

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**DYNAMIC MODELLING, SIMULATION BASED ANALYSIS AND
OPTIMIZATION OF HYBRID SHIP PROPULSION SYSTEMS**



Ph.D. THESIS

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Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

DECEMBER 2022

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**GEMİ HİBRİT TAHRİK SİSTEMLERİNİN DİNAMİK MODELLEMESİ,
OPTİMASYONU VE SİMULASYON TEMELLİ ANALİZİ**

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Date of Submission : 14.11.2022

Date of Defense : 12.12.2022





To my family,



FOREWORD

I would like to convey my heartfelt appreciation to my thesis advisor, Prof. Dr. Cengiz DENİZ for his guidance, understanding, and contribution, and valuable support during my PhD studies. I am greatly indebted to my valuable family for their support and encouragement all of my life and trust in me.

Besides, I would like to thank my thesis committee: Assoc. Prof. Dr. Gökem KÖKKÜLÜNK and Assist. Prof. Dr. Burak ZİNCİR for their valuable comments and sharing their experiences during the dissertation.

I would also like to thank Assoc. Prof. Dr. Jean-Frédéric CHARPENTIER from French Naval Academy and Assist. Prof. Dr. Çağlar DERE from Izmir Katip Çelebi University for their support and guidance during the thesis studies.

Lastly, I should point out that this thesis study is supported by Scientific Research Project Departments of Istanbul Technical University under project number: 43546.

November 2022

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ABBREVIATIONS

AC	: Alternative Current
ACOA	: Ant Colony Optimization Algorithm
AFC	: Alkaline Fuel Cell
AHP	: Analytic Hierarchy Process
ANN	: Artificial Neural Network
CapEx	: Capital Expenditures
CF	: Carbon Factor
CGH2	: Cryogenic Hydrogen
CI	: Consistency Index
CR	: Consistency Ratio
DG	: Diesel Generator
DPA	: Dynamic Programming Algorithm
DEA	: Differential Evolution Algorithm
DFDE	: Dual-Fuel Diesel Engine
ECMS	: Equivalent Consumption Minimization Strategy
EEDI	: Energy Efficiency Design Index
EEOI	: Energy Efficiency Operational Indicator
EGR	: Exhaust Gas Recirculation
EMS	: Energy Management System
ESS	: Energy Storage System
FC	: Fuel Cell
GA	: Genetic Algorithm
GHG	: Greenhouse Gas
HFO	: Heavy Fuel Oil
HPS	: Hybrid Propulsion System
ICE	: Internal Combustion Engine
IEM	: Internal Engine Modifications
IGF Code	: International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	: International Maritime Organization
LNG	: Liquefied Natural Gas
LPG	: Liquefied Petroleum Gas
LH2	: Liquefied Hydrogen
LOHC	: Hydrogenation of Carrier Substance
MARPOL	: International Convention for the Prevention of Pollution from Ships
MCFC	: Molten Carbonate Fuel Cell
MDO	: Marine Diesel Oil
MEPC	: Marine Environment Protection Committee
MGO	: Marine Gas Oil
NMC	: Lithium Nickel Manganese Cobalt Oxide
OSV	: Offshore Supply Vessel
OpEx	: Operational Expenditures
PAFC	: Phosphoric Acid Fuel Cell
PEMFC	: Proton Exchange Membrane Fuel Cell

PM	: Particulate Matter
PSO	: Particle Swarm Optimization
RES	: Renewable Energy Source
SAA	: Simulated Annealing Algorithm
SC	: Super Capacitor
SCR	: Selective Catalytic Reduction
SEEMP	: Ship Energy Efficiency Management Plan
SOFC	: Solid Oxide Fuel Cell



SYMBOLS

i	: Current [A]
I	: Moment of Inertia [kgm^2]
J	: Advance Coefficient
K_T	: Torque Coefficient [Nm]
K_F	: Thrust Coefficient [kN]
k_{RG}	: Reduction Ratio of Reduction Gear
kW	: Kilowatt
m	: Mass of the Disc [kg]
P_{BAT,min}	: Minimum Battery Power [kW]
P_{BAT,opt}	: Optimal Battery Power [kW]
P_{BAT,max}	: Maximum Battery Power [kW]
P_{DG,max}	: Maximum Diesel Generator Power [kW]
P_{DG,min}	: Minimum Diesel Generator Power [kW]
P_{DG,opt}	: Optimal Diesel Generator Power [kW]
P_{FC,max}	: Maximum Fuel Cell Power [kW]
P_{FC,opt}	: Optimal Fuel Cell Power [kW]
P_T	: Total Power [kW]
R_{BAT,max}	: Maximum Ramp Rate of Battery [kW/s]
R_{FC,max}	: Maximum Ramp Rate of Fuel Cell [kW/s]
R_{DG,max}	: Maximum Ramp Rate of Diesel Generator [kW/s]
r	: Radius [m]
T_m	: Motor Torque [Nm]
ω	: Rotational Velocity [s^{-1}]



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DYNAMIC MODELLING, SIMULATION BASED ANALYSIS AND OPTIMIZATION OF HYBRID SHIP PROPULSION SYSTEMS

SUMMARY

Today, air pollution, harmful emissions, global warming, and climate change issues are of great importance both for the future of our world and for human health. It is aimed to keep the emission levels under control and to reduce the emission levels with international agreements such as the Kyoto Protocol and the Paris Agreement, which are regulated on a global scale but are not binding. However, exceeding the levels targeted in these agreements raises concerns for the future of both our world and human life. Greenhouse gases emitted into the atmosphere cause global warming and climate change. The most important indicators of climate change are shifts in seasonal cycles, excessive precipitation or drought, melting of glaciers, and severe natural events such as hurricanes and floods. Carbon dioxide is one of the greenhouse gases. At the same time, emissions such as nitrogen oxides, sulfur oxides, and carbon monoxide, which are other harmful emissions, cause acid rain and are extremely harmful to human health. Therefore, it is vital to control and, if possible, eliminate carbon dioxide emissions in all areas of life.

90% of world trade is carried out by sea transportation. Although it is an efficient transportation network on the basis of freight transported, it is predicted that, together with the increasing trade volume and the number of ships, ship-related emissions will increase between 90% and 130% until 2050. For all these reasons, emissions from maritime transport must also be brought under control and reduced. The International Maritime Organization (IMO) is working to reduce carbon dioxide emissions from ships. In this context, with the MARPOL Annex-VI contract, Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Operational Indicator (EEOI) and regulations that measure design, voyage and operational efficiency have been introduced. Not just limited to these, IMO has set limits based on engine speed for certain emission control areas with the NO_x Code and standardized the production and use of machinery in accordance with the limits set for both machinery manufacturers and ships operating in this region. For sulfur oxide and particulate matter emissions, limits are set on the fuel content used. Diesel engines are used to a great extent for the propulsion of ships. Ship diesel engines use heavy fuels, which are fossil fuel derivatives. The chemical component of these fuels contains 85-87% carbon. For this reason, carbon dioxide gas comes out as a result of these heavy fuels burned in diesel machines. According to studies, the maritime sector causes 2.2% of global carbon dioxide emissions. As a result of the continued use of fossil fuels, it is not possible to significantly reduce the amount of emissions and reach the targets. Therefore, it is possible to reduce these emissions with alternative fuels, electric or hybrid propulsion systems, emission reduction technologies, speed reduction or operational improvements.

All operations based on energy efficiency on ships, aiming to reduce fuel consumed and therefore emissions, should be specific for each ship. Many variables need to be examined separately according to the ship's usage area, ship size, ship type, and operation profile. The measures to be taken for a large crude oil ship operating in the ocean and for a ferry operating in the city are not the same. Likewise, there may be differences between ships with similar usage areas in terms of volume, area, and operation profile. Therefore, each study remains specific to the ship on which it is based.

The efficiency of diesel engines, which act as the ship's main power generator and ensure the movement of the ship, is around 50%, and only half of the chemical energy of the fuel can be obtained from the propeller. Especially in ships operating short distances and making many take-offs and berthing maneuvers during the cruise, the diesel engine load changes many times and may move away from the efficient operating point. In these cases, it is inevitable that the system efficiency will drop below half. For this type of ship, the hybrid propulsion system can give efficient results. In general, when the load fluctuation is high, it is aimed to provide the high-power demand with electricity by keeping the load of the diesel engine constant. In this way, non-ideal fluctuations in the diesel engine operation map can be prevented. Within the scope of this thesis, operational and shipbuilding data were collected from a ferry connected to the City Lines in Istanbul, and a hybrid propulsion system was proposed and analyzed. The prepared thesis consists of five chapters. The second, third and fourth chapters have been published as articles, and the last chapter has been approved for publication as a book chapter. The first part states the introduction and the aim and scope of the study. In the same section, the introduction of the case ship and the data collection process are mentioned. The data of the ship was taken by personally participating in the voyages on the ship and the average of the data collected for the same voyage was taken as the subject of a case study. The electrical power generated from four diesel engines on the ship is transferred to the propellers by means of two electric motors. Classified as diesel-electric as its operating principle, this ship has a bow thruster to facilitate take-off and berthing maneuvers. The ship voyage was made between Kadıköy - Karaköy city lines piers.

Many different power generators and energy storage technologies can be used in hybrid systems. Putting an alternative power generator next to the existing diesel engines on the ship will reduce fossil fuel consumption, thus positively affecting emissions. At this point, fuel cells come to the fore due to their zero-emission power generation potential and their use in land vehicles. However, today, there are five different fuel cells that are commercially available and industrially used. Which of these types is suitable for use on the ship and which should be selected are the research subjects. The second part of the thesis is an article prepared and published to seek an answer to this research question. In this study, alkaline, proton exchange membrane, molten carbonate, solid oxide and phosphoric acid fuel cells were compared with the analytical hierarchy method, which is one of the multi-criteria decision-making methods. Eight different criteria determined; safety, emissions, efficiency, cost, life, power output, fuel type and size. Fourteen experts from different fields of the maritime industry, received their opinions through questionnaires and the criteria are ranked in order of importance. While safety is the most important evaluation criterion in this ranking, size comes last. In this context, the diesel oil using molten carbonate fuel cell and the hydrogen using proton exchange membrane fuel cell took the first two places.

Following the determination of the fuel cell to be used in the hybrid system, it is also necessary to determine the type of fuel that should be used in the main target of marine decarbonisation. There are two types of alternative fuels that do not contain carbon; these are ammonia and hydrogen. As a result of the use of these two fuels in fuel cells, no carbon emissions occur. However, these two fuels have been examined from many aspects by using the analytical hierarchy method to determine the appropriate fuel. While ammonia stands out as a short-term solution due to the convenience of storage conditions, in parallel with the development of storage technology in the medium and long term, hydrogen stands out with its harmless structure compared to ammonia. Following studies continued by considering the hydrogen as fuel.

After determining the fuel cell type and fuel, in the fourth part of the thesis, hybrid propulsion systems, their components, management styles, and architectural structures on ships are emphasized. In the published article, hybrid elements for ships are on power generators, energy storage systems, energy management systems, and hybrid system architecture, respectively. The title of power generators, diesel machines, fuel cells, and renewable energy sources (wind turbines and solar cells) are explained and studies in the literature are explained. In energy storage systems, batteries, flywheels, and supercapacitors that can be used on ships are examined. In the energy management system, the most used approaches and algorithms of rule-based and optimized management systems are introduced. The hybrid system architecture is shown in serial, parallel, and serial-parallel configurations. In the last part of the article, a generic table has been prepared in which hybrid system compatibility is established depending on the ship types. According to this table, equipment compatibility for energy storage, system architecture, and power generation for eight different ship types is shown.

In the last part of the thesis before the conclusion, the publication prepared as a book chapter is included. After reviewing hybrid systems in this publication, a case study is made. In the case study, four 100 kW proton exchange membrane fuel cells in serial architecture and only two of the four 450 kW marine diesel engine were used as power generators, and two 100 kWh lithium-ion batteries were used as energy storage devices. Mathematical models of all equipment in the system are shown, these are mechanical and electrical equipment such as shaft, electric motors, converters and speed reducers. Ship hull resistance was calculated parametrically with the Holtrop-Mennen method depending on the speed. The energy management system, on the other hand, is prepared according to the fully charged state of the battery on a rule-based basis. Depending on the power demand, the conditions for the battery to switch on and off are determined. According to the results of the analysis, fuel consumption decreased by 35% and the ship's total emissions decreased by 45% at take-off, 79% at berthing and 100% at port. On the other hand, a 31% reduction was observed in the emissions made in the steady-state sailing.



GEMİ HİBRİT TAHRİK SİSTEMLERİNİN DİNAMİK MODELLEMESİ, OPTİMASYONU VE SİMULASYON TEMELLİ ANALİZİ

ÖZET

Günümüzde, hava kirliliği, zararlı emisyonlar, küresel ısınma ve iklim değişikliği konuları hem dünyamızın geleceği hem de insan sağlığı açısından çok büyük önem arz eden meselelerdir. Küresel ölçekte düzenlenen fakat bağlayıcılığı olmayan önce Kyoto Protokolü ardından Paris Anlaşması gibi ülkeler arası sözleşmelerle emisyon seviyelerinin kontrol altında tutulması ve azaltılması hedeflenmektedir. Ancak bu sözleşmelerde hedeflenen seviyelerin aşılması gerek dünyamızın gerek insan hayatının geleceği için endişe yaratmaktadır. Atmosfere yayılan sera gazları küresel ısınmaya ve iklim değişikliğine sebep olmaktadır. İklim değişikliğinin en önemli göstergeleri, mevsim döngülerinde kaymalar, aşırı yağış veya kuraklık, buzulların erimesi, kasırga, sel gibi şiddetli doğa olaylarının yaşanmasıdır. Sera etkisi yaratan gazların başında karbondioksit gelmektedir. Aynı zamanda, diğer zararlı emisyonlar olan azot oksitler, kükürt oksitler, karbon monoksit gibi emisyonlar da asit yağmurlarına neden olup insan sağlığına da son derece zararlıdır. Dolayısıyla, karbondioksit emisyonlarının hayatın her alanında kontrol altına alınması ve hatta mümkünse ortadan kaldırılması hayati bir durumdur.

Dünya ticaretinin %90'ı deniz taşımacılığıyla yapılmaktadır. Taşınan yük bazında verimli bir ulaşım ağı olmasına karşın, artan ticaret hacmi ve gemi sayısı ile beraber gemi kaynaklı emisyonların da 2050 yılına kadar %90 ile %130 arasında artacağı öngörülmektedir. Tüm bu nedenlerden dolayı, deniz taşımacılığının emisyonları da kontrol altına alınmalı ve azaltılmalıdır. Uluslararası Denizcilik Örgütü (IMO) gemi kaynaklı karbondioksit emisyonlarının azaltılması için çalışmalar yapmaktadır. Bu kapsamda, MARPOL Ek-VI sözleşmesi ile Enerji Verimliliği Dizayn İndeksi (EEDI), Gemi Enerji Verimliliği Yönetim Planı (SEEMP) ve Enerji Verimliliği Operasyonel Göstergesi (EEOI) ile dizayn, sefer ve operasyonel verimliliği ölçücü regülasyonlar getirmiştir. Sadece bunlarla sınırlı kalmayan IMO, NO_x Kod ile belirli emisyon kontrol alanları için makine devir hızına bağlı limitler belirlemiş ve hem makine üreticileri hem de bu bölgede çalışan gemiler için belirlenen limitlere uygun makine üretimi ve kullanımını standart hale getirmiştir. Kükürt oksit ve partikül madde emisyonları için ise kullanılan yakıt içeriğine sınırlar getirilmiştir.

Gemilerin sevki için çok büyük oranda dizel makineleri kullanılmaktadır. Gemi dizel makineleri, fosil yakıt türevleri olan ağır yakıtlar kullanılmaktadırlar. Bu yakıtların kimyasal bileşeninde %85-87 oranlarında karbon bulunmaktadır. Bu nedenle dizel makinelerinde yakılan bu ağır yakıtlar sonucunda karbondioksit gazı ortaya çıkmaktadır. Çalışmalara göre denizcilik sektörü küresel karbondioksit emisyonunun %2,2'sine neden olmaktadır. Fosil yakıtların kullanılmaya devam etmesi sonucunda emisyon miktarlarının dikkate değer biçimde azaltılması ve hedeflere ulaşılması mümkün değildir. Dolayısıyla, bu emisyonların azaltılması için alternatif yakıtlar,

elektrikli veya hibrit tahrik sistemleri, emisyon azaltma teknolojileri, hız düşümü veya operasyonel iyileştirmelerle mümkün olabilmektedir.

Gemilerde enerji verimliliği temelli, tüketilen yakıtın ve dolayısıyla emisyonların azaltılmasını amaçlayan tüm operasyonlar her gemi için özel olmalıdır. Geminin kullanım alanına, gemi büyüklüğüne, gemi tipine ve operasyon profiline göre birçok değişkenin ayrı ayrı irdelenmesi gerekmektedir. Okyanus aşırı çalışan büyük bir ham petrol gemisiyle şehir içi çalışan bir vapur için alınacak tedbirler aynı olmamaktadır. Aynı şekilde, benzer kullanım alanına sahip gemiler arasında da hacimsel, alansal ve operasyon profili açısından da farklılıklar söz konusu olabilmektedir. Dolayısıyla her çalışma esas alınan gemi özelinde kalmaktadır.

