Corvus
190	COEY VIKING	OSV	2020	89.2	20.0		4 799	621					H	Corvus
191	WINDEA JULES VERNE	OSV	2020	93.4	18.9		6 081	565					H	Corvus
192	ALCATRAZ CLIPPER	OSV	2020	38.0	11.0	3.3		1 446					H	Corvus
193	VIKING AVANT	OSV	2020	92.2	20.4		6 545	565					H	Corvus
194	ATLANTIC HARRIER	OSV	2020	89.7	19.6		4 000	648					H	Corvus
195	BOKA TIAMAT	OSV	2020	98.1	20.1		6 133	497					H	Corvus
196	NORMAND SYGNA	OSV	2020	94.7	21.0		4 797	565					H	Corvus
197	OCEAN STAR	OSV	2020	90.4	20.0		4 800	746					H	Corvus
198	VIKING NEPTUN	OSV	2020	146.6	31.0	9.0	19 760	1 740					H	Corvus
199	HARVEY ENERGY	OSV	2020	92.0	19.5	6.0	4 458	746					H	Corvus
200	SEACOR WARRIOR	OSV	2020	87.0	89.2	7.4	3 601	497					H	Corvus
201	SEACOR DANUBE	OSV	2020	85.7	18.0	6.5	3 000	452					H	Corvus
202	SEACOR VIKING	OSV	2020	87.1	89.2	7.4	3 601	497					H	Corvus
203	HST ELLA	OSV	2021	23.7	8.9	3.4	120	188					H	Corvus
204	SIEM STINGRAY	OSV	2021	120.8	23.0		37 447	1 422					H	Corvus
205	HARVEY AMERICA	OSV	2021	94.5	19.5		5 397	746					H	Corvus
206	HARVEY FREEDOM	OSV	2021	94.5	19.5		5 397	746					H	Corvus
207	HARVEY LIBERTY	OSV	2021	94.5	19.5		5 397	746					H	Corvus
208	HARVEY POWER	OSV	2021	94.5	19.5		5 397	746					H	Corvus
209	SIEM SYMPHONY	OSV	2021	89.2	19.0		4 768	565					H	Corvus
210	ATLANTIC SHRIKE	OSV	2021	85.6	22.6		6 053	1 068					H	Corvus
211	MHO APOLLO	OSV	2021	35.0	11.0		413	78					H	Corvus
212	MHO ASGARD	OSV	2021	35.0	11.0		413	78					H	Corvus
213	CBO FLAMENGO	OSV	2021	88.8	19.0		4 063	870					H	Corvus
214	TSS PIONEER	OSV	2021	84.7	18.9	7.3	6 000	745					H	Corvus
215	EDDA FAUNA	OSV	2021	108.7	23.0		6 200	1 243					H	Corvus
216	EDDA FLORA	OSV	2021	95.0	20.0		4 900	1 243					H	Corvus
217	COOPER VIKING	OSV	N	89.2	19.0		4 803	621					H	Corvus
218	SEACOR PARANA	OSV	N	85.7	18.0	6.5	4 125	452					H	Corvus
219	SEACOR NILE	OSV	N	85.7	18.0	6.5	4 125	452					H	Corvus
220	SEACOR CONGO	OSV	N	85.7	18.0	6.5	4 125	452					H	Corvus
221	SPIRIT OF THE SOUND II	RV	2016	19.5	6.5	1.3		91					H	Corvus
222	SPIRIT OF THE SOUND	RV	2016	19.5	6.5	1.3		91					H	Corvus
223	JOHAN HJORT	RV	2017	64.4	13.0	5.4	1 851	292					H	Corvus
224	ARANDA	RV	2018	66.3	13.6	4.6	1 969	226					H	Corvus
225	MATTHEW TURNER	RV	2019	40.2	7.6			93					H	Corvus
226	UIKKU	Tanker	2018	155.4	24.0	9.5	17 500	181					H	Corvus
227	LUNNI	Tanker	2018	155.4	24.0	9.5	17 500	181					H	Corvus
228	AURORA SPIRIT	Tanker	2019	177.0	46.0	16.5	90 000	610					H	Corvus
229	ALTERA WIND	Tanker	2020	245.0	43.8		64 000	1 808					H	Corvus