Gemi ana güç üretici olarak görev yapan ve geminin hareketini sağlayan dizel makinelerinin verimleri %50 dolaylarında bulunmakta olup, yakıtın kimyasal enerjisinin ancak yarısı pervaneden alınabilmektedir. Özellikle, kısa mesafelerde çalışan ve seyir sırasında birçok kalkma ve yanaşma manevrası yapan gemilerde dizel makine yükü çok kez değişmekte ve verimli çalışma noktasından uzaklaşabilmektedir. Bu durumlarda sistem veriminin yarımın da altına düşmesi kaçınılmazdır. Bu tip gemiler için hibrit tahrik sistemi verimli sonuçlar verebilmektedir. Genel anlamda yük dalgalanmasının fazla olduğu sırada dizel motorunun yükü sabit tutularak yüksek güç talebinin elektrikle sağlanması hedeflenmektedir. Bu sayede dizel motor çalışma haritasında ideal dışı dalgalanmaların önüne geçilebilmektedir.

Bu tez kapsamında, İstanbul içerisinde Şehir Hatlarına bağlı çalışan bir vapurdan operasyon ve gemi inşa verileri toplanmış olup, bir hibrit tahrik sistemi önerilmiş ve analiz edilmiştir. Hazırlanan tez beş bölümden oluşmaktadır. İkinci, üçüncü ve dördüncü bölümler makale olarak yayımlanmış olup, son bölüm ise bir kitap bölümü olarak basımı onaylanmıştır. İlk bölüm, giriş ve çalışmanın amaç ve kapsamını belirtmektedir. Yine aynı bölümde vaka gemisinin tanıtımı ve veri toplama sürecinden bahsedilmektedir. Geminin verileri gemi üzerinde bizzat seferlere katılarak alınmış ve aynı sefer için toplanan verilerin ortalaması alınarak vaka çalışmasına konu edilmiştir. Gemide dört adet dizel motordan üretilen elektrik gücü iki adet elektrik motoru vasıtasıyla pervanelere aktarılmaktadır. Çalışma prensibi olarak dizel-elektrik olarak sınıflandırılan bu gemide kalkış ve yanaşma manevralarını kolaylaştırmak için baş pervanesi bulunmaktadır. Gemi seferi Kadıköy – Karaköy şehir hatları iskeleleri arasında yapılmıştır.

Hibrit sistemlerde birçok farklı güç üretici ve enerji depolama teknolojisi kullanılabilir. Gemi üzerinde mevcut bulunan dizel motorların yanına alternatif bir güç üretici konması fosil yakıt tüketimini azaltacağından, emisyonlara direkt olarak olumlu etki etmektedir. Bu noktada yakıt hücreleri sıfır emisyonlu güç üretme potansiyelleri ve kara taşıtlarında kullandığından dolayı öne çıkmaktadır. Fakat günümüzde ticari olarak satışı ve endüstriyel olarak kullanımı olan beş farklı yakıt pili bulunmaktadır. Bu tiplerden hangisinin ya da hangilerinin gemi üzerinde kullanılmak üzere uygun olduğu ve seçilmesi gerektiği ise bir araştırma konusudur. Tezin ikinci bölümü tam olarak bu araştırma sorusuna cevap aramak üzere hazırlanmış ve yayımlanmış bir makaledir. Bu çalışmada, alkalın, proton değişim membranlı, ergimiş karbonat, katı oksit ve fosforik asit yakıt hücreleri çok kriterli karar verme yöntemlerinden biri olan analitik hiyerarşi yöntemiyle kıyaslanmıştır. Belirlenen sekiz farklı kriter; emniyet, emisyon, verimlilik, maliyet, ömür, güç çıktısı, yakıt tipi ve ebat olmak üzere, denizcilik sektörünün farklı alanlarından on dört uzmanın anket yoluyla

görüşleri alınarak önem sırasına konmuştur. Emniyet bu sıralamada en önemli değerlendirme kriteri olurken son sırada ise ebat gelmektedir. Bu bağlamda, dizel yakıtı kullanan ergimiş karbonat yakıt hücresi ve proton değişim membranlı yakıt hücresi ilk iki sırayı almıştır. Ardından gelen çalışmalarda proton değişim membranlı yakıt hücresi kullanılmıştır.

Hibrit sistemde kullanılmak üzere yakıt pilinin belirlenmesinin ardından, denizciliğin karbonsuzlaşması temel hedefinde kullanılması gereken yakıt tipinin de belirlenmesi gerekmektedir. İçerisinde karbon ihtiva etmeyen iki çeşit alternatif yakıt bulunmaktadır; bunlar amonyak ve hidrojenidir. Bu iki yakıtın da yakıt hücrelerinde kullanılması sonucunda herhangi bir karbon emisyonu oluşmamaktadır. Fakat yine uygun yakıtın tespiti için analitik hiyerarşi yöntemi kullanılarak bu iki yakıt birçok açıdan incelenmiştir. Kısa vadeli çözüm olarak depolama şartlarının elverişliliği sebebiyle amonyak öne çıkarken, orta ve uzun vadede depolama teknolojisinin gelişmesine paralel olarak amonyağa göre sağlığa zararsız yapısıyla hidrojen öne çıkmaktadır. Ardından gelen çalışmalarda hidrojen yakıtı üzerinden devam edilmiştir.

Yakıt hücresi tipinin ve yakıtın belirlenmesinin ardından, tezin dördüncü bölümünde gemilerde hibrit tahrik sistemlerinin, elemanlarının, yönetim biçimlerinin ve mimari yapılarının üzerinde durulmuştur. Yayınlanan makalede, gemiler için hibrit elemanları sırasıyla güç üreteçleri, enerji depolama sistemleri, enerji yönetim sistemleri ve hibrit sistem mimarisi üzerinedir. Güç üreteçleri başlığı altında dizel makineleri, yakıt pilleri ve yenilenebilir enerji kaynakları (rüzgâr türbinleri ve güneş pilleri) açıklanmış ve literatürdeki çalışmalar anlatılmıştır. Enerji depolama sistemlerinde ise gemilerde kullanılabilen bataryalar, volan ve süper kapasitörler incelenmiştir. Enerji yönetim sisteminde ise, kural bazlı ve optimize yönetim sistemleri en çok kullanılan yaklaşım ve algoritmaları tanıtılmıştır. Hibrit sistem mimarisi ise seri, paralel ve seri-paralel konfigürasyonları üzerinden gösterilmiştir. Makalenin son bölümünde ise gemi tiplerine bağlı olarak hibrit sistem uyumluluğunun oluşturulduğu bir jenerik tablo hazırlanmıştır. Bu tabloya göre, belirlenen sekiz farklı gemi tipi için enerji depolama, sistem mimarisi ve güç üretimi için ekipman uyumlulukları gösterilmiştir.

Tezin sonuçtan önceki son bölümünde ise kitap bölümü olarak hazırlanan yayına yer verilmiştir. Bu yayında hibrit sistemler gözden geçirildikten sonra vaka çalışması yapılmıştır. Vaka çalışmasında seri mimaride dört adet 100 kW gücünde proton değişim membranlı yakıt hücresi ve vapurdaki mevcut 450 kW gücündeki dört makineden sadece ikisi güç üreteçleri olarak, iki adet 100 kWh enerji kapasiteli lityum iyon batarya ise enerji depolama cihazı olarak kullanılmıştır. Gemideki güç kapasitesi mevcut gemideki halinden değiştirilmemiş ve emisyonun minimize edilebileceği şekilde optimize edilmiştir. Sistemdeki tüm ekipmanların matematik modelleri gösterilmiştir, bunlar şaft, elektrik motorları, konvertörler ve devir düşürücü gibi mekanik ve elektrik ekipmanlardır. Gemi gövdesi direnci hıza bağlı parametrik olarak Holtrop-Mennen yöntemiyle hesaplanmıştır. Enerji yönetim sistemi ise kural bazlı olarak bataryanın tam şarjlı durumuna göre hazırlanmıştır. Güç talebine bağlı olarak bataryanın devreye girip çıkacağı durum şartları belirlenmiştir. Analiz sonuçlarına göre, yakıt tüketimi %35 düşmüş olup, geminin toplam emisyonu kalkışta %45, yavaşmada %79, limanda ise %100 azalmıştır. Sabit seyirde yapılan emisyonlarda ise %31 azalma gözlenmiştir.



1. INTRODUCTION

In today's world, maritime transportation has an important influence on the global trade. More than 90% of the goods are transported by ships all over the world (Harrould-Kolieb, 2008). By the way, increasing volume of the global economy, and trading goods cause an increase on the request for the new-built ships, and workload of the existing ships. For instance, according to UNCTAD, in the world, there are more than 95,000 ships with 1.97 million dead-weight tons carrying capacity. Moreover, day-by-day increasing capacity of the world fleet steers the industry to improve the transportation efficiency to compete with other competitors to have a bigger piece from the cake while the two last decades, compound annual growth in maritime trade has been 2.9% (UNCTAD, 2021).

Although shipping is more economical and environmentally friendly transportation way compared to airways, railways, and road transport per unit load, conventionally, ships use fossil-based fuels like marine diesel oil, marine gas oil, and heavy fuel oil. International Maritime Organization (IMO) states that ships consume more than 300 million tons of fossil fuel per year. Obviously, this high amount of consumed fuel causes that ships have a great influence on the environmental pollution. Specifically, according to the Fourth IMO Greenhouse Gas Study, the greenhouse gas (GHG) emissions of total shipping have increased 9.6%, from 977 million tons in 2012 to 1,076 million tons in 2018. On the other hand, the total CO₂ emissions have increased by 9.3% from 2012 to 2018. Another dramatic data shows that the share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 (IMO, 2020a). The GHG emissions are the major reasons of the global warming. Also, one of the main reasons of the climate change is the global warming which indirectly affects the human health. Therefore, one of the biggest challenges facing the maritime transportation industry is harmful emissions.

Shipping emissions are extremely important topics and notable rules and regulations are coming into force by the International Maritime Organization. The IMO has been working on emission mitigation strategies for the maritime transportation industry to

reduce ship-sourced GHG emissions. The International Convention for the Prevention of Pollution from Ships (MARPOL) convention is adopted by IMO to prevent marine environmental pollution by ships, and the scope is getting wider day by day (IMO, 2020b). The regulated emissions are CO₂, NO_x, SO_x, and PM. Energy Efficiency Design Index (EEDI) (IMO, 2012a), and Ship Energy Efficiency Management Plan (SEEMP) are the two important mandatory amendments to CO₂ emissions by IMO. Another important regulation for CO₂ emissions is the Monitoring, Reporting, Verification Regulation (MRV) entered into force by the European Union. Annual recording of the consumed fuel for carbon emission calculation for ships larger than 5000 GRT was started on 1st January 2018. Another regulated emission NO_x is under control by the NO_x Technical Code, Regulation 13 of MARPOL Annex-VI. The code entered into force in 2008 by the resolution of the Marine Environmental Protection Committee which is a sub-committee of IMO. The code limits of the nitrogen oxide emissions vary according to the main engine-rated speed. The SO_x and PM emissions are also limited under MARPOL Annex-VI. The sulfur content of the consumed fuel differentiates by the zone where the ship sails. For the determined emission control areas, the limit is 0.1% mass by mass and 0.5% for the outside since 1st January 2020 (IMO, 2020b).

The mentioned emissions are extremely harmful for all living creatures, especially when the sources of emissions are close to urban region. The exhaust gases which is a mixture of chemicals and so, air pollutants can be easily transported to highly populated centers (Walther, 2011). There are reference dose limits to predict the potential health problems according to concentration of emission in the air and exposure time of human beings to this air. Inhalation exposure to petroleum hydrocarbons indicate many risks of respiratory tract diseases and increases potential risk of developing cancer as well as chronic and acute non-cancer health effects (McKenzie et al., 2012). For instance, an emission analysis in Gothenburg by Tang et al. (2020) shows that local and international shipping reduce life expectancy by 0.015 year per person (Tang et al., 2020). The similar scenario is valid for Istanbul; the intensive ship traffic at the Bosphorus and local sea transportation units like ferries and commercial transportation boats result in high emission of air pollutants around the city. The level of air pollution is already high in crowded cities like Istanbul, and so each source of emission should be under control.

1.1 Purpose and Scope of the Thesis Study

Increasing the energy efficiency of the conventional system or changing the powering technology of the ship can lead to reducing the fuel consumption and GHG emissions from ships. When the GHG emissions are located in urban areas, the severity radically increases compared to oceanic areas. For this reason, under changing the powering system title, this thesis covers a possible hybrid propulsion system and its components for a ferry that operates in Istanbul. Therefore, a methodological approach was established by determining the main goals and objectives, and then guiding research questions were asked to bring out the responses to the objectives. The thesis is constituted of 3 articles and 1 book chapter that serves to objectives and answer the research questions.

The purpose and objectives of this thesis can be listed as follows:

- Investigating hybrid propulsion system components that are feasible and applicable to use onboard a ship that operates inland waters for urban transportation.
- Determining the optimal hybrid propulsion architecture for the selected case ship.
- Establishing a proper energy management system according to the operation profile.
- Optimizing the element sizing in the manner of power output and power split regarding the operation profile.
- Analyzing and estimating the fuel consumption and emission reduction potential of the hybrid system.

To achieve these objectives, the following research questions are tried to be answered, respectively:

- How to reduce or eliminate waterborne emissions that operate for inland transportation?
- What are the applicable and viable hybrid system components and what are the hybridization techniques that can be used for ships?
- Which fuel cell types are available and applicable in the market and what are the parameters to select the feasible fuel cell type to use on board the ship?
- If we can switch to alternative fuels, which fuel can show better performance for the decarbonization of maritime transportation?

- What is the most common equipment of hybrid systems for ships and how do select them according to ship type?
- How to optimize the power capacity, establish an energy management system and how figure out an operation profile for a ship?
- What are the advantages, disadvantages, and barriers for hybrid systems onboard ships?

By asking the research questions, and in light of answers, a ship should be selected as a case study to understand the efficiency of methodology and results of the work. Hence, “ŞH-Beyoğlu” from Şehir Hatları is selected, Figure 1.1. The ship works between Asia and Europe coasts of Istanbul. The vessel is 747.36 gross tons, she has a length of 67.96 meters with 2.95 meter draft.



Figure 1.1 : Case ship “ŞH-Beyoğlu” (URL-1).

The harbor lines can be changed by the operational management of the company. However, since the data is gathered physically onboard, during the collection of operational data, the harbors were Kadıköy-Karaköy line. Many voyages have been completed with the crew and the average of the collected data is accepted for the case study. The voyage of the ship is shown with the red line in Figure 1.2 which is a part of the Istanbul map. The right land is the Asian side (Kadıköy) and the left land is the European side (Karaköy) of Istanbul.

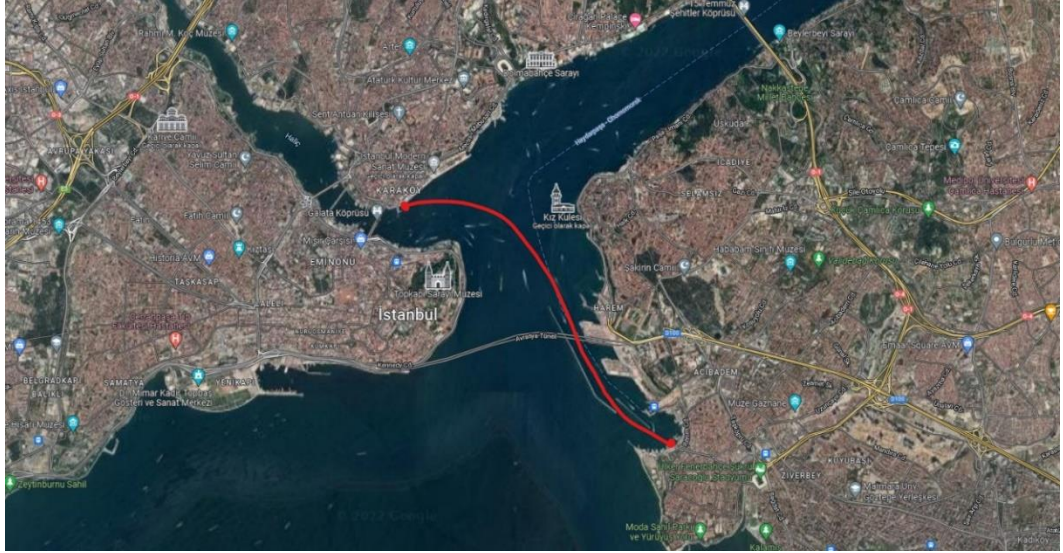


Figure 1.2 : Voyage of the case ship.

The ship is equipped with four diesel generators (Volvo Penta D16C-A MG) with 450 kW and 1500 rpm for both propulsion and hotel loads. The ship uses a diesel-electric propulsion system with two electric motors to drive two propellers with three blades. The electric motors can be seen in Figure 1.3.