NO	SHIP NAME	TYPE	YEAR	LOA	W	D	GT	ESS	CAR	PAX	PTD	TTD	T	MANU.
230	CURRENT SPIRIT	Tanker	2020	227.0	46.0	16.5	90 000	610					H	Corvus
231	TIDE SPIRIT	Tanker	2020	227.0	46.0	16.5	90 000	610					H	Corvus
232	RAINBOW SPIRIT	Tanker	2020	177.0	46.0	16.5	90 000	610					H	Corvus
233	ALTERA WAVE	Tanker	2021	245.0	43.8		64 000	1 808					H	Corvus
234	VB KRATCH	Tug	2014	31.6	12.0	5.9	463	78					H	Corvus
235	RYVINGEN	Tug	2018	46.6	12.0	3.6	1 133	3 164					H	Corvus
236	VILJA	Tug	2019	36.0	13.0	7.0	775	312					H	Corvus
237	SVITZER PERENTIE	Tug	N	33.0	13.0		679	546					H	Corvus
238	SVITZER DUGONG	Tug	N	33.0	13.0		679	546					H	Corvus
239	SVITZER BOODIE	Tug	N	33.0	13.0		679	546					H	Corvus
240	SVITZER EURO	Tug	N	33.0	13.0		679	546					H	Corvus
241	MY SAVANNAH	Yacht	2015	83.5	11.8	4.2	2 350	1 000					H	Corvus
242	MY LONIAN	Yacht	2019	87.0	14.0		2 691	441					H	Corvus

B. October 2021 Schedule

LINE 1				
TRIP NO	**KARŞIYAKA DEPARTURE**	**KONAK ARRIVAL**	**KONAK DEPARTURE**	**KARŞIYAKA ARRIVAL**
1	07:00	07:15	07:20	07:35
2	07:15	07:30	07:35	07:50
3	07:30	07:45	07:50	08:05
4	07:45	08:00	08:05	08:20
5	08:00	08:15	08:20	08:35
6	08:15	08:30	08:35	08:50
7	08:30	08:45	08:50	09:05
8	08:45	09:00	09:05	09:20
9	09:00	09:15	09:20	09:35
10	09:15	09:30	09:35	09:50
11	09:30	09:45	09:50	10:05
12	09:45	10:00	10:05	10:20
13	10:00	10:15	10:20	10:35
14	10:20	10:35	10:40	10:55
15	10:40	10:55	11:00	11:15
16	11:00	11:15	11:20	11:35
17	11:20	11:35	11:40	11:55
18	11:40	11:55	12:00	12:15
19	12:00	12:15	12:20	12:35
20	12:20	12:35	12:40	12:55
21	12:40	12:55	13:00	13:15
22	13:00	13:15	13:20	13:35
23	13:20	13:35	13:40	13:55
24	13:40	13:55	14:00	14:15
25	14:00	14:15	14:20	14:35
26	14:20	14:35	14:40	14:55
27	14:40	14:55	15:00	15:15
28	15:00	15:15	15:20	15:35
29	15:20	15:35	15:40	15:55
30	15:40	15:55	16:00	16:15
31	16:00	16:15	16:20	16:35
32	16:15	16:30	16:35	16:50
33	16:30	16:45	16:50	17:05
34	16:45	17:00	17:05	17:20
35	17:00	17:15	17:20	17:35
36	17:15	17:30	17:35	17:50
37	17:30	17:45	17:50	18:05
38	17:45	18:00	18:05	18:20
39	18:00	18:15	18:20	18:35
40	18:15	18:30	18:35	18:50
41	18:30	18:45	18:50	19:05
42	18:45	19:00	19:05	19:20
43	19:00	19:15	19:20	19:35
44	19:15	19:30	19:35	19:50
45	19:30	19:45	19:50	20:05
46	19:45	20:00	20:05	20:20
47	20:00	20:15	20:20	20:35