Figure 1.3: Electric motors to drive the propeller of the case ship.

The diesel engines, pumps, tank entrances, filters, and electrical main control systems was in the engine room. A part of the engine room with 2 diesel generators can be seen in the Figure 1.4.

The operational data is collected at the wheelhouse as an authorized person. The engine monitoring system, and power management system was in the bridge with required data of motors, and other electrical components. Diesel engine data are also could be followed at the bridge via monitoring screens. Figure 1.5 and 1.6 are the photos of the monitoring systems for power management and engine control data, respectively.



Figure 1.4 : Part of engine room of the case ship.

Time-based operational data is also vital to reveal the operation profile. The operation is mainly divided into four section for one voyage: Departure, steady-state sailing, arrival manoeuvring and at port. The average voyage takes 24 minutes approximately while the last four is the at port condition (25. minutes is the start of the new trial). The peak power requirement happens at the end of departure when the ship totally defeats the resistance and bow thruster's cut-off, the figure 5.4 clearly shows the periods of the operation profile. Lastly, it should be noted that, the data is manually collected without connecting the computer to the ship's system.

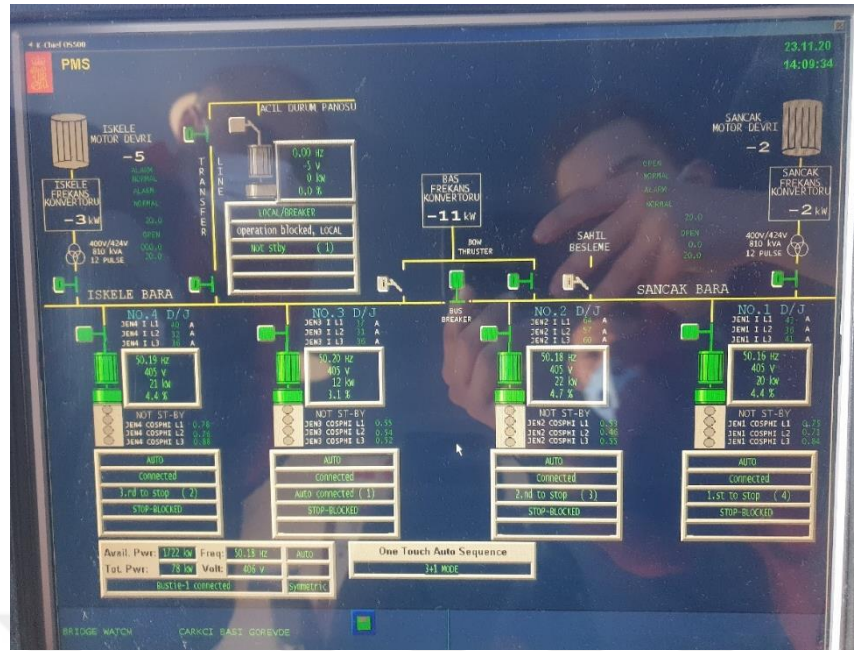


Figure 1.5 : Power management panel of the case ship.



Figure 1.6 : Diesel generators control panel.

1.2 Organization of the Thesis

The thesis study consisted of four parts. Considering the literature review, important gaps were identified and studies were carried out in this context. Each article addresses selected topics which are; (a) fuel cell selection according to ship types respecting their general operation profile by using multi-criteria decisions analysis, (b) selecting the

proper fuel to use in the selected fuel cell system which was determined at the previous article, (c) reviewing the hybrid propulsion systems, equipment, power generation, and energy storage devices and proposing a generic system selection model for different ship types, and lastly, (d) a selected case ship is analyzed for hybrid propulsion.

The thesis work consists of four chapters consisting of three articles and a book chapter. Each chapter has its introduction, methodology, discussion, and conclusions. The following sections are focused on how the article topics are selected and what are their contributions to the thesis.

1.2.1 The second chapter

The first article is named “Assessment of fuel cell types for ships: Based on multi-criteria decision analysis”.

This article aims to provide sufficient information about fuel cells to use in ships, and assess them under maritime perspective. Fuel cells are very promising and exciting technologies with their clean power generation abilities. After spending many years of research and development, the industrial use had started with small capacities of power for mobile application. However, in recent years, their use in the automotive industry especially in Far East countries and brands, causes them to be seen as an option for maritime application. The ability of producing power with zero emission is compatible with the ultimate goal of the maritime industry. Hence, availability and applicability of the fuel cell onboard ship should be elaborated for different criteria by the experts in the maritime industry.

In this perspective, fuel cell types are assessed for onboard applications. Only commercial fuel cell types are analyzed in the article; PEMFC, MCFC, SOFC, PAFC, and AFC. Eight parameters; cost, fuel types, efficiency, emissions, size, safety, power capacity, and lifetime have been chosen to detail the fuel cells for each criterion. The importance rate of each criterion is determined by the expert’s comments using Analytic Hierarchy Process (AHP) tool. Fourteen experts from different level of maritime industry have weighted the criteria according to importance of each criterion. The results of the survey show that safety, emissions, cost, lifetime, power output, fuel types, and size are important among them, respectively. Hence, the fuel cells are reanalyzed according to the results of the survey, and points are given for each fuel cell type for each attribute. Although all the fuel cells can use hydrogen as fuel, the high-temperature types, MCFC, and SOFC can use hydrocarbons (LNG and diesel oil)

as fuel also. For this reason, these two types are considered two different versions of the same fuel cell. Therefore, five main fuel cell types with two options for two them have been considered for ships.

Diesel oil using MCFC and SOFC fuel cells is advantageous from power output and fuel flexibility sides. Fuel type is very important during the comparison of fuel cell types due to maritime conditions. The oceangoing vessels have to store enough amount of fuel for long voyages, and they should have refill opportunities with sprawling bunkering nets. Therefore, although hydrogen seems disadvantageous from this point of view, PEMFC is more experienced and has a wide application area in the transportation sector, especially land-based transportation, which puts forward in order. PEMFC type is ranked marginally in the second place after diesel oil using molten carbonate fuel cells and before diesel oil using solid oxide fuel cells. The analysis shows that for long-term sea trials hydrogen cannot be considered as a solution due to hard storage conditions although it has a positive impact on the environment. However, in case of short sea voyages it can naturally be an alternative to diesel engines thanks to its environmentally friendly works.

1.2.2 The third chapter

The second article constitutes the third chapter of the thesis study, and it is named “Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia”.

This article aims to find the most appropriate fuel for zero-carbon shipping. In this manner, two promising alternative fuels, hydrogen and ammonia are evaluated to use in a fuel cell. The main reason for selecting them is due to their carbon-free structures. Although they can be burnt in diesel engines, the requirement for a pilot fuel makes the ultimate zero-carbon emission goal impossible. Therefore, using these fuels in the fuel cells becomes mandatory and only option.

The methodology followed in the article is similar to the previous article. The attributes safety, cost, storage, environmental impact, and sustainability are chosen to compare the selected fuels. The weightings of each criterion are found by using the AHP tool and a sensitivity analysis is carried out for findings. As a preliminary analysis, different techniques for propulsion powering the ships are revealed under four subtitles: fuel cell, diesel engine, renewable energy, and battery. All available fuel types are considered for both fuel cell and diesel engines however only ammonia and hydrogen

can show zero-carbon characteristics. The diesel engine is also becoming out of scope due to the pilot fuel problem as mentioned before. On the other renewable energy and battery are strong alternatives for ammonia and hydrogen fuel cells with their zero-carbon structures. However, the technological maturity of renewable energy and the limited energy capacity of batteries drive them to be the second option for shipping applications.

For the selected fuel types, the attributes are lined as follows: safety and environmental impact at the first places then, sustainability, storage, and cost, respectively. Safety is considered as threats like explosion or fire with impact on human life, equipment, and environment. Environmental impact is considered as operational emissions and production emissions. Since both alternatives have carbon-free structures, production emissions are gaining importance. For the sustainability criterion, bunkering infrastructures and global availability are considered reference points. Although both ammonia and hydrogen have similar positions in global fuel availability, ammonia has easier bunkering infrastructures conditions compared to hydrogen. A similar approach can be followed for the storage criterion also, the liquid form of hydrogen requires a cold and compressed environment. The energy requirement is relatively higher than ammonia and also both have lower volumetric energy density compared to conventional marine fuels. Cost is the last criterion to compare the fuels by considering the production and storage cost of the options.

At last, by giving the points and calculating the weights of the fuel types, ammonia showed better performance than hydrogen for short-term and long-voyage shipping. Easier and more reliable storage conditions for ammonia with current technological maturity are the primary advantages against hydrogen. Since the comparison and analysis are a generic approach to the shipping industry, therefore, a case base analysis can change the results to apply the alternative fuel.

1.2.3 The fourth chapter

The third article forms the fourth chapter of the thesis study and it is named “Hybrid power and propulsion systems for ships: Current status and future challenges”.

This article reviews the power generation methods, energy storage equipment, energy management systems, and hybrid propulsion topologies. Then, according to the analysis of the systems, a generic methodological approach is followed according to ship structural and operational types. The power generation methods are investigated

under three sub-titles; firstly, the most common way of the onboard power generation solution, internal combustion engines, mainly marine diesel engines are elaborated with different fuel types, general operations, emissions, and future challenges. Although marine diesel engines are the major driver for the propulsion power of the ships (more than 90%) current and also incoming emission limitations seem as substantial technical obstacles for the future of the shipping industry. Marine diesel oil, marine gas oil, and heavy fuel oil are the three important fuel types of diesel engines and all are fossil-based. Therefore, emission abatement technologies such as scrubbers, exhaust gas recirculation, or selective catalytic reduction become mandatory to operate the ships environmentally-friendly. However, not only emission reduction but also alternative propulsion powering systems are some strong options. Secondly, energy storage devices are also investigated under three sub-titles; batteries, supercapacitors, and flywheels. In this perspective, hybridization of the diesel engines with the reviewed energy storage devices and with other power generation methods like fuel cells or renewable energy sources are gaining importance. From the energy storage side, batteries and supercapacitors lead the maritime industry that technologically follows the automotive sector. While supercapacitors are more efficient for short-term power supply, batteries are advantageous at the capacity side. Thirdly, energy management strategies of the hybrid propulsion systems are summarized as rule-based and optimized techniques. The pros and cons of the different strategies are compared, then rule-based and optimized energy management techniques are described.

Hybrid propulsion architectures are also reviewed in this chapter. There are 3 main topologies to connect the different levels of energy devices; serial, parallel, and serial-parallel. If the equipment is connected to a common main bus bar and this bar feeds the electric motors, it is called a serial configuration. But, if a power source is alternatively connected to propellers instead of the main bus bar, it is called a parallel configuration. At last, if a power or energy source shows both characteristics, it is named serial-parallel. All configurations have different properties, advantages, and disadvantages when compared between them. Their place of use is also different and directly depends on the ship's properties. Therefore, to decide the correct topology, the ship engine room volume, and operation profile must be analyzed properly. For this reason, at the end of this article, eight different ship types are discussed in energy storage, power generation, and hybrid topology manners. Since the different

operational profiles require different hybridization approaches, a generic methodological approach is formed with the evaluation of possible components.

1.2.4 The fifth chapter

The fifth section of the thesis is a book chapter named “Electrification and hybridization of ferries: State of the art and case study”.

The chapter uses the knowledge of the previous works and makes an analysis of the case ship which operates at the Bosphorus. The case ship’s “ŞH-Beyoğlu” operational data has been gathered onboard the ship by accompanying the voyages.

First, a brief review of the hybrid systems, their components, and power management strategies are studied. Following this, the case study is started with the ship's properties. The architectural properties of the ship are given in table form, and the ship’s general power generation characteristics are summarized. The most important data, the ship’s operation profile is revealed under the power-time diagram. The diagram (Figure 5.4) clearly shows the peak power zones, sailing duration, sailing stages, and minimum required load. The ship is equipped with bow thrusters for rapid and easy maneuvering. The increased maneuvering ability also causes increased power needed during departure and arrival maneuvering. In the current system, the peak power is supplied by increasing the load of the diesel engines, and it causes an to work inefficient area. Therefore, hybridization of the case ship seems as meaningful in the preliminary analysis.

Secondly, the chapter continues with the modeling steps of the hybrid equipment. The equipment is decided with the aim of minimizing transportation emissions. Also, the sizing of the equipment is considered according to ship size, engine room volume, and power needs during the operation. Respecting the previous studies’ results, hydrogen using PEMFC is selected. Furthermore, a battery system is also added to shave the peak loads. The amount of diesel engines, which was four, is also reduced to two owing to additional power generators like batteries and fuel cells. So, for the powering side of the model, the diesel engine, battery, and fuel cell mathematical models are shown in this chapter. Then, the additional electrical and mechanical equipment models are summarized like converters, shafts, hull, propellers, reduction gear, and electric motors. The Hull model is prepared and ship resistance is calculated according to the Holtrop-Mennen technique. Lastly, a rule-based energy management strategy is established for the power management of the ship according to the revealed operation

profile. Diesel engine load is set for the most efficient point by minimizing the specific fuel consumption by shutting down during at the port and night. The fuel cell is established to work all the time owing to the ability of clean power generation. A more specific energy management system is established for batteries respecting their state of charge position as can be seen in Figure 5.11. The battery is acting differently for each state of the charge level in coherence with the total power demand data that comes from the operation profile. The operation is divided into four sections; departure, steady-state sailing, arrival, and port. The fuel consumption and emissions are calculated for each step of the operation, and the reduction amount and ratios are given in the conclusion section of the paper.

1.2.5 The interaction of the studies in the general layout

Ship energy chain constitutes complex and different levels of energy domains containing various sub-systems. This is why the ship energy distribution system is separated into different sections to clearly show the systems and their interactions. The articles that form the whole thesis study investigate different parameters of the ship energy chain under technical feasibility, system selection, emission reduction, and energy efficiency point of view.

The ship hybrid powering system is categorized under six categories: fuel types, power generation, energy storage, consumers, system topology, and energy management. Each category has different subtitles with different characteristics. For instance, while the fuel types are about physical fuel storage and bunkering, system topology and energy storage are about electric energy distribution. Figure 1.7 represent the methodological approach of the articles and their interactions for the whole thesis study.

As can be seen in the figure, the power generation sub-system is divided into three; diesel engines, fuel cells, and renewable energy sources. Diesel engines are one of the greatest power generation technology considering the high industrial experience with high bunkering nets. Also, hybridization with diesel engines is the popular approach due to their advantageous operability both in industry and literature. Secondly, fuel cells are also divided into five commercial types. The first article, which is the second chapter of this thesis study is focused on this part by investigating the most feasible fuel cell types for fuel cell-equipped hybrid propulsion systems. Lastly, renewable energy is considered as the third option but since the system requires additional

architectural design and is highly depended on the natural conditions, all-year availability is found weak to investigate on the case ship.

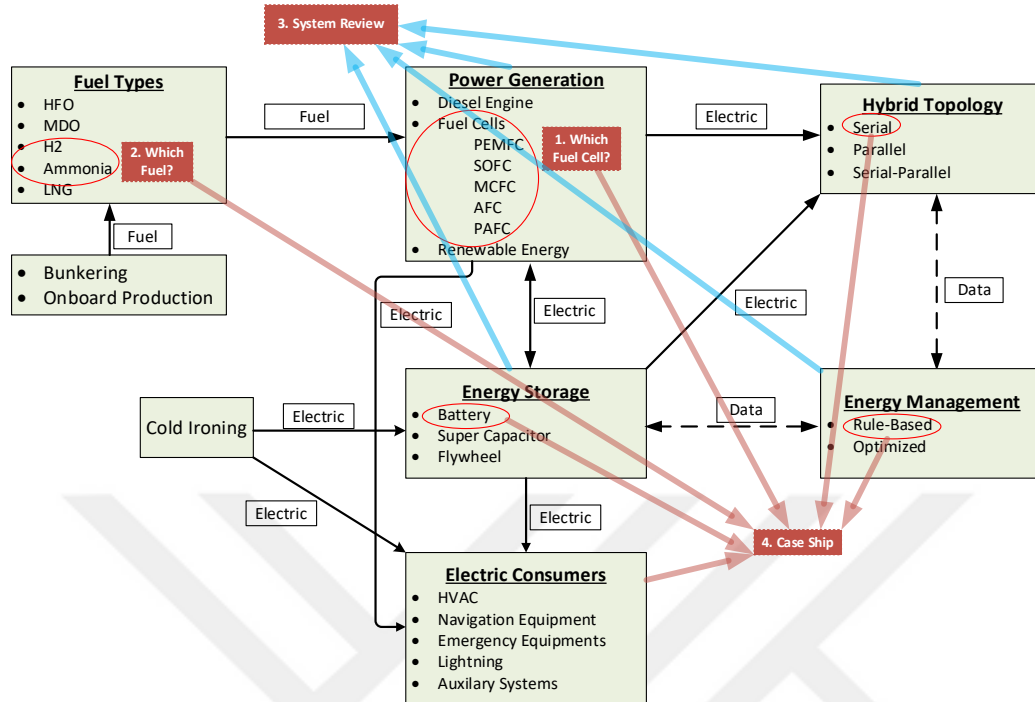


Figure 1.7 : Interactions between studies.

The second sub-system is fuel types, and the most common conventional and alternative fuels are listed as heavy fuel oil, marine diesel oil, hydrogen, ammonia, and LNG. The second article which is the third chapter of this thesis study is focused on the fuel selection to use in the fuel cell. The fuel cells mainly use hydrogen in the pure form but, ammonia can be used as a hydrogen carrier after proper dehydrogenation which leads to hydrogen and nitrogen as major products. The other fuel options are not evaluated due to the weak performances to use in the selected fuel cell in the previous article. Moreover, the idea is the decarbonization of inland sea transportation and the analyzed fuels are the only options with their carbon-free chemical structure. Thirdly, energy storage is considered another sub-system for a hybrid ship. Batteries, flywheels, and supercapacitors are the major driver options to store electric energy for maritime applications. Only flywheels store the required energy in kinetic form but they are not widely applicable for shipping. All energy storage options are reviewed in the third article which forms the fourth chapter of the thesis. Fourthly, the hybrid system architecture is divided into three: serial, parallel, and serial-parallel. The differences, pros, and cons are reviewed in the third article by reviewing the literature. Energy management of the hybrid system is another sub-system with rule-based and

optimized control strategies. With the energy storage, hybrid topology, and power generation sub-systems, this topic is reviewed in the third article. Finally, the fourth publication, the book chapter, forms the fifth chapter of the thesis that includes the results of the previous studies for a case study. In the case study, hydrogen using PEMFC is hybridized with batteries, and diesel engines are managed with rule-based energy management by connecting serially to the propellers. The red arrows are the components that are analyzed during the study.





2. ASSESSMENT OF FUEL CELL TYPES FOR SHIPS: BASED ON MULTI-CRITERIA DECISION ANALYSIS¹

2.1 Introduction

Sea transportation constitutes the most significant portion of the transportation sector with a 90% share of global trade (Deniz and Zincir, 2016; Harrould-Kolieb, 2008). Therefore, the national and international shipping industry consumes the largest amount of fuel in the transportation sector (Deniz and Zincir, 2016). This consumed fuel produces vast amount of greenhouse gases (GHG) and regulated emissions such as; nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), carbon dioxide (CO₂) and particulate matter (PM), which are known to play a great role in climate change and air pollution. According to the Third IMO GHG Study 2014, international shipping emitted 796 million tons of CO₂ and this is about 2.2% of the global carbon dioxide emissions in 2012, besides, shipping sourced NO_x and SO_x emissions are 15% and 13% of global emissions in that year, respectively. Therefore, as a result of the growth in global trade, shipping emissions are likely to continue to increase (Fan et al., 2018).

The shipping industry is under pressure to reduce its GHG emissions. Thus, IMO constituted the International Convention for the Prevention of Pollution from Ships (MARPOL), Annex VI Regulations for the Prevention of Air Pollution from Ships as the global strategy for reducing shipping emissions (Ling-Chin and Roskillly, 2016; Moreno-Gutiérrez et al., 2019). From this perspective, according to IMO, Tier III NO_x emission limits have already been applied in emission control areas (ECAs) since 2016 and outside the ECA zones, it is entered into force in 2020. Besides, the global sulfur cap will be reduced from 3.5% to 0.5%. It will be difficult for the shipping industry, to stay under new emission limits with conventional diesel engines (Brynnolf et al.,

¹ Inal, O.B., Deniz C. 2020. Assessment of Fuel Cell Types for Ships: Based on Multi-Criteria Decision Analysis, Journal of Cleaner Production, Volume 265, 2020, 121734. <https://doi.org/10.1016/j.jclepro.2020.121734>

2014; Dere and Deniz, 2019). Therefore, the shipping industry needs an efficient and clean energy production alternative for internal combustion engines.

Diesel engine constitutes the bigger part of the main power systems in the shipping industry, which produces electricity or propelling power by converting the chemical energy of fuel via thermal and mechanical energy. However, in fuel cell systems, the chemical energy of the fuel is converted directly into electrical energy. So, the non-presence of high-temperature combustion causes the lesser NO_x formation. In addition, lesser mechanical parts reduce noise and vibrations. Furthermore, the flexibility of fuel type for fuel cell systems gives opportunity to reduce SO_x and CO₂ to ship owners while navigating in ECA zones.

Fuel cell technology is a very promising technology related to its high energy efficiency and low environmental impact (Yan et al., 2020). Fuel cells are outstanding innovations for electric power generation with a high potential for versatile applications specifically for shipping (Álvarez Jordán et al., 2018; Cruz Champion and Kabelac, 2017). Hydrogen fuel cells are in use especially in first fuel cell vehicles, as portable power and backup power (Pratt and Klebanoff, 2016). In comparison to internal combustion engines, fuel cells have dramatically lower emissions with higher efficiency (Sohani et al., 2020; Bicer and Dincer, 2018). Fuel cell technology studies in the maritime environment offer an insight into the potential commercial applications in the future. Furthermore, there are several projects have been demonstrated and tested on ships. These studies have variations from the usage of the fuel cell for electric supply of the ship, to the main propulsion unit while using different types of fuel like hydrogen, diesel or LNG (McConnell, 2010; Tronstad et al., 2017). In another study, it was reviewed of fuel cell systems for maritime applications by some performance criteria such as fuel consumption, power, and energy density, load-following capabilities and environmental impacts (van Biert et al., 2016). Moreover, fuel cells to grid interface and electrical configurations are also reviewed and trends are revealed (Inci and Türksoy, 2019). Despite all this study, fuel cell system and selection parameters are not clearly proposed to retrofit or new built ships. Also, there is any investigation for fuel cells from the maritime operability perspective. Since maritime conditions are different than land-based facilities; fuel type due to global bunkering availability, then land-based transportation, the ranking shows a substantial separation for ships. Furthermore, emission and size seem important for vessels in comparison to power stations due to limited space onboard and regulations. This investigation brings

a novelty from a shipping perspective and elaborates on the usage of fuel cells for maritime.

The aim of the paper is to find and investigate the parameters of fuel cell types for the specification of which would be the most promising one among different types. In this study, fuel cell types which can be used in merchant vessels were analyzed. Since there is not a typical capacity ranges classification for ships in literature, maximum 5-megawatt main engine power is assumed. Comparison criteria such as cost, efficiency, fuel type, emission, safety, size, power capacity and lifetime are defined from maritime perspective and a comparison method, analytic hierarchy process, is applied to find the most suitable fuel cell type which can be put into operation. Experts from maritime industry; marine chief engineers, ship captains, naval architects, academicians and technical managers from shipping companies were ranked the criteria according to importance for using and selecting the fuel cell system onboard. As a result, diesel oil using molten carbonate fuel cell is found as the most suitable fuel cell type for ship applications by a close margin against proton exchange membrane fuel cells.

2.2 Fuel Cell Types

2.2.1 Proton Exchange Membrane Fuel Cell (PEMFC)

PEMFC is the most flexible fuel cell type and it has the largest range of application, so, they become the most promising cell to spread in applications (Sharaf and Orhan, 2014). The PEM type fuel cell has platinum-based electrodes and the electrolyte is an ion exchange membrane, which perfectly transfers protons but an electric insulator (Tronstad et al., 2017). The operating temperature is generally between 65 - 85 °C and the fuel cell must work under 100 °C because of the water, which is produced in cathode side (Dai et al., 2009). To provide the porosity for protons, the membrane needs to stay humid. The PEM uses hydrogen as a fuel and in presence of oxygen it produces water, moreover, electricity and heat due to an exothermic reaction.

The proton exchange membrane fuel cell has a relatively low working temperature which provides flexible operation and less stringent material requirements that makes the research and development focuses on it. The efficiency of the PEMFC system is around 50-60% (Tronstad et al., 2017). For the efficient working of PEMFC pure hydrogen must be fed into the cell because of the platinum catalyst can be poisoned by carbon monoxide (Baschuk and Li, 2001). Hydrocarbons can be used as a fuel but, as

stated before, due to low tolerance to carbon, fuels have to pass from a steam reforming unit and subsequent water-gas-shift system to ensure the purity of fuel (Sasank et al., 2016). The disadvantages of PEM fuel cells are the need for platinum as a catalyst, difficulty of water management in cell and use of pure hydrogen as fuel. PEM fuel cells are generally used in automotive and portable applications.

Another important development for PEMFC is the high operating temperature version which is less mature than low temperature option. This type can operate up to 200 °C and is less sensitive to carbon included fuels in comparison with conventional PEM types. The high temperature type is addressing some of the problems of conventional PEM like, sensitivity to impurities and water management (Tronstad et al., 2017). The higher temperature lessens the affectability towards impurities and provides to feed carbon included fuels after extraction of hydrogen in a reforming unit. This allows to use carbon included fuels like diesel oil, LNG or methanol. Also, water management is simplified since the water passes to gas phase due to high temperature.

2.2.2 Alkaline Fuel Cell (AFC)

Alkaline fuel cell is the first fuel cell developed in 1939 by Bacon (De-Troya et al., 2016). In general power output is 1-5 kW, however recently some test reports of stationary AFCs can reach to 200 kW (Tronstad et al., 2017). AFC's electrolyte is alkaline and as electrode it uses nickel for anode and silver for cathode. As the fuel cell name implies the electrolyte is an alkaline solution generally potassium hydroxide (KOH), hydroxyl ions (OH⁻) are transported through the electrolyte from the cathode to anode and its working temperature is generally below 100 °C (De-Troya et al., 2016). The AFC tolerance is nearly zero for carbon dioxide (CO₂) due to the reaction with electrolyte so, the hydrogen and oxygen must be pure before entering to cell unit. Because of the basic characteristic of the electrolyte and acidic carbon dioxide can react and produces solid potassium carbonate particles, as a result, this reaction reduces the concentration of the electrolyte and reduces the efficiency of the cell, which can be considered as a disadvantage. The alkaline fuel cells are mostly used in NASA space shuttles related to their pure water and heat production. This type of fuel cell is relatively low cost with low-cost catalyst (Tronstad et al., 2017). Moreover, low temperature working, low weight and volume and simple operation principles can be seen as advantages (Andújar and Segura, 2009)

2.2.3 Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cell operates at high temperatures between 150 to 220 °C (Saxena and Anurag, 2015). PAFC uses phosphoric acid in liquid form as electrolyte. Also, in this fuel cell type, the fuel which enters from the anode side, ionizes via catalyst. The protons (H^+) move to cathode side through liquid phosphoric acid electrolyte. In presence of oxygen and with the electrons coming from external circuit they produce water at the cathode. According to data, which were collected from experiments, the electrical performance is about 38 - 40% and thermal performance is around 40 - 45%, therefore, total performance can reach to 85% in combined systems (De-Troya et al., 2016). Due to higher working temperatures, hydrogen is not only the fuel source for PAFC, hydrocarbons such as liquefied natural gas and diesel fuel can be used (Tronstad et al., 2017). The hydrocarbons need to be reformed before entering the cell. However, after reforming unit some carbon dioxide and NO_x will be occurred.

The efficiency of PAFC is not limited just with electrically, with heat recovery combined system its efficiency is relatively higher than PEMFC and AFC. Besides, the higher temperature makes it less sensitive to carbon monoxide. In spite of these advantages, PAFC has low power density. So, for the same power generation, the system will be larger and heavier (Mench, 2008). Moreover, because of high operation temperature PAFC start up is slower (Saxena and Anurag, 2016).

2.2.4 Molten Carbonate Fuel Cell (MCFC)

The molten carbonate fuel cell is another high temperature working fuel cell and it operates approximately between 600 – 700 °C (Marefati and Mehrpooya, 2019). This high temperature provides an effective ion conductivity, furthermore minimizes the needs for high cost catalyst such as platinum. The electrolyte is a mixture of a molten alkali metals carbonates (Mench, 2008). The carbonate ions (CO_3^{2-}) consumed in the anode follow out the transportation (De-Troya et al., 2016). Nickel at the anode and nickel oxide at the cathode can be used as electrodes. Thanks to high working temperature MCFC can reach to high total efficiencies. The flue gases can be used after cell exit via gas turbines or steam turbines. The electrical efficiency is around 50 – 60% however with a cogeneration systems, as mentioned before for PAFC, the total efficiency can reach to 85% (Tronstad et al., 2017). The high temperature makes the MCFC more flexible from fuel perspective. Differently from the PAFC, molten

carbonate fuel cell does not need a reforming unit for hydrocarbons fuels, because the reforming occurs in the fuel cell. Slow start-up, low power density, and related to high temperature high corrosion and cracking of components can be claimed as disadvantages for MCFC. The MCFC type fuel cell using area is generally focused on the high energy demanding areas.

2.2.5 Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cell is one the high temperature working fuel cells. Its working temperature is between 800 – 1000 °C (Marefati and Mehrpooya, 2019; Mench, 2008). Solid oxide fuel cells use solid state yttrium stabilized zirconia as electrolyte. Same as with molten carbonate fuel cells, solid oxide fuel cells use a nickel alloy as the anode, however the cathode is made of lanthanum strontium manganite (Tronstad et al., 2017). Electrical efficiency of SOFC is changing between 50 – 60%, but as MCFC due to high temperature SOFC can be used in the heat combined systems and the total efficiency can reach to 75 – 80% (Tronstad et al., 2017). As a result of this high temperature, SOFC does not need expensive catalysts as PEMFC.

Differently than others, the SOFC has two possible geometries; planar and tubular (De-Troya et al., 2016). The planar SOFC is the same with other types; an electrolyte between two electrodes. But, in a tubular SOFC, the inner and outer tubes are the electrodes and between them, there is an electrolyte. Airflow is the inside and fuel is fed from the outer side of the cell. The planar SOFC has a higher energy density and it is easier to produce. The most important advantage of the SOFC is the highly efficient electric generation and during this operation, it produces waste heat at high quality. Also, the SOFC has multiple options of fuel such as LNG, methanol, hydrogen, and hydrocarbons as diesel. The reforming of the fuel occurs in the cell unit (Tronstad et al., 2017). The SOFCs are generally used in high capacity power generation facilities and for alternative power sources.

2.3 Comparison Criteria for Fuel Cells

In order to compare fuel cells for onboard use, firstly, criteria are determined and fuel cell types are evaluated and ranked for each criterion. Secondly, a matrix table is constituted taking into consideration evaluation scales. There are five evaluation scales for each comparison criteria, given in table 2.2. Comparison criteria are selected by

considering cost, efficiency, fuel type, emission, safety, size, power capacity and lifetime.

Table 2.1 : Summary of fuel cell types (Inal and Deniz, 2018; Sharaf and Orhan, 2014; Tronstad et al., 2017; van Biert et al., 2016; Welaya et al., 2011)

Fuel Cell Type	Fuel Options	Emissions	Efficiency	Operation Temperatures
Alkaline Fuel Cell (AFC)	Hydrogen	Water	%50-60	50 – 230 °C
Phosphoric Acid Fuel Cell (PAFC)	Natural Gas, Diesel, Hydrogen	CO ₂ if carbon included fuel is used.	%40-50	150 – 220 °C
Molten Carbonate Fuel Cell (MCFC)	Natural Gas, Diesel, Hydrogen	CO ₂ if carbon included fuel is used.	%30-70	600 – 700 °C
Proton Exchange Membrane Fuel Cell (PEMFC)	Hydrogen	Water	%40-60	50 – 130 °C
Solid Oxide Fuel Cell (SOFC)	Natural Gas, Diesel, Hydrogen	CO ₂ if carbon included fuel is used.	%40-70	500 – 1000 °C

Table 2.2 : Evaluation scales.

Evaluation Scale	Indication
1	Worst
2	Worse
3	Moderate
4	Fairly Well
5	Best

2.3.1 Cost

Fuel cells have not a prominent market share due to their high cost compared to diesel engines, but many companies see the potential to lessen the expense (Garche and Jörissen, 2015; van Biert et al., 2016). In this regard, the US Department of Energy

forecasts that direct hydrogen PEM fuel cell stacks cost will be reduced nearly \$45/kW, when manufactured at a volume of 100,000 units per year and \$45/kW at a volume of 500,000 units per year by 2020 and 2025 (Marcinkoski et al., 2017). This cost indicates that fuel cells can compete with diesel engines in the near future (Pratt and Klebanoff, 2016). In this section, the cost is divided into two sections as capital expenditures (CapEx) and operational expenditures (OpEx) during the application of fuel cells onboard. CapEx is the investment cost including fuel cell unit, fuel storage and system components such as compressors, pumps, piping and safety systems. However, system components are not constituting the major CapEx difference, so the main cost criteria will come from the fuel cell unit and fuel storage. Fuel options for fuel cells are mainly hydrogen, LNG and diesel oil. Diesel oil is already one of the main logistic fuel for shipping since years and storage condition seems more affordable and well-proven against the other options. From the LNG and hydrogen part, the major cost driver for all types of vessels in the storage tanks. Specifically for LNG, depending on the tank capacity, the capital expenses can vary between 5 to 20 million USD (Schinas and Butler, 2016). On the other hand, the same problem goes for hydrogen. The three main hydrogen processing and transportation procedures are compression of hydrogen (CGH₂), liquefaction of hydrogen (LH₂) and hydrogenation of carrier substance (LOHC) which are more expensive than the conventional fuel storage system (Teichmann et al., 2012). Despite the higher cost of hydrogen storage, diesel oil and LNG require a fuel processing unit to obtain hydrogen to use in fuel cell systems, so, this increases the cost and complexity of the system.