LINE 2 & 3						
TRIP NO	**BOSTANLI DEPARTURE**		**KONAK ARRIVAL**	**KONAK DEPARTURE**		**BOSTANLI ARRIVAL**
1	07:10		07:25	07:30		07:45
2	07:25		07:40	07:45		08:00
3	07:40		07:55	08:00		08:15
4	07:55		08:10	08:15		08:30
5	08:10		08:25	08:30		08:45
6	08:25		08:40	08:45		09:00
7	08:40		08:55	09:00		09:15
8	08:55		09:10	09:15		09:30
9	09:10		09:25	09:30		09:45
10	09:25		09:40	09:45		10:00
11	09:40		09:55	10:00		10:15
12	09:55		10:10	10:15		10:30
13	10:10		10:25	10:30		10:45
14	10:40		10:55	11:00		11:15
15	11:10		11:25	11:30		11:45
16	11:40		11:55	12:00		12:15
17	12:10		12:25	12:30		12:45
18	12:40		12:55	13:00		13:15
19	13:10		13:25	13:30		13:45
20	13:40		13:55	14:00		14:15
21	14:10		14:25	14:30		14:45
22	14:40		14:55	15:00		15:15
23	15:10		15:25	15:30		15:45
24	15:40		15:55	16:00		16:15
25	16:10		16:25	16:30		16:45
26	16:25		16:40	16:45		17:00
27	16:40		16:55	17:00		17:15
28	16:55		17:10	17:15		17:30
29	17:10		17:25	17:30		17:45
30	17:25		17:40	17:45		18:00
31	17:40		17:55	18:00		18:15
32	17:55		18:10	18:15		18:30
33	18:10		18:25	18:30		18:45
34	18:25		18:40	18:45		19:00
35	18:40		18:55	19:00		19:15
36	18:55		19:10	19:15		19:30
37	19:10		19:25	19:30		19:45
38	19:25		19:40	19:45		20:00
39	19:40		19:55	20:00		20:15
40	19:55		20:10	20:15		20:30
41	20:05		20:20	20:30		20:45
TRIP NO	**BOSTANLI DEPARTURE**	**KARŞIYAKA ARR. - DEP.**	**KONAK ARRIVAL**	**KONAK DEPARTURE**	**KARŞIYAKA ARR. - DEP.**	**BOSTANLI ARRIVAL**
42	20:20	20:30	20:45	20:50	21:05	21:15
43	20:50	21:00	21:15	21:20	21:35	21:45
44	21:20	21:30	21:45	21:50	22:05	22:15
45	21:50	22:00	22:15	22:20	22:35	22:45
46	22:20	22:30	22:45	22:50	23:05	23:15
47	22:50	23:00	23:15	23:20	23:35	23:45

LINE 4				
TRIP NO	**KARŞIYAKA DEPARTURE**	**ALSANCAK ARR. - DEP.**	**PASAPORT ARR. - DEP.**	**KARŞIYAKA ARRIVAL**
1	07:20	07:35	07:45	08:00
2	07:35	07:50	08:00	08:15
3	07:50	08:05	08:15	08:30
4	08:05	08:20	08:30	08:45
5	08:20	08:35	08:45	09:00
6	08:35	08:50	09:00	09:15
7	08:50	09:05	09:15	09:30
8	09:05	09:20	09:30	09:45
9	09:20	09:35	09:45	10:00
10	09:35	09:50	10:00	10:15
11	09:50	10:05	10:15	10:30
12	10:05	10:20	10:30	10:45
TRIP NO	**KARŞIYAKA DEPARTURE**	**PASAPORT ARR. - DEP.**	**ALSANCAK ARR. - DEP.**	**KARŞIYAKA ARRIVAL**
13	10:35	10:50	11:00	11:15
14	11:05	11:20	11:30	11:45
15	11:35	11:50	12:00	12:15
16	12:05	12:20	12:30	12:45
17	12:35	12:50	13:00	13:15
18	13:05	13:20	13:30	13:45
19	13:35	13:50	14:00	14:15
20	14:05	14:20	14:30	14:45
21	14:35	14:50	15:00	15:15
22	15:05	15:20	15:30	15:45
23	15:35	15:50	16:00	16:15
24	16:05	16:20	16:30	16:45
25	16:35	16:50	17:00	17:15
26	16:50	17:05	17:15	17:30
27	17:05	17:20	17:30	17:45
28	17:20	17:35	17:45	18:00
29	17:35	17:50	18:00	18:15
30	17:50	18:05	18:15	18:30
31	18:05	18:20	18:30	18:45
32	18:20	18:35	18:45	19:00
33	18:35	18:50	19:00	19:15
34	18:50	19:05	19:15	19:30
35	19:05	19:20	19:30	19:45
36	19:20	19:35	19:45	20:00
37	19:35	19:50	20:00	20:15
38	19:50	20:05	20:15	20:30