OpEx is operational costs, which include maintenance cost and fuel cost. The effect of the maintenance cost on the OpEx is much lower than fuel price and annually it is close among fuel cell types (Steward et al., 2009). Therefore, fuel types price must be reviewed. Despite the storage cost advantage of diesel oil, LNG price is lesser in maritime. However, this situation is different for hydrogen. Nowadays, hydrogen bunkering is not a common application for commercial ships, by the way, it is very expensive. Therefore, it seems like onboard hydrogen production is a strong option as a solution to overcome this issue which increases the CapEx.

2.3.2 Fuel types

Although the main fuel of fuel cells is hydrogen, as mentioned earlier, several types can use diesel fuel and LNG. Therefore, all three types of fuels were examined as a

fuel possibility. Properties of hydrogen, LNG and diesel fuel are given in table 4 and it shows differences between fuel options.

2.3.2.1 Hydrogen

Hydrogen is the most plenteous element in the universe, yet is infrequently found in pure structure (Schlapbach and Züttel, 2001). Hydrogen is the main fuel option for fuel cells and can be obtained from various sources such as diesel oil, natural gas, biomass or electrolysis. Hydrogen has a low storage density and this is a major disadvantage from a logistic fuel perspective. Hydrogen is often stored in high pressurized tanks or cryogenic at a temperature of $-253\text{ }^{\circ}\text{C}$ (Durbin and Malardier-Jugroot, 2013). Alternatively, the two other methods; metal hydrides and chemical compounds are still under investigation and commercially are not available for merchant vessels (van Biert et al., 2016). On the other hand, LNG and diesel oil should also be seen as the hydrogen carriers for fuel cells due to their fuel processing and indirect use.

2.3.2.2 LNG

Natural gas comprises paraffinic hydrocarbons such as methane, ethane, propane, and butane (Deniz and Zincir, 2016). It is underuse of two physical aspects; liquefied natural gas which is formed by chilling of the natural gas to $-162\text{ }^{\circ}\text{C}$ and compressed natural gas (CNG) by pressurizing with 250 bar (Elgohary et al., 2014). However, when necessitated spaces for LNG and CNG storage are taken into consideration, LNG is, for the most part, utilized onboard ship. As a result of LNG contains hydrocarbons, CO₂ and NO_x emissions can occur. Notwithstanding, LNG using fuel cell emissions are substantially lower than conventional diesel engines. Moreover, LNG as a fuel also decreases the harmful emissions except for carbon monoxide in conventional engines. LNG is offering moderate environmental benefits and can be feasible to satisfy ship emission rules in the short-term (Balcombe et al., 2019). Related to many studies on the effects of LNG and hydrogen on diesel engine performance and emissions are shown in table 2.3.

2.3.2.3 Diesel oil

Diesel oil can be used in high temperature working fuel cell which, do not require high impurity of fuel. Among the fuel options, the highest carbon content belongs to diesel oil; as a result, CO₂ emission will occur in comparison with other fuel types. On the

other hand, the main reason for the SO_x emissions from ships, sulfur content is highly found in diesel oil in comparison with other fuels. On-board conversion of diesel oil to hydrogen is required to use in fuel cell systems, because of the wide range of bunkering options compared to hydrogen, which is significantly more expensive. However, the conversion of diesel oil to hydrogen needs a fuel processor which increases complexity and the cost of the system. Despite its disadvantages on emissions, diesel oil is a well-known and highly recognized conventional fossil fuel in the maritime industry. Global bunkering opportunities and easier onboard storage availability are the strong elements of this fuel type. Furthermore, biodiesel is also a strong option due to its specialties like renewability or non-toxicity. Utilization of biodiesel reduces sulfur oxide and GHG emissions in comparison to fossil-based fuels (Chuah et al., 2017).

Table 2.3 : Properties of fuel alternatives for fuel cells.

	Unit	Diesel Oil (Heywood, 1988; Deniz And Zincir, 2016)	Lng (Herdzik, 2011; Elgohary Et Al., 2014; Sroka, 2007)	Hydrogen (Deniz And Zincir, 2016; Zincir And Deniz, 2014; Sroka, 2007)
Density	(Kg/M ³)	833-881	450	0.0838
Lower Heating Value	(Mj/Kg)	42.5	46 – 50.2	119.9
Stoich. Air-Fuel Ratio On Mass Basis		14.5	17.2	34.3
Carbon Content	(Wt %)	85	75	0
Hydrogen Content	(Wt %)	15	25	100
Oxygen Content	(Wt %)	0	0	0
Sulphur Content	(Wt %)	<350 Ppm	0	0

2.3.3 Efficiency

Generally, fuel cell efficiency is greater than conventional diesel engines (De-Troya et al., 2016). Fuel cells have a total electrical efficiency between 50-65% (Barbir, 2005). In contrast of diesel engines, the direct conversion of chemical energy of the fuel mainly constitutes this higher efficiency, instead of converting thermal and mechanical, respectively. The efficiency advantage can be greater for high temperature working fuel cells such as SOFC and MCFC with different cogeneration units (Tronstad et al., 2017). The produced hot air by fuel cell, in the meaning of exhaust gas, can be utilized via gas or steam turbine systems for an additional electric generation. In this case, total efficiency of the system can reach to 70 – 80% (De-Troya et al., 2016). This type of fuel cells has also other fuel alternatives, different from hydrogen, such as natural gas and diesel oil. Reported electrical efficiencies based on LHV and related to fuel type, which are given in table 2.4.

Table 2.4 : Reported electrical efficiencies of fuel cells related to different fuel types.

Fuel Cell	Diesel Oil (%)	Natural Gas (%)	Hydrogen (%)
PEMFC (Van Biert et al., 2016)	30 – 40	35 – 45	40 – 60
MCFC (Van Biert et al., 2016)	29 – 54	40 – 55	–
SOFC (Aguilar et al., 2008; Van Biert et al., 2016; Kazempoor et al., 2009; Lanzini et al., 2017)	45 – 55	45 – 60	42 – 67

2.3.4 Emissions

Emission is the key concept for the utilization of fuel cells in maritime. The alternative fuel cells have various effects on emissions depending on their fuel usage. Hydrogen using fuel cell types only emits water. However, fuel cells like SOFC, PAFC or MCFC can also put into operation carbon included fuels like diesel or LNG after a fuel processing unit. Using hydrocarbons gives a flexibility for fuel usage and it seems cost effective than hydrogen (Mohammed et al., 2019). Moreover, on board storage is easier and well proven than hydrogen. In this case, CO₂ and low levels of NO_x occur

as emission in addition to water and heat (Choudhury et al., 2013). Especially for alkaline fuel cells and proton exchange membrane fuel cells' pureness of hydrogen and supply air is very important. In any case of using carbon included fuel, electrolyte reacts and it reduces the effectiveness of fuel cell. As a reason of hydrogen storage difficulties on board, fuel flexibility becomes more attractive. So, for maritime application SOFC, MCFC or PAFC seems more advantageous than other types of fuel cells.

2.3.5 Size

There are two options to compare size of fuel cells, either specific power or power density. Equation (2.1) and equation (2.2) show the specific power and the power density, respectively.

$$\text{Specific Power:} \quad \frac{kW}{kg} = \frac{\text{Output Power}}{\text{Mass}} \quad (2.1)$$

$$\text{Power Density:} \quad \frac{kW}{m^3} = \frac{\text{Output Power}}{\text{Volume}} \quad (2.2)$$

The objective is to reach to maximum value for both, meaning the fuel cell has relatively less mass with small volume with maximum power output. Fuel cells require auxiliary equipment such as pumps, blowers, power conditioning equipment etc. and this is called as a system by manufacturers. So, calculations for system will be more accurate to determine the correct specific power and power density for onboard applications. Power density comparison of fuel cell types is shown in Table 2.5. A number of studies have found that PEMFC has the highest power density, besides PAFC and SOFC are the lowest.

Table 2.5 : Power density comparison of fuel cell types (Pratt and Klebanoff, 2016; Tronstad et al., 2017)

Fuel Cell Type	Relative Power Density (kW/m ³)
PEMFC	Very High
SOFC	Low
MCFC	Medium
AFC	High
PAFC	Low

Another point of view for size of fuel cells includes fuel processing and hydrogen obtaining systems for high temperature working fuel cells. MCFC or SOFC need an additional fuel conditioning system to use diesel oil or LNG as fuel and this causes an increase both volume and mass, so it reduces power density.

2.3.6 Safety

The major fuel cell safety issue is related to high-temperature exhaust gases and electricity production. Especially for SOFC and MCFC, the exhaust gas temperature is relatively higher than the other types. During the discharge of exhaust from the fuel cell, pipes must have a double layer and effectively insulated to prevent any leakage (Pratt and Klebanoff, 2016). Additionally, internal equipment like membrane, electrolyte, and electrodes must be maintained in good condition to reach the maximum efficiency and safer operation. In any case of leakage of electrolyte from the cell unit, it will be hazardous to human life. Secondly, as an additional precaution for the pure hydrogen using fuel cell units, the storage tank and delivering pipes have to be insulated. Due to the physical properties of hydrogen, volatile and highly explosive, transfer between the storage tank and anode side of the fuel cell must comply with the two barrier principle and it is either achieved by ventilation and gas-tight enclosure (Vogler and Würsig, 2011). Furthermore, safety measures are expected to avoid fuel spills, to give plentiful ventilation to required limited spaces, and to screen the enclosed spaces to guarantee any fuel collection is identified (Klebanoff et al, 2017). Related to the safety aspect, low-temperature fuel cells have an advantage due to their safe operability but the need for hydrogen or hydrogen production units causes to need more regulations and standards. In contrast, standards and regulations for the fuel cell systems depend on the usage intensity on board.

2.3.7 Power capacity

Power output capacity of fuel cells is generally around kW levels, but there are also some examples in MW levels especially for high temperature working fuel cells (van Biert et al., 2016). The most promising fuel cell types are MCFC and SOFC for onboard application in the meaning of power output. Moreover, MCFC and SOFC are eligible fuel cells for cogeneration systems with their higher exhaust gas temperatures and their total efficiency can be raised with steam or gas turbines. On the other hand, high market value and technological maturity make the PEMFC a prominent

alternative in the meaning of modularity and total power output. However, because of the limited power output capacity, using AFC and PEMFC as a main propulsion power generator seems hard for big size ships but for electric generation, it can be feasible. For AFC, research and development have decreased dramatically in comparison with PEMFC, so, commercially they lost their attractiveness in maritime in addition to their power capacity (Pratt and Klebanoff, 2016).

2.3.8 Lifetime

Lifetime of fuel cells depends on the working temperature since it limits the material life-cycle capacity due to thermal stresses which causes fatigue during operations (Dodds et al., 2015). Furthermore, because of the high operating temperature, start-up and shut-down sensitivity of the system increases. So, reducing the output power and keeping the stack in hot condition may be a solution for shipping but in contrast, this procedure reduces the durability of the fuel cell system. For instance, MCFC or SOFC, high temperature working fuel cells, suffer from a limited lifetime (Remick et al., 2010). The latest results showed that SOFC stacks have worked up to 30,000 hours durability and single cells have demonstrated up to 90,000 hours, moreover some residential systems in European Union are sold with a guaranteed lifetime of 10,000 – 20,000 h (Ellamla et al., 2015). On the other hand, PEMFC manufacturers indicate that the improvement in fuel cell system durability is growing exponentially over the past fifteen years (Ellamla et al., 2015; Staffell, 2015). From this perspective, the lifetime of fuel cells is increasing with technological developments and seems like a promising technology for shipping in the near future.

2.4 Fuel Cell Selection and Discussion

The aim of this study is to find the most suitable fuel cell type for shipping. Table 2.6, is formed to find the weighting of the selection criteria using the AHP method. Eight different criteria were determined and explained; safety, emissions, efficiency, cost, lifetime, power output, fuel type, and size. The weight point of each criterion is determined by fourteen experts, who are academicians, ship captains, marine engineers, technical managers, and naval architects according to their importance during integrating and operating the fuel cell system into ship, from one to three points.

Table 2.6 : Results of the survey to find the weighting of the fuel cell attributes for using on board.

Criterion Notation	Attributes	Total Score
C1	Safety	40
C2	Emissions	37
C3	Efficiency	36
C4	Cost	35
C5	Lifetime	33
C6	Power Output	32
C7	Fuel Type	32
C8	Size	26

Academicians have various scopes such as; hybrid-electric propulsion systems, ship emissions and alternative fuels for marine engines like methanol and ethanol. Chief engineers, captains and technical managers from shipping companies who worked or still working for more than ten years onboard vessels. Experts were ranked differently according to their professional background. From the industrial perspective; cost, safety, and emissions received greater points than other criteria. Via adding up all received points for each attribute, the criteria are ranked by their importance and their total score as shown in Table 2.6. Safety is the top of the ranking, notated as C1 and size is at the bottom of the ranking, notated as C8 according to answers of the experts. The scale of relative importance is shown at table 2.7.

Table 2.7 : Scale of Relative Importance (Ren and Sovacool, 2015)

Scale	Definition	Note
1	Equal Importance	i is equally important to j
3	Moderate Importance	i is moderately important to j
5	Essential Importance	i is essentially important to j
7	Very Strong Importance	i is very strongly important to j
9	Absolute Importance	i is very absolutely important to j
2, 4, 6, 8	Intermediate Values	the relative importance of i to j is between adjacent judgement

Table 2.8 : Relative importance scale equivalent of expert ranking difference intervals.

Scales	Ranking Difference Intervals
1	0 – 1.55
2	1.56 – 3.10
3	3.11 – 4.66
4	4.67 – 6.22
5	6.23 – 7.78
6	7.79 – 9.34
7	9.35 – 10.90
8	10.91 – 12.46
9	12.47 – 14.00

Relative importance of criteria is calculated via differentiating the expert points for each two criteria. The maximum point difference is found 14 and it is divided to AHP scale to find the relative importance, as shown at table 2.8. The weightings of the criteria are calculated by Analytic Hierarchy Process (AHP). Comparison matrix is constituted using given expert points for all comparison criteria at table 2.9.

Table 2.9 : Comparison matrix of criteria.

Comparison Criteria	C1	C2	C3	C4	C5	C6	C7	C8	Weighting Points (Wp)
C1	1,00	2,00	3,00	4,00	5,00	6,00	6,00	9,00	0,337
C2	0,50	1,00	1,00	2,00	3,00	4,00	4,00	8,00	0,187
C3	0,33	1,00	1,00	1,00	2,00	3,00	3,00	7,00	0,144
C4	0,25	0,50	1,00	1,00	2,00	2,00	2,00	6,00	0,112
C5	0,20	0,33	0,50	2,00	1,00	1,00	1,00	5,00	0,084
C6	0,17	0,25	0,33	0,50	1,00	1,00	1,00	4,00	0,058
C7	0,17	0,25	0,33	0,50	1,00	1,00	1,00	4,00	0,058
C8	0,11	0,13	0,14	0,17	0,20	0,25	0,25	1,00	0,020

$\lambda_{\max} = 8.573$ (maximum eigenvalue)

CI = 0.082 (consistency index)

CR = 0.058 < 0.1 (consistency ratio)

In this comparison matrix, weighting of every criteria was calculated, then, maximum eigenvalue ($\lambda_{\max}$) and consistency index were calculated for consistency check. Average random index is taken as 1.41 (Ren and Sovacool, 2015). Consistency ratio is found 0.058 which is lower than 0.1 and it agrees with the rule. Cost of fuel cell system was separated as capital expenditures and operational expenditures in previous sections. Therefore, to find the correct weight point of total cost for each fuel cell, CapEx and OpEx must be taken into account. During determining weights of criteria, cost also evaluated by experts and the weight of CapEx were found 70% compared to OpEx which constitutes 30%. Table 2.10 shows the ranking of fuel cell types considering their cost. The results are directly used in general ranking at Table 2.11, as point of cost criteria. The cheaper options had greater point, thus hydrogen bunkering, production and onboard storage options were found as the major cost drivers as stated.

Table 2.10 : Ranking of fuel cell by their costs.

	CapEx (70%)	OpEx (30%)	Average
PEMFC	5	2	4.1
AFC	2	2	2
PAFC	3	2	2.7
D/O MCFC	4	4	4
LNG MCFC	2	3	2.3
D/O SOFC	4	4	4
LNG SOFC	2	3	2.3

Total comparison points of fuel cell types according to comparison criterions are calculated from formula (2.3). Maximum total point, 5.000 is calculated by using formula (2.4) and CP_{TOT} is maximum total comparison point. CP_{ij} is comparison point for i with comparison criterion of j fuel cell. CP_{ij} is the key element for the ranking of fuel cell types, it shows the point of each fuel cell from each criterion. WP_i is weight point for i comparison criteria, and RP_{ji} is ranking point of j fuel cell at i comparison criteria in formula.

$$CP_{ij} = WP_i \cdot RP_{ji} \quad (2.3)$$

$$CP_{TOT} = \sum (WP_i \cdot RP_{ji}) \quad (2.4)$$

Table 2.11 : Final comparison matrix.

	RP	RP	RP	RP	RP	RP	RP	RP	CP _{TOT}
	C1	C2	C3	C4	C5	C6	C7	C8	
WP	0.337	0.187	0.144	0.112	0.084	0.058	0.058	0.02	5.000
PEMFC	4	5	4	4.1	4	3	2	5	4.044
AFC	4	5	2	2	3	1	2	4	3.301
PAFC	4	5	3	2.7	2	3	2	3	3.535
D/O	4	3	5	4	4	5	5	3	4.053
MCFC									
LNG	3	4	5	2.3	4	5	4	3	3.766
MCFC									
D/O	4	3	5	4	3	5	5	3	3.969
SOFC									
LNG	3	4	5	2.3	3	5	4	3	3.571
SOFC									

Inferences from table 11 are:

- Safety is found as the most important criteria by experts. Safety requirements are not fully known since fuel cell technology is not yet widely applied on ships. However, we still have some strong references such as IGF Code or Class and Lloyd reports for the transportation of explosive cargo. So, any fuel cell type could get five points from this criterion. However, LNG using fuel cells are found riskier than hydrogen due to its lower auto ignition temperature and higher density compared to hydrogen. In any case of leakage from the storage tank or fuel cell unit, hydrogen will disappear quickly, while LNG lasts. Furthermore, storage tank location is also important to evaluate the safety according to fuel type. In case of conventional tank location, underwater and at the bottom of ship, the results explosion risk would be similar for each type of fuel. But, if outdoor storage tanks chosen, LNG would cause methane slip in any case of release and this is a catastrophic situation for environmental safety. Despite diesel oil is well proven and highly recognized as a fuel option for ships, diesel oil using fuel cells operate at high temperature and they classified as less reliable than low-temperature types.
- Emission is the second important criterion for the selection of fuel cells. As the main motivation for fuel cells is to reduce ship-based emissions, using direct hydrogen capability is the most advantageous and the most preferred option among fuel cells for a total adaptation to the new emission regulations for shipping without any CO, CO₂, SO_x and NO_x. PEMFC, PAFC, and AFC had

five points from this criterion. Other types need fuel conditioning and processing unit to use LNG and diesel oil. In this case, fossil fuels release CO₂ during the extraction of hydrogen. LNG has fewer emissions in comparison with diesel oil due to its physical properties and had one more point than diesel oil. It should be noted that, despite their hazardous emission, fuel cells are still advantageous in comparison to conventional internal combustion engines.

- Efficiency is the third important criteria and fuel cell types are evaluated based on literature. One of the major drivers of fuel cell efficiency is the working temperature. Higher temperature allows to reduce of concentration losses at the core of the cell unit. Also, high temperature working cells are found more efficient with their adaptability to cogeneration systems using their high-temperature exhaust gases. Efficiency does not vary substantially according to fuel type. So, all types of MCFC and SOFC had the same point and greater point in comparison to low temperature types.
- Cost is considered under the CapEx and OpEx sections. From the CapEx perspective; since PEMFC is the major research and development subject thanks to the automotive industry, it is the maximum CapEx efficient type among fuel cells. However, from the OpEx point of view, the need for pure hydrogen and storage cost seem as disadvantages to onboard use of PEMFC. The other important fuel cell types MCFC and SOFC are received the same points due to their closer CapEx and almost the same OpEx. The main difference for OpEx is shown by their fuel types; despite fuel price advantage of LNG against diesel oil, hard fuel storage conditions and management systems of LNG and global bunkering availability increase CapEx of the system, therefore they received less point than diesel oil option.
- Lifetime is evaluated according to the literature. In general, many lifetime estimations for fuel cells are the results of research and experiments under steady-state conditions. However, it is a common concurrence that low temperature working fuel cells keep their efficiency much longer than the other types. The degradation rate inside the core, in the meaning of electrolyte, is quicker for high temperature types. This causes a decrease in efficiency after thousands of hours of operating. Despite that, new technological development in the material of cell unit and electrolyte contributions shows that a longer lifetime is reached for MCFC and SOFC. So, both PEMFC, MCFC and SOFC

had similar points due to their closer lifetimes and received greater points against AFC and PAFC.

- The high temperature working fuel cells are eligible for cogeneration systems, thus, SOFC and MCFC have a significant vantage in power output capacity. However, whether the system is used only for electric generation onboard, PEMFC or PAFC also can produce enough power for ships. In this paper, fuel cells are mainly considered for the propelling unit, therefore, high-temperature systems had a major point. Despite being able to integrate multiple fuel cells to increase power output, the required space and increased weight make this choice less attractive than high temperature types.
- Fuel type is another important criterion for the selection of fuel cells. Therefore, logistic fuels are considered as options, so, bunkering and storage feasibility for ships is much more important than land-based facilities. Global bunkering availability of fuel type, easy and safe storage onboard are taken into account, therefore, diesel oil, LNG and hydrogen are ranked, respectively. Since diesel oil is a well-proven conventional marine fuel, it has a greater point compared to other fuel options. However, as the main objective is to produce sustainable clean energy for ships, biodiesel must be taken into account. In the case of using biodiesel, more than fuel flexibility, emission advantage will be greater and satisfying. LNG is another growing fuel option but still weaker than diesel oil in terms of shipping experience and bunkering station options. Hydrogen for ships seems difficult in the near future because of the weak bunker station network and also hard cryogenic storage conditions at -253 C temperature. Onboard production via electrolysis may be a solution, however, production and consummation rate must be well analyzed and can be changeable for each type of ship and route.
- Size is the last important criterion for the selection of the fuel cell system. PEM is the most advantageous fuel cell type in the meaning of power density according to literature knowledge. Its vast experience in the transportation sector among different types, design and working principles put it at the top of the ranking. For high-temperature fuel cells, one of the previous advantages; fuel flexibility, necessitates bringing the fuel conditioning unit also. As well, high efficiency due to cogeneration makes the total system more complex and requires more places onboard. Under the same conditions, whether the

system's required space increases, ship profitability decreases on the same route due to reduced cargo capacity of the ship. As a result, PEMFC seems as the most advantageous type in terms of size against other types.

2.5 Conclusion

This paper aims to find the most suitable fuel cell type for merchant vessels regarding maritime industry conditions. Criteria were defined, explained from the shipping perspective and lastly, the analytic hierarchy process was made to find and calculate the importance of each criterion and find the most promising fuel cell type. The lack of internationally accepted standards for using hydrogen and particularly fuel cell systems is caused by the intensity of usage. For several years, the regulatory basement for alternative fuel usage in shipping is increasing due to the limitation of hazardous emissions from ships. More specifically, expanding global hydrogen trade will provide a higher demand and wider utilization of fuel cells in shipping.

The top three fuel cell types are ranked as diesel oil using molten carbonate fuel cell, proton exchange membrane fuel cell and diesel oil using solid oxide fuel cell, which are received 4.053, 4.044 and 3.969 respectively from the total point 5.000. Despite PEMFC has a wide application area in the transportation sector among fuel cell types, the need for bunkering and safe storage hydrogen as a fuel seems very difficult for the shipping industry. Finally, diesel oil using molten carbonate fuel cells was found as the most promising fuel cell type for shipping thanks to its fuel flexibility, power capacity, and efficiency. However, it should be noted that MCFC is marginally in front of the PEMFC and diesel oil using SOFC, so it is obvious that both can be selected according to the considered ship and working area.

Fuel cells can play a key role in reducing ship emissions and they may be a solution for new emission regulations with their fewer hazardous emissions in comparison with internal combustion engines. Dramatically decreases in regulated emissions such as NO_x , PM and SO_x and an important amount of CO_2 is highlighting the importance of fuel cells for the shipping industry. Fuel cells are still under investigation period for large scale energy-demanding facilities, however, they started to find a place in the road transportation sector. For the commercial maritime sector, it is a very new technology and still at the investigation and demonstration stage. In the next study, environmental and economic analysis of different fuel cell types can be investigated

according to different ship types. Also, an optimization study between diesel engines and selected fuel cell system can be carried out depending on routes and maneuvering periods of considered ship or fleet.



3. INVESTIGATION ON THE DECARBONIZATION OF SHIPPING: AN APPROACH TO HYDROGEN AND AMMONIA²

3.1 Introduction

Global energy consumer areas are buildings, industry, and transportation. According to the U.S. Energy Information Administration (EIA) data, the transportation sector constitutes approximately 19% of global energy consumption in 2015 and the estimated data shows that it will remain the same in 2040 (EIA, 2017). Aviation, railway, road, and maritime transportation are the transportation types worldwide. Maritime transportation is the most efficient mode of transport, with 98,140 commercial ships of 100 gross tonnages (GRT) and above in January 2020 (UNCTAD, 2020). The use of maritime transportation has been raised by more than a 150% since 1990 (Baldi et al., 2020; Inal and Deniz, 2021). The worldwide transfer of goods depends on maritime transportation since it forms 90% of global transportation (Deniz and Zincir, 2016). Despite, maritime transportation being an effective way to transport goods and passengers, 99% of the worldwide fleet has an internal combustion engine propulsion system (Rattazzi et al., 2021) and fossil fuels are still in use. According to the research of the International Maritime Organization (IMO), 300 million tons of fossil fuels are consumed annually (IMO, 2015). Approximately, 72% of fossil fuel consumption is heavy fuel oil (HFO), 26% is marine diesel oil (MDO), and 2% is liquefied natural gas (LNG) (Gray et al., 2021). Depending on the fossil fuel consumption, there are an increase in total greenhouse gas (GHG) emissions (CO₂, methane, and nitrous oxide) from 977 million tons to 1,076 million tons, and CO₂ emissions from 962 million tons to 1,056 million tons from the year 2012 to 2018 (IMO, 2020). Maritime transportation is responsible for around 3.1% of the total CO₂ emissions worldwide, equal to the sixth most CO₂ emitter country in the world (Balcombe et al., 2019), and IMO estimates indicate that CO₂ emissions will increase

² Inal, O.B., Zincir, B., Deniz C. 2022. Investigation on the Decarbonization of Shipping: An Approach to Hydrogen and Ammonia, *International Journal of Hydrogen Energy*, Volume 47, Issue 45, pp. 19888-19900. <https://doi.org/10.1016/j.ijhydene.2022.01.189>

between 50% and 250% by 2050 (IMO, 2015; Rivarolo et al., 2020) if there will be no mitigation plan or strategy (Wu & Bucknall, 2020).

IMO has been working on mitigating CO₂ and GHG emissions from shipping. The Regulations on Energy Efficiency for Ships is one of the integral parts of mitigation measures of CO₂ emissions. It entered into force on 1 January 2013 and came with the mandatory terms Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), and a voluntary term the Energy Efficiency Operational Indicator (EEOI) (IMO, 2011). The EEDI is for new building ships and encourages energy-efficient materials and technologies by limiting new building ships with an index value. On the other hand, the SEEMP has to be on board existing ships and this plan includes operational energy efficiency measures for the specific ship. The EEOI is a voluntary index that shows voyage efficiency by taking into consideration of ton CO₂ per cargo-carrying work. Another step of IMO is Data Collection System that entered into force on 1 March 2018 (IMO, 2021). The purpose of the regulation is to record the annual voyage-based CO₂ emissions of ships larger than 5000 GRT which do international voyages. Besides the regulations, in 2018, IMO created an Initial Greenhouse Gas Strategy with dual objectives for maritime transport (IMO, 2018). The first aim is to diminish CO₂ emissions per transport work at least 40% by 2030 and 70% by 2050, compared to 2008. And the second aim is to decrease GHG emissions from maritime transportation to 50% below the 2008 levels in 2050. Short (2018-2023), medium (2023-2030), and long-term (2030-...) candidate measures to achieve these targets were announced under the Initial GHG Strategy. The main areas of the candidate measures are operational measures, market-based measures, policy measures, and technology-based measures. One or a combination of more than one candidate measure can be used to reduce CO₂ and GHG emissions from ships (Yalcin and Suner, 2020). Although there are several ways and combined measures to achieve decarbonized shipping, alternative fuel use is a common candidate measure across all terms of the strategy. A transition from low-carbon alternative fuels to zero-carbon alternative fuels is aimed from short-term to long-term. Alternative fuels with a lower carbon content than conventional marine fuels such as liquefied natural gas (LNG) and methanol are used for short-term measures in maritime transportation and will continue to be used for medium-term measures. However, long-term measures include zero-carbon fuels and electric ships (IMO, 2018). Therefore, ammonia and hydrogen are promising alternative fuels for the complete decarbonization of maritime

transportation with zero carbon content (Inal and Deniz, 2018; Zincir, 2020). Both ammonia and hydrogen can be used as blends with conventional marine fuels in marine diesel engines. The most notable marine engine manufacturers MAN and Wartsila have been especially working on ammonia to combust it at their marine diesel engines with a small amount of pilot diesel fuel (Zincir, 2020). But these efforts do not result in zero-carbon maritime transportation. Therefore, ammonia and hydrogen have to be used for providing energy to produce electricity for full-electric propulsion on ships. Ammonia and hydrogen are suitable fuels for fuel cells to be used for full-electric propulsion as a long-term measure (Wan et al., 2021; Balestra and Schjølborg, 2021; Rivarolo et al., 2018). Fuel cells are units that electrochemically convert the energy of hydrogen to electricity (Inal and Deniz, 2018). The maritime industry is interested in ammonia and hydrogen fuel cells and there are ongoing projects on fuel cell applications. Nemo H2, Zero-V, and ZEMSHIP projects are examples of hydrogen-fueled fuel cells on ships (Xing et al., 2021; Madsen et al., 2020), and the part of the ShipFC project focuses on ammonia-fueled fuel cells on a ship (URL-4).

The starting point of this paper is the IMO Initial GHG Study. IMO targets to reduce the carbon content in the fuels by using low carbon fuel at the mid-term and then aims zero-carbon shipping by using zero-carbon fuels and electric propulsion. Thus, the purpose of this paper is to find suitable fuel options to achieve zero-carbon shipping. In this context, the study starts from the beginning by considering fuel cells, diesel engines, batteries, and renewable energy sources as power sources for marine propulsion systems. While ammonia, diesel, fuel oil, hydrogen, methanol, and LNG were fuel options for fuel cells, the same fuels other than hydrogen were fuel options for diesel engines (Inal and Deniz, 2021). Renewable energy sources were assumed as solar and wind energy. A preliminary evaluation was conducted to find the best routes for zero-carbon shipping. After preliminary evaluation, ammonia and hydrogen were compared to find out which is the best possible fuel option for fuel cells. At the end of the study, there was a discussion for sustainable decarbonization of shipping towards zero-carbon shipping.

The paper is organized as follows; section 2 gives the methodology followed in this paper. After a preliminary evaluation, two promising zero-carbon alternative fuels are introduced. Evaluation criteria are established, and point of view, analytic hierarchy process, and sensitivity analysis are described respecting fuel's properties. Section 3 explains the result of the evaluation process and sensitivity analysis is carried out

according to different weightings and scenarios for each criterion. Lastly, section 4 concludes the paper by giving the future scope and possible research areas.

3.2 Methodology

Considering the insufficiency of conventional marine fuels with the way through shipping goes, a first evaluation of the fuel and powering options for the decarbonized shipping has been carried out. Hydrogen and ammonia seem feasible selections, and they are explained and examined with their properties after revealing the most possible pathway at this aim. Secondly, safety, cost, storage, environmental impact, and sustainability in the meaning of bunkering and global availability are determined as crucial criteria for adapting the selected options. Weightings of the hydrogen and ammonia for each criterion are decided using the analytic hierarchy process by asking experts in the maritime field. Thirdly, fuels are pointed and a better option is found with following the sensitivity analysis for the findings. The detailed explanations of the methodology followed are given in further sections.

3.2.1 Preliminary evaluation of pathways for zero-carbon shipping

There are different methods of powering ships, and for the scope and purpose of this study, Figure 1 details the options that offer zero-carbon shipping. In the first step, power sources are given under different main headings such as fuel cells, diesel engines, renewable energy, and batteries. Then, these options are classified with subheadings according to their fuel usage. Secondly, the carbon content of the fuel types and their usability about the cruising range of the ship was examined as a reference. In this context, three different scales were determined; The best is the green light, which symbolizes zero carbon with long cruising range, the yellow light, which represents zero carbon but short-range capability, and the red light with carbon content at long range. The main motivation for this article is to compare zero-carbon options, therefore, carbon-containing fuels are marked with a red light and are therefore not considered an option in the next steps of the article.