LINE 5 & 6						
TRIP NO	**BOSTANLI DEPARTURE**		**PASAPORT ARR. - DEP.**	**ALSANCAK ARR. - DEP.**		**BOSTANLI ARRIVAL**
1	07:20		07:35	07:45		08:00
2	07:35		07:50	08:00		08:15
3	07:50		08:05	08:15		08:30
4	08:05		08:20	08:30		08:45
5	08:20		08:35	08:45		09:00
6	08:35		08:50	09:00		09:15
7	08:50		09:05	09:15		09:30
8	09:05		09:20	09:30		09:45
9	09:20		09:35	09:45		10:00
10	09:35		09:50	10:00		10:15
11	09:50		10:05	10:15		10:30
12	10:05		10:20	10:30		10:45
TRIP NO	**BOSTANLI DEPARTURE**		**ALSANCAK ARR. - DEP.**	**PASAPORT ARR. - DEP.**		**BOSTANLI ARRIVAL**
13	10:35		10:50	11:00		11:15
14	11:05		11:20	11:30		11:45
15	11:35		11:50	12:00		12:15
16	12:05		12:20	12:30		12:45
17	12:35		12:50	13:00		13:15
18	13:05		13:20	13:30		13:45
19	13:35		13:50	14:00		14:15
20	14:05		14:20	14:30		14:45
21	14:35		14:50	15:00		15:15
22	15:05		15:20	15:30		15:45
23	15:35		15:50	16:00		16:15
24	16:05		16:20	16:30		16:45
25	16:35		16:50	17:00		17:15
26	16:50		17:05	17:15		17:30
27	17:05		17:20	17:30		17:45
28	17:20		17:35	17:45		18:00
29	17:35		17:50	18:00		18:15
30	17:50		18:05	18:15		18:30
31	18:05		18:20	18:30		18:45
32	18:20		18:35	18:45		19:00
33	18:35		18:50	19:00		19:15
34	18:50		19:05	19:15		19:30
35	19:05		19:20	19:30		19:45
36	19:20		19:35	19:45		20:00
37	19:35		19:50	20:00		20:15
TRIP NO	**BOSTANLI DEPARTURE**	**KARŞIYAKA ARR. - DEP.**	**PASAPORT ARR. - DEP.**	**ALSANCAK ARR. - DEP.**	**KARŞIYAKA ARR. - DEP.**	**BOSTANLI ARRIVAL**
38	**20:05**	**20:15**	**20:30**	**20:40**	**20:55**	**21:05**
39	**20:35**	**20:45**	**21:00**	**21:10**	**21:25**	**21:35**
40	**21:05**	**21:15**	**21:30**	**21:40**	**21:55**	**22:05**
41	**21:35**	**21:45**	**22:00**	**22:10**	**22:25**	**22:35**
42	**22:05**	**22:15**	**22:30**	**22:40**	**22:55**	**23:05**
43	**22:35**	**22:45**	**23:00**	**23:10**	**23:25**	**23:35**

LINE 7					
TRIP	**KARŞIYAKA**	**ÜÇKUYULAR**	**GÖZTEPE**	**KARANTİNA**	**KARŞIYAKA**
NO	**DEPARTURE**	**ARR. - DEP.**	**ARR. - DEP.**	**ARR. - DEP.**	**ARRIVAL**
1	07:30	07:50	07:55	08:05	08:25
2	16:50	17:10	17:15	17:25	17;45
3	17:50	18:10	18:15	18:25	18:45

LINE 8				
TRIP	**ÜÇKUYULAR**	**GÖZTEPE**	**PASAPORT**	**ALSANCAK**
NO	**DEPARTURE**	**ARR. - DEP.**	**ARR. - DEP.**	**ARRIVAL**
1	07:50	07:55	08:10	08:20
TRIP	**ALSANCAK**	**PASAPORT**	**GÖZTEPE**	**ÜÇKUYULAR**
NO	**DEPARTURE**	**ARR. - DEP.**	**ARR. - DEP.**	**ARRIVAL**
2	18:00	18:10	18:30	18:35