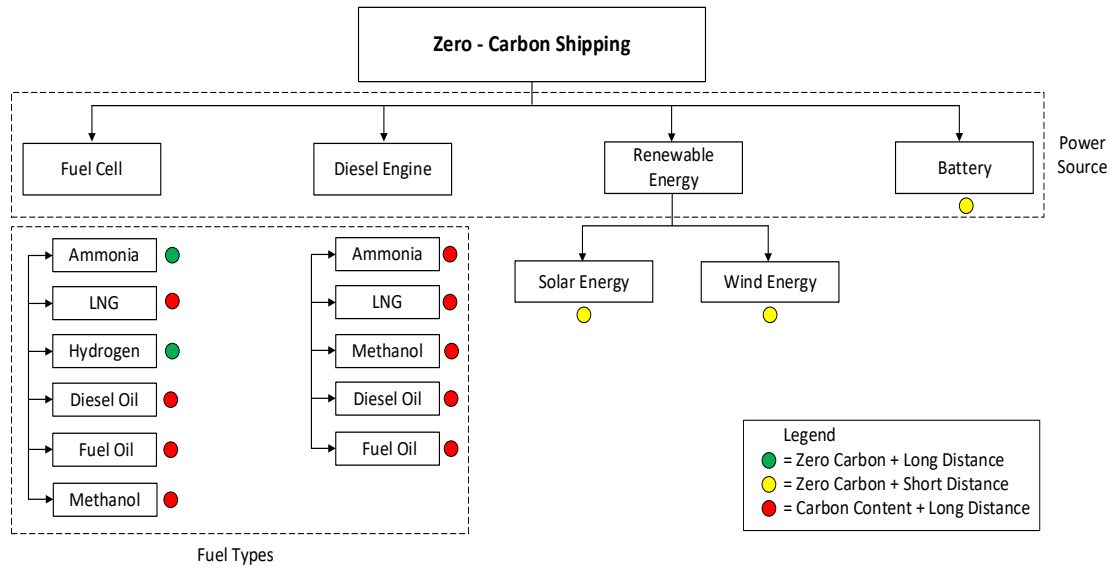


Figure 3.1 : Pathways for zero-carbon shipping.

Firstly, starting from the fuel cells, six different fuel options have been considered, but carbon-free options are just ammonia and hydrogen. Fuel cells types have been considered with a general approach and all fuel types are considered as an option. On the other hand, five fuel options are considered for the diesel engine and as it is known, all of them have carbon content except ammonia. However, the diesel engine cannot ignite ammonia directly and it requires diesel oil as pilot fuel, so it is impossible to achieve zero carbon for marine diesel engines. It is well-known that ammonia dramatically reduces CO₂ emissions compared to diesel oil but still reaching zero carbon emission is impossible. Lastly, renewable energy (solar and wind) and batteries are considered additional power sources for ships by hybrid propulsion due to limited capacity (Tang et al., 2018). High dependence on the environmental conditions of the renewable energy sources and limited capacity of the batteries for oceangoing ships restrain their wider usage. Despite several examples in short sea shipping, currently, all-electric ships with zero emissions are under development and today's technological maturity does not allow to consider as a solution for merchant ships. As a result, hydrogen and ammonia using fuel cells appear to be major primary solutions for shipping decarbonization in the near term.

3.2.1.1 Ammonia

Ammonia is a colorless gas with a pungent odor that can be detected in air at 5 ppm (Ayvalı et al., 2021). Ammonia is a compound with a carbon-free structure. It consists of one nitrogen atom and three hydrogen atoms. Ammonia is a hydrogen energy carrier

with a hydrogen content of 17.6% by weight, and the volumetric energy density of liquid ammonia is higher than liquid hydrogen (Dimitriou and Javaid, 2020).

Global annual ammonia production was 150 million tons in 2019 (Al-Aboosi et al., 2021). About 80% of the produced ammonia is used for fertilizer, and other areas are synthetic fibers and resins, plastics, explosives, refrigerants, and some chemicals (Brinks and Hektor, 2020). Currently, most of the ammonia production is done with the Haber-Bosch (H-B) process, invented by Fritz Haber and Carl Bosch about 100 years ago (Aziz et al., 2020). The main raw materials for the hydrogen production in the ammonia synthesis process are natural gas (72%), coal (22%), heavy fuel oil (1%), naphtha (1%), refinery gas, and coke oven gas (1%) (Bicer et al., 2017). And nitrogen is produced by using air at cryogenic distillation, polymer membrane separation, or pressure swing absorption methods (Ash and Scarbrough, 2019). If hydrogen is produced by renewable energy – electrolysis and nitrogen are captured using renewable energy, ammonia is a completely carbonless fuel.

The toxicity of ammonia is an important issue for shipboard storage and use. It is three times more toxic than methanol and gasoline (Morlanes et al., 2021). The toxicity of ammonia is well-known and spillage of ammonia into the sea can pose serious risks to aquatic life. Ammonia dissolves in the water and forms ammonium hydroxide (NH_4OH) and ammonium ions (NH_4^+) (de Vries, 2019; Ayvalı et al., 2021). Ammonia is biodegradable in the long term, but direct exposure causes damage and fatal consequences to organisms. The aquatic life restores itself by the nitrogen cycle in a long term. Another important feature of ammonia is that it is corrosive. Ammonia is incompatible with some substances. These materials are alloys of aluminum, brass, copper, magnesium, and zinc (Klüssmann et al., 2020). In addition, ammonia has a low fire risk compared to other potential alternative marine fuels. Ammonia has a narrow flammability range of 16 – 25% by volume in air, 2-3 times more ignition energy than conventional hydrocarbon fuels, and a low combustion rate (four times lower than methane) (ABS, 2020). However, ammonia is a well-known substance to the maritime community, as it is used as refrigerant onboard ships and as a NOX reducing agent in selective catalytic reactors (SCR), it has also been transported as a liquefied gas cargo. (Kim K. et al., 2020). The procedures and safety measures for shipboard storage and usage were developed.

Ammonia is one of the preferred fuels for fuel cells due to its hydrogen carrying capacity. Alkaline fuel cells (AFCs) and solid oxide fuel cells (SOFCs) can use

ammonia directly in their stacks to generate electricity. AFCs are affected by CO₂ in the air due to low durability (Wan et al., 2021). SOFCs have fuel flexibility and high-power capacity (Inal and Deniz, 2021). Therefore, SOFCs have been preferred in ammonia studies. The first direct ammonia SOFC was operated in 1980 (Vayenas and Farr, 1980). Recently, an application of direct ammonia SOFC has been made by Kishimoto et al. (2020). They investigated a 30-cell ammonia-SOFC with a power output of 1 kW and an efficiency of 57%. The application achieved 1000 h of operation. Direct ammonia SOFCs are not commercially available and are currently under development. An ammonia-fueled SOFC project, ShipFC, continues. The aim is to convert one of the gensets of the ship named, Viking Energy, to an ammonia-fueled SOFC. The first tests of the 100-kW ammonia-fueled SOFC will be on land, and the scaled SOFC will be installed onboard in late 2023 (Brinks and Hektor, 2020).

3.2.1.2 Hydrogen

Hydrogen is the most available and lightest element in the universe, but it is usual in impure form. It is an energy carrier that is in a gas state. It is naturally in a carbon-free structure. This causes a great amount of attention from policymakers, researchers, and companies in the shipping industry. The potential of hydrogen in shipping is growing substantially in line with the intensity of its use in other transportation sectors such as automotive.

Feedstock for hydrogen production is diesel oil, natural gas, coal, and biomass (Inal and Deniz, 2020). It can also be produced by electrolysis by using renewable energy such as wind or solar. Fifty-one percent of hydrogen production is for ammonia production, while 31% is for oil refining, 10% for methanol production, and 8% for other applications (Kannah et al., 2021). Hydrogen is produced from different feedstocks that 96% of them are fossil fuels (natural gas 48%, oil 30%, and coal 18%) and 4% from renewable resources (Taibi et al., 2018). The energy consumption of annual worldwide hydrogen production equals 2% of the global energy demand (ABS, 2021). Hydrogen production methods from hydrocarbon fuels are hydrocarbon reforming and pyrolysis. These two hydrogen production methods are the most mature and used methods that meet almost the total global hydrogen demand (Nikolaidis and Poullikkas, 2017). Hydrogen production from hydrocarbon fuels can be done at high efficiencies and low costs (Baykara, 2018). Water splitting is another hydrogen production way and it can be done by three methods. These methods are electrolysis,

thermolysis, and photo-electrolysis. Hydrogen from water splitting is the cleanest energy when the energy for water splitting is provided from renewable energy sources (Nikolaidis and Poullikkas, 2017). Lastly, hydrogen from biomass is the renewable production way.

Table 3.1 : Properties of hydrogen and ammonia (Erdemir and Dincer, 2020; Klüssmann et al., 2020; Gray et al., 2021; Korberg et al., 2021)

Properties	Gaseous Hydrogen	Liquid Hydrogen	Ammonia
Auto-ignition temperature (°C)	571	571	651
Flashpoint (°C)	N/A	N/A	-33.4
Flammability limits (Vol. %)	4 - 75	4 - 75	16 - 25
Flame speed (m/s)	3.51	3.51	0.15
Lower heating value (MJ/kg)	120.1	120.1	18.8
Octane number	>130	>130	110
Density (kg/m ³)	17.5 – 20.54	70.85 - 71.1	602.8
Energy density (MJ/m ³)	2101	8539	11333
Storage type	Compressed gas	Cryogenic liquid	Compressed liquid
Storage temperature (°C)	25	-253	25
Storage pressure (bar)	300	1	10.3
Onboard storage cost (€/kWh)	1.29 – 1.71		0.23 – 0.29
Fuel cost (€/kWh)	153		120
			Grid electricity: 173
Well to wheel life cycle emissions (gco ₂ /MJ)	Grid electricity: 139 Wind electricity: 2.59 – 20.74 Solar PV electricity: 6.67 – 66.67		Wind electricity: 3.24 – 25.93 Solar PV electricity: 8.33 – 83.33

There are two main categories for hydrogen production from biomass. One of them is the thermochemical process and the other one is the biological process. The subcategories of the thermochemical process are pyrolysis and gasification. The biological process contains bio-photolysis, dark fermentation, and photo-fermentation. Although there are various ways of hydrogen production from biomass, most of the

techniques are not mature enough, and the hydrogen production rate is not adequate to replace with fossil-based fuels (Qyyum et al., 2021).

Hydrogen has a low energy density (Table 3.1) and it is the main disadvantage for being a transportation fuel. The four main storage technologies are compressed liquid, solid-state, and alternative carriers. In general, hydrogen is stored in high pressurized tanks as a compressed gas or cryogenic liquid at a temperature of -253°C (Deniz and Zincir, 2016). Hydrogen's wide flammability limits and high flame speed are the properties that attention to be given during storage and fuel operations. Hydrogen has neither toxic nor corrosive properties. Many projects on the use of hydrogen and fuel cells onboard ships have been started and continuing (Tronstad et al., 2017). In the meaning of weight, hydrogen is a substantial energy carrier regarding its lower heating value (LHV) which is roughly 3 times of diesel oil, 33 kWh/kg, and 11 kWh/kg, respectively. In contrast, under atmospheric conditions hydrogen is in gaseous form and volumetric energy capacity is roughly 3000 times lesser compared to diesel oil.

3.2.2 Decision Making

This study aims to understand the position and determine the better option of these two zero-carbon alternative fuels by giving common criteria to use in ships. Designating criteria for the study is an essential step in the decision-making process. Hence, the criteria of the various studies in the literature are investigated. Table 3.2 shows the criteria of previous studies in the literature. According to the previous studies in the literature, the most used criteria are in the fields of safety, economy, environment, and technology. The criteria in this study are determined by the aid of the criteria at the previous studies in the literature. In this approach; safety, cost, storage, sustainability, and environmental impact are established as the main categories to decide the most promising one. The further sections are detailing the criteria by giving the perspective of the followed methodology.

Table 3.2 : Comparison criteria of previous studies in the literature.

Year	Criteria	Study Area	Authors
2016	Safety, applicability, feedstock, maturity, reliability, efficiency, cost	Onboard hydrogen production	Zincir and Deniz
2016	Safety, global availability, bunker capability, durability, adaptability, the effect on engine performance, effect on engine emissions	Alternative fuels	Deniz and Zincir

Table 3.2 (continued) : Comparison criteria of previous studies in the literature.

2017	Environmental, economic, technological, social	Alternative fuels	Ren and Liang
2017	Technical, investment cost, fuel price, operational cost, global warming potential (GWP), exhaust emissions, infrastructure, risk of explosion/fire, public opinion, political and strategic aspects	Alternative fuels, nuclear power, wind power	Ren and Lützen
2018	Economic, global warming potential (GWP), life cycle assessment, exhaust emissions	Alternative fuels	Kirstein et al.
2019	Global warming potential (GWP), life cycle performance, exhaust emissions, market/availability, ethics, regulation	Alternative fuels	Balcombe et al.
2019	Fuel price, global warming potential (GWP), exhaust emissions	Alternative fuels, fuel cells	Brahim et al.
2019	Price, infrastructure, regulation, scalability, environmental impact, technology, CAPEX, OPEX	Alternative fuels, fuel cells, wind-assisted propulsion, batteries	DNV GL
2019	Economic, technical, environmental, social	Alternative fuels	Hansson et al.
2020	Cost, fuel types, efficiency, emissions, size, safety, power capacity, lifetime	Fuel cells	Inal & Deniz
2020	Environmental impact, the risk to humans, business value	Alternative fuels	Kim H. et al.
2020	Environmental, technical, economic, other (safety, infrastructure availability, fuel availability)	Alternative fuels	Andersson et al.
2021	Volumes, weights, investment and operational costs, CO ₂ and pollutant emissions	Alternative fuels	Rattazzi et al.
2021	Feedstock security, applicability on board a ship, global warming potential (GWP)	Alternative fuels	Xing et al.
2021	Energy density, costs, well-to-wheel GHG emissions, land area	Alternative fuels	Gray et al.

Criteria

Safety

Safety is considered under four sections such as explosion/fire risk, toxicity, corrosiveness, and cryogenic property of hydrogen and ammonia. The physical and chemical properties of hydrogen and ammonia are taken as reference points and benchmarked during comparison. Hydrogen has a high auto-ignition temperature (571°C), wide flammability limits (4 - 75%), and high flame speed (3.51 m/s) (Erdemir and Dincer, 2020). The auto-ignition of hydrogen is hard during onboard storage, but the wide flammability limits in the air result in high explosion/fire risk on a ship. In addition to this, high flame speed provides quick spreading of flames of hydrogen that is hard to extinguish. In contrast, ammonia has a higher auto-ignition temperature (651 °C) than hydrogen, narrow flammability limits (16 – 25%), and low flame speed (0.15 m/s) (Erdemir and Dincer, 2020). A higher auto-ignition temperature and narrow flammability limits in the air of ammonia reduce the risk of explosion and fire. Furthermore, the low flame speed does not lead to the quick spreading of flames and it is easier to take it under control compared to hydrogen. From the toxicity and corrosiveness perspective, hydrogen shows better performance than ammonia. Hydrogen is not a toxic substance and does not have any corrosiveness on materials. Nevertheless, if hydrogen is stored as a cryogenic liquid there is a cold burn risk for the ship crew. However, ammonia is a toxic substance that if inhaled in a concentration between 2000 and 3000 ppm within half an hour, and a rapid death can take place when exposed to more than 5000 ppm (Wan et al., 2021). Ammonia is also a corrosive substance. It reacts with brass, copper, and zinc alloys (Ayvalı et al., 2021) since it is important to select compatible materials at the storage system, fuel lines, and fuel cell. Ammonia is not a cryogenic liquid, thus there is no cryogenic risk. Hydrogen has high explosion/fire risk and high cryogenic risk, no toxicity, and corrosiveness, on the other hand, ammonia has low explosion/fire risk, high toxicity, corrosiveness, and no cryogenic risk.

Cost

Cost includes fuel cost and onboard storage cost in this study. Hydrogen has a fuel cost of 153 €/kWh and ammonia has a fuel cost of 120 €/kWh. Moreover, the onboard storage operation costs are between 1.29 – 1.71 €/kWh and 0.23 – 0.29 €/kWh for

hydrogen and ammonia (Korberg et al., 2021), respectively. The fuel cost depends on electricity price and infrastructure. Even ammonia production requires hydrogen production and nitrogen capture from the air that consumes higher electricity than hydrogen production, the large amount of produced hydrogen has to be stored in cryogenic tanks. The cryogenic storage comes with additional electricity consumption and special infrastructure requirements. Thus, hydrogen has a higher fuel cost than ammonia. Hydrogen is mostly stored as a cryogenic liquid that results in a higher onboard storage cost than ammonia since ammonia can be easily stored at 10 bar and 25°C.

Storage

Investigation of the onboard storage conditions of hydrogen and ammonia constitutes the principle approach to the storage criterion. The key difference between these two types of fuel is that the determination of requirements to store enough fuel for one voyage in terms of weight and volume per power. Also, technological maturity, capital, and operational cost of storage technique form the second point of view while choosing the better option.