LINE 9				
TRIP NO	**BOSTANLI DEPATURE**	**ÜÇKUYULAR ARRIVAL**	**ÜÇKUYULAR DEPATURE**	**BOSTANLI ARRIVAL**
1	-	-	07:15	07:40
2	-	-	07:30	07:55
3	07:15	07:40	07:45	08:10
4	07:30	07:55	08:00	08:25
5	07:45	08:10	08:15	08:40
6	08:00	08:25	08:30	08:55
7	08:15	08:40	08:45	09:10
8	08:30	08:55	09:00	09:25
9	08:45	09:10	09:15	09:40
10	09:00	09:25	09:30	09:55
11	09:15	09:40	09:45	10:10
12	09:30	09:55	10:00	10:25
13	09:45	10:10	10:15	10:40
14	10:00	10:25	10:30	10:55
15	10:15	10:40	10:45	11:10
16	10:30	10:55	11:00	11:25
17	10:45	11:10	11:15	11:40
18	11:00	11:25	11:30	11:55
19	11:15	11:40	11:45	12:10
20	11:30	11:55	12:00	12:25
21	11:45	12:10	12:20	12:45
22	12:00	12:25	12:40	13:05
23	12:20	12:45	13:00	13:25
24	12:40	13:05	13:15	13:40
25	13:00	13:25	13:30	13:55
26	13:15	13:40	13:45	14:10
27	13:30	13:55	14:00	14:25
28	13:45	14:10	14:15	14:40
29	14:00	14:25	14:30	14:55
30	14:15	14:40	14:45	15:10
31	14:30	14:55	15:00	15:25
32	14:45	15:10	15:15	15:40
33	15:00	15:25	15:30	15:55
34	15:15	15:40	15:45	16:10
35	15:30	15:55	16:00	16:25
36	15:45	16:10	16:15	16:40
37	16:00	16:25	16:30	16:55
38	16:15	16:40	16:45	17:10
39	16:30	16:55	17:00	17:25
40	16:45	17:10	17:15	17:40
41	17:00	17:25	17:30	17:55
42	17:15	17:40	17:45	18:10
43	17:30	17:55	18:00	18:25
44	17:45	18:10	18:15	18:40
45	18:00	18:25	18:30	18:55
46	18:15	18:40	18:45	19:10
47	18:30	18:55	19:00	19:25
48	18:45	19:10	19:15	19:40
49	19:00	19:25	19:30	19:55
50	19:15	19:40	19:45	20:10
51	19:30	19:55	20:00	20:25
52	19:45	20:10	20:20	20:45

LINE 9				
TRIP NO	**BOSTANLI DEPATURE**	**ÜÇKUYULAR ARRIVAL**	**ÜÇKUYULAR DEPATURE**	**BOSTANLI ARRIVAL**
53	20:00	20:25	20:40	21:05
54	20:20	20:45	21:00	21:25
55	20:40	21:05	21:20	21:45
56	21:00	21:25	21:40	22:05
57	21:20	21:45	22:00	22:25
58	21:40	22:05	22:20	22:45
59	22:00	22:25	22:40	23:05
60	22:20	22:45	23:00	23:25
61	22:40	23:05	23:20	23:45
62	23:00	23:25	-	-
63	23:20	23:45	-	-

LINE 11						
TRIP NO	**BOSTANLI DEPARTURE**	**KARŞIYAKA ARR. – DEP.**	**KONAK ARR. – DEP.**	**KONAK ARR. – DEP.**	**KARŞIYAKA ARR. – DEP.**	**BOSTANLI ARRIVAL**
1	07:30	07:40	07:55	08:00	08:15	08:25
2	08:00	08:10	08:25	08:30	08:45	08:55
3	08:30	08:40	08:55	09:00	09:15	09:25
4	09:00	09:10	09:25	09:30	09:45	09:55
5	09:30	09:40	09:55	10:00	10:15	10:25
6	10:00	10:10	10:25	10:30	10:45	10:55
7	10:30	10:40	10:55	11:00	11:15	11:25
8	11:00	11:10	11:25	11:30	11:45	11:55
9	11:30	11:40	11:55	12:00	12:15	12:25
10	12:00	12:10	12:25	12:30	12:45	12:55
11	12:30	12:40	12:55	13:00	13:15	13:25
12	13:00	13:10	13:25	13:30	13:45	13:55
13	13:30	13:40	13:55	14:00	14:15	14:25
14	-	13:55	14:10	14:15	14:30	-
15	14:00	14:10	14:25	14:30	14:45	14:55
16	-	14:25	14:40	14:45	15:00	-
17	14:30	14:40	14:55	15:00	15:15	15:25
18	-	14:55	15:10	15:15	15:30	-
19	15:00	15:10	15:25	15:30	15:45	15:55
20	-	15:25	15:40	15:45	16:00	-
21	15:30	15:40	15:55	16:00	16:15	16:25
22	-	15:55	16:10	16:15	16:30	-
23	16:00	16:10	16:25	16:30	16:45	16:55
24	-	16:25	16:40	16:45	17:00	-
25	16:30	16:40	16:55	17:00	17:15	17:25
26	-	16:55	17:10	17:15	17:30	-
27	17:00	17:10	17:25	17:30	17:45	17:55
28	-	17:25	17:40	17:45	18:00	-
29	17:30	17:40	17:55	18:00	18:15	18:25
30	-	17:55	18:10	18:15	18:30	-
31	18:00	18:10	18:25	18:30	18:45	18:55
32	-	18:25	18:40	18:45	19:00	-
33	18:30	18:40	18:55	19:00	19:15	19:25
34	-	18:55	19:10	19:15	19:30	-
35	19:00	19:10	19:25	19:30	19:45	19:55
36	-	19:25	19:40	19:45	20:00	-
37	19:30	19:40	19:55	20:00	20:15	20:25
38	20:00	20:10	20:25	20:30	20:45	20:55
39	20:30	20:40	20:55	21:00	21:15	21:25
40	21:00	21:10	21:25	21:30	21:45	21:55
41	21:30	21:40	21:55	22:00	22:15	22:25
42	22:00	22:10	22:25	22:30	22:45	22:55
43	22:30	22:40	22:55	23:00	23:15	23:25

LINE 12						
TRIP	**BOSTANLI**	**KARŞIYAKA**	**PASAPORT**	**ALSANCAK**	**KARŞIYAKA**	**BOSTANLI**
NO	**DEPARTURE**	**ARR. – DEP.**	**ARR. – DEP.**	**ARR. – DEP.**	**ARR. – DEP.**	**ARRIVAL**
1	07:45	07:55	08:10	08:20	08:35	08:45
2	08:15	08:25	08:40	08:50	09:05	09:15
3	08:45	08:55	09:10	09:20	09:35	09:45
4	09:15	09:25	09:40	09:50	10:05	10:15
5	09:45	09:55	10:10	10:20	10:35	10:45
6	10:15	10:25	10:40	10:50	11:05	11:15
7	10:45	10:55	11:10	11:20	11:35	11:45
8	11:15	11:25	11:40	11:50	12:05	12:15
9	11:45	11:55	12:10	12:20	12:35	12:45
10	12:15	12:25	12:40	12:50	13:05	13:15
11	12:45	12:55	13:10	13:20	13:35	13:45
12	13:15	13:25	13:40	13:50	14:05	14:15
13	13:45	13:55	14:10	14:20	14:35	14:45
14	14:15	14:25	14:40	14:50	15:05	15:15
15	14:45	14:55	15:10	15:20	15:35	15:45
16	15:15	15:25	15:40	15:50	16:05	16:15
17	15:45	15:55	16:10	16:20	16:35	16:45
18	16:15	16:25	16:40	16:50	17:05	17:15
19	16:45	16:55	17:10	17:20	17:35	17:45
20	17:15	17:25	17:40	17:50	18:05	18:15
21	17:45	17:55	18:10	18:20	18:35	18:45
22	18:15	18:25	18:40	18:50	19:05	19:15
23	18:45	18:55	19:10	19:20	19:35	19:45
24	19:15	19:25	19:40	19:50	20:05	20:15
25	19:45	19:55	20:10	20:20	20:35	20:45
26	20:15	20:25	20:40	20:50	21:05	21:15
27	20:45	20:55	21:10	21:20	21:35	21:45
28	21:15	21:25	21:40	21:50	22:05	22:15
29	21:45	21:55	22:10	22:20	22:35	22:45
30	22:15	22:25	22:40	22:50	23:05	23:15

CURRICULUM VITAE

Surname, Name: Pense, Caner

EDUCATION

Degree	Institution	Year of Graduation
MS	METU, Earth System Sciences	2019
BS	Dokuz Eylül University, Maritime Faculty	2010
High School	Atakent Anadolu High School, İzmir	2005

FOREIGN LANGUAGES

Fluent English

PUBLICATIONS

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