Hydrogen storage technologies are mainly separated into four different techniques: compressed, liquid, solid-state, and alternative carriers (Van Hoecke et al. 2021; Rivard, Trudeau, and Zaghib 2019). Firstly, compressed hydrogen is the most well-experienced storage technology compared to others, however, it increases the cost and energy needs for pressurizing the tank where the material gains importance but in contrast, high pressure around 350-700 bar is an advantage with gravimetric density. Alternatively, liquefaction of hydrogen by cooling down to -253°C is another storage method. The logic is similar to high pressure, and the aim is to maximize hydrogen density than vaporous structure (Inal, Dere, and Deniz 2021). The critical side of this method is limiting the heat transfer as much as possible to minimize evaporation. The spherical storage tank shapes are in favor of having the biggest volume surface ratio but still, it reduces the cargo space onboard ships. Solid-state storage of hydrogen is the third approach but under maritime conditions and regarding limited ship volume, gravimetric and volumetric storage capacity does not seem suitable. Lastly, alternative hydrogen carriers can address to storage issue for ships but the major part of the carriers is ammonia. Therefore, instead of carrying the hydrogen, direct use of ammonia is easier and affordable. Alternatively, CO₂-based and organic liquid-based

storage is available in the market. However, additional process requirements to extract the hydrogen increase the onboard energy needs. The efficiency is directly evaluated from the point of view of the energy needed for hydrogen storage requirements. Van Hoecke et al. analyzed the total energy required to produce and store 1 kg hydrogen and the compressed hydrogen requirements seem like the optimum one among different methods (Van Hoecke et al., 2021).

Ammonia has two storage options. It can be stored as a liquid at 1 bar at -33°C or 10 bars at room temperature (Ayvalı et al., 2021). Compared to hydrogen, ammonia is much easier to store on a ship as hydrogen is mostly stored as a compressed gas in high-pressure tanks (300 bar) or as a cryogenic liquid at -253°C temperature (Deniz and Zincir, 2016).

Sustainability

Global fuel availability and bunkering infrastructure (connections and fuel distribution) of hydrogen and ammonia are forming the sustainability criterion in this paper. Firstly, ammonia has well-established manufacturing, storage, transportation technologies, and bunkering ports; and it is the second most-produced substance worldwide (Cardoso et al., 2021). Annual ammonia production consumes about half of the global hydrogen (Al-Aboosi et al., 2021). From the fuel availability perspective, hydrogen and ammonia are almost in similar positions, thus mostly the bunkering infrastructure determines the sustainability result of hydrogen and ammonia. The physical and chemical properties of hydrogen lead to infrastructure challenges (Lesmana et al., 2019). Cryogenic storage and the risk of explosion/fire are some of the challenges. On the other hand, ammonia has properties easier to cope with since there are not any main issues like hydrogen (Hansson et al., 2020). Therefore, ammonia can be more sustainable fuel with a larger number of bunkering ports with adequate infrastructure.

Environmental Impact

The route on the decarbonization of the shipping was the main trigger question of this paper. As well, hydrogen and ammonia were found as the best options for the short term. Therefore, as the main idea serves, the usage of hydrogen and ammonia at fuel cells does not emit any CO₂ emissions. However, well-to-wheel emissions of these fuels should be considered for the correct environmental impact assessment. Hydrogen

has a lifecycle emission of 139 gCO₂/MJ if it is produced by using grid electricity, 2.59 – 20.74 gCO₂/MJ if it is produced by using wind power, and 6.67 – 66.67 gCO₂/MJ if it is produced by using solar PV electricity. On the other hand, ammonia has a lifecycle emission of 173 gCO₂/MJ, 3.24 – 25.93 gCO₂/MJ, and 8.83 – 83.33 gCO₂/MJ at the same type of electricity usage, respectively (Gray et al., 2021). Hydrogen has a higher lower heating value than ammonia (see Table 1) that provides a lower lifecycle emission per MJ during the production of hydrogen.

AHP & Sensitivity Analysis

Analytic hierarchy process (AHP) is one of the popular and powerful multi-criteria decision-making methods which was created by Saathy (Saathy, 1980). AHP provides a pair-wise comparison of criteria and alternatives, is easy to be used, does not require intensive data, and has the easiness to apply various areas with performance-type decision-making requirements (Velasquez and Hester, 2013). Another advantage of AHP is the process can be applied when data are quantitative and qualitative or weightings were given according to expert opinions (Winebrake and Creswick, 2003). There are various AHP studies about decision-making on alternative fuels and fuel cells including but not limited to Papalexandrou et al. (2008), Tsita and Pilavachi (2012), Deniz and Zincir (2016), Mansson (2017), and Inal and Deniz (2020).

Figure 3.2 shows the steps of AHP. To start the first step of AHP, the relative importance scale, which is shown in Table 3, is used to find the importance level of criteria or alternatives. After completing the calculations at steps 2 and 3 of AHP, the last step is the consistency check. The consistency of the formed AHP table is checked by calculating the consistency ratio (CR). Equations 3.1 to 3.3 are used to calculate the CR (Render and Stair, 1999).

$$\lambda_{\max} = \sum_{i=1}^n (W_i \cdot \sum_{i=1}^n a_i) \quad (3.1)$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3.2)$$

$$CR = \frac{CI}{RI} \quad (3.3)$$

W_i is the weighting of i type of criterion or alternative. The a_i is the sum of the row of the i type of criterion or alternative. CI is the consistency index, RI is the random index, and CR is the consistency ratio. The RI was taken from Table 3.4. The CR has to be lower than 0.1 to provide a consistent AHP table.



Figure 3.2 : Analytic hierarchy process steps (Kunz, 2010).

Table 3.3 : Relative importance scale (Ren and Sovacool, 2015).

Relative importance	Scale	Definition
Equal importance	1	x is equally important to y
Moderate importance	3	x is moderately important to y
Essential importance	5	x is essentially important to y
Very strong importance	7	x is very strongly important to y
Absolute importance	9	x is very absolutely important to y
Intermediate values	2, 4, 6, 8	The relative importance of x to y is between to adjacent judgment

Table 3.4 : Random index values (Saathy and Tran, 2007).

Order	2	3	4	5	6	7	8	9	10	11	12	13	14
Random index (RI)	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58

This study has two alternatives (ammonia and hydrogen) and five criteria (safety, cost, storage, sustainability, and environmental impact). AHP is applied only to criteria since the pair-wise comparison of ammonia and hydrogen can be done by giving performance points to them. Table 3.5 shows the performance points for the alternatives.

Table 3.5 : Performance points for the alternatives.

Performance point	Indication
1	Worst
2	Worse
3	Moderate
4	Fairly well
5	Best

The performance points are given according to the properties of ammonia and hydrogen and data from the literature to evaluate the performance of these fuels at each criterion. The weightings of criteria are determined by taking expert opinions. Twelve experts are from the maritime industry and academic area. Five of the experts have been working in the maritime industry for many years and have adequate knowledge of alternative fuels. Seven of the experts are active academicians and have various studies on alternative fuels and the decarbonization of maritime transportation. Experts give the important points that are similar to performance points (5 points for the highest importance to 1 point for the lowest importance) to each criterion. Criterion can get the same important point with other criteria. These points are summed and a total importance point for each criterion is derived. According to the difference between each criterion, the relative importance scale (Table 3) is determined. These relative importance scales of criteria are used at the AHP matrix table. This technique was used in previous studies (Deniz and Zincir, 2016; Zincir and Deniz, 2018; Inal and Deniz, 2020).

Sensitivity Analysis

Further work after introducing the findings of the study is the application of the sensitivity analysis. It shows which weighting changes affect the result and to what extent. Since the criteria importance points are given by the experts, these points are subjective and can be different if there is another expert group. Therefore, the sensitivity analysis presents the effects of changes at the weightings on the outcome (either ammonia or hydrogen should be preferred for fuel cells).

Table 3.6 : Sensitivity analysis cases.

Cases	Definition
I	Base weightings
II	Safety + 25% weighting
III	Environmental impact + 25% weighting
IV	Sustainability + 25% weighting
V	Storage + 25% weighting
VI	Cost + 25% weighting
VII	Equal weightings

The sensitivity analysis is done by adding 25% weighting of the specific criterion weighting and reducing weighting from the remaining criteria depending on their

weighting ratio among all criteria. This scenario is applied to all criteria. The last case of the sensitivity analysis is to observe the effect, during which all criteria are equally weighted.

3.3 Result and Discussion

This section includes the criteria weightings according to the expert opinions, criteria performance points of ammonia and hydrogen, and final performance weightings of ammonia and hydrogen with the sensitivity analysis at different cases.

3.3.1 Criteria weightings

The criteria weightings are found by getting expert opinions at a survey study. According to the opinions of twelve experts, criteria from C1 to C5 are scored. The experts' total scores for the criteria are shown in Table 3.7. The C1 (safety) and C2 (environmental impact) are the most important criteria with 60 points for the experts while using alternative fuels at fuel cells onboard. The remaining criteria get 44 points for the C3 (sustainability), 39 points for the C4 (storage), and 36 points for the C5 (cost). The next step after getting the expert scores is to adapt the expert scores to the relative importance scales (Table 3) from 1 to 9. Table 3.8 shows the interval points equivalent to the relative importance scale. According to the difference between the criteria expert scores, the relative importance scales are determined and a weighting matrix is formed.

Table 3.7 : Experts opinion results on alternative fuels for fuel cell onboard.

Notation	Criteria	Experts Total Score
C1	Safety	60
C2	Environmental impact	60
C3	Sustainability	44
C4	Storage	39
C5	Cost	36

Table 3.9 presents the weightings of the criteria. The weighting matrix has a consistency ratio of 0.014 which is lower than the maximum acceptable limit of 0.1. The C1 (safety) and C2 (environmental impact) criteria get the weighting of 0.413 while C3 (sustainability), C4 (storage), C5 (cost) criteria receive the weightings of 0.086, 0.053, and 0.036, respectively.

Table 3.8 : Relative importance scales according to the expert's opinions.

Scales	Interval points
1	0 – 2.67
2	2.68 – 5.34
3	5.35 – 8.01
4	8.02 – 10.68
5	10.69 – 13.35
6	13.36 – 16.02
7	16.03 – 18.69
8	18.70 – 21.36
9	21.37 – 24.00

These weightings will be further used for the calculation of the performance weightings of ammonia and hydrogen.

Table 3.9 : Weighting matrix of criteria.

Criteria	C1	C2	C3	C4	C5	Weighting
C1	1.00	1.00	6.00	8.00	9.00	0.413
C2	1.00	1.00	6.00	8.00	9.00	0.413
C3	0.17	0.17	1.00	2.00	3.00	0.086
C4	0.13	0.13	0.50	1.00	2.00	0.053
C5	0.11	0.11	0.33	0.50	1.00	0.036

$\lambda_{\max} = 5.063$, $CI = 0.016$, $CR = 0.014 < 0.1$

3.3.2 Criteria performance points of ammonia and hydrogen

The criteria weightings were calculated in the previous section. The further step for the decision-making process is to determine the performance points of ammonia and hydrogen at each criterion. The performance points (Table 3.5) are given to ammonia and hydrogen by taking into consideration of the fuel properties and data in the literature and they are shown in Table 3.10.

Safety (C1)

The safety issues have some threats or impacts on different levels and they are categorized as personnel, equipment, and environment. Risk of injury or loss of life to people are considered under personnel threats, therefore, explosion and fire risks are considered as the major personnel risk triggers. Similarly, results of the explosion and fire aspects may have catastrophic impacts on the environmental level which can be harmed due to a failure during storage or usage of fuels. In this manner, hydrogen seems disadvantageous compared to ammonia. On the other hand, toxicity is forming

a second level of risk for personnel life and environmental impact. From the equipment perspective, both are effectively usable and promising in the case of applying proper materials. As a result, ammonia is showing better performance compared to hydrogen in safety criteria. Therefore, by taking into consideration of the safety issues of ammonia and hydrogen, 3 points are given to ammonia, and 2 points are given to hydrogen.

Environmental impact (C2)

The environmental impact criterion considers emissions of the production phase of ammonia and hydrogen since ammonia and hydrogen are carbon-free alternative fuels for fuel cells. The production emissions in Table 1 are used to give the performance points for ammonia and hydrogen. Ammonia has a lifecycle emission of 173 gCO₂/MJ, 3.24 – 25.93 gCO₂/MJ, and 8.83 – 83.33 gCO₂/MJ, and hydrogen has a lifecycle emission of 139 gCO₂/MJ if it is produced by using grid electricity, 2.59 – 20.74 gCO₂/MJ if it is produced by using wind power, and 6.67 – 66.67 gCO₂/MJ if it is produced by using solar PV electricity. Hydrogen has a higher lower heating value than ammonia that provides a lower lifecycle emission per MJ during the production of hydrogen. According to these data, hydrogen receives 5 points and ammonia receives 4 points at this criterion.

Sustainability (C3)

The sustainability criterion depends on global fuel availability and bunkering infrastructure. Ammonia is the most-produced substance worldwide, and half of the hydrogen is used for ammonia production. Thus, ammonia and hydrogen are almost in similar positions from the fuel availability perspective. The bunkering infrastructure of ammonia and hydrogen is decisive for the performance points. Cryogenic storage and the risk of explosion/fire are some of the challenges of hydrogen bunkering infrastructure. On the other hand, ammonia has properties easier to cope with since there are not any risks of cryogenic storage and a lower risk of explosion/fire than hydrogen. Therefore, ammonia can be more sustainable fuel with a larger number of bunkering ports with adequate infrastructure. The given performance points for ammonia is 4 points and hydrogen is 3 points.

Storage (C4)

The performance points of ammonia and hydrogen, which are given at the storage criterion, are delivered by the consideration of storage methods and volumetric energy density. Ammonia has two storage options; one of them is compressed storage and the second one is liquid storage. Despite hydrogen having four different storage options (compressed, liquid, solid-state, and alternative carriers), the most mature storage options for onboard storage are compressed and liquid storage. Both ammonia and hydrogen have the same storage options for onboard storage, thus the volumetric energy density is decisive for the performance point at this criterion. The volumetric energy density of ammonia is 11333 MJ/m³ while gaseous hydrogen and liquid hydrogen have 2101 MJ/m³ and 8539 MJ/m³, respectively. When the volumetric energy densities of ammonia and hydrogen with the conventional marine fuels, are lower than the volumetric energy densities of conventional fuels. Therefore, 3 points are given to ammonia, and 2 points are given to hydrogen at this criterion.

Cost (C5)

The performance points are given to ammonia and hydrogen at the cost criterion according to the fuel cost and onboard storage cost. Hydrogen has a fuel cost of 153 €/kWh and ammonia has a fuel cost of 120 €/kWh. Moreover, the onboard storage operation costs are between 1.29 – 1.71 €/kWh and 0.23 – 0.29 €/kWh for hydrogen and ammonia, respectively. Hence, hydrogen has a higher fuel cost than ammonia. Since ammonia does not the cheapest fuel option in the maritime industry, 4 points are given to ammonia. Hydrogen has a higher fuel cost and onboard storage cost than ammonia and 2 points are given to hydrogen.

Table 3.10 : Performance points of alternative fuels at each criterion.

Alternative fuels	Criteria				
	Safety	Cost	Storage	Sustainability	Environmental impact
Ammonia	3 (.600)	4 (.667)	3 (.600)	4 (.571)	4 (.444)
Hydrogen	2 (.400)	2 (.333)	2 (.400)	3 (.429)	5 (.556)

3.3.3 Final results and sensitivity analysis

The performance points of ammonia and hydrogen are multiplied by each criterion weighting which was indicated in Table 3.9 and then the results are summed to find the performance weightings of ammonia and hydrogen. Since the expert opinions can be subjective and the criteria weightings can change if there are different experts than this study, the sensitivity analysis is done. The sensitivity analysis shows the effects of the criteria weighting change on the performance weightings of ammonia and hydrogen. To do this, six additional cases are added. Table 3.11 shows all cases including the base case that is the result of this study according to the expert opinions who were involved in the study. The application of the sensitivity analysis was explained in the methodology section. It can be seen from Table 3.11 that the criteria weightings are changed and priority is given to a criterion at each case, except case VII, because this is the case of equal criteria weightings.

Table 3.11 : Criteria weightings at different cases.

Scenarios	Criteria Weightings					Definition
	C1	C2	C3	C4	C5	
I	0.413	0.413	0.086	0.053	0.036	Base
II	0.516	0.340	0.071	0.044	0.030	C1 + 25%
III	0.340	0.516	0.071	0.044	0.030	C2 + 25%
IV	0.403	0.403	0.108	0.052	0.035	C3 + 25%
V	0.407	0.407	0.085	0.066	0.035	C4 + 25%
VI	0.409	0.409	0.085	0.053	0.045	C5 + 25%
VII	0.200	0.200	0.200	0.200	0.200	Equal

Table 3.12 shows the performance weightings of ammonia and hydrogen at the base case and all sensitivity analysis cases, and Figure 3.3 visually exhibits the change at the weightings. The calculations indicate that ammonia has a higher weighting (0.536) than hydrogen (0.465) at the base case. The performance weightings of ammonia and hydrogen at cases IV, V, and VI can be assumed as the same as the base case. It can be said that the variation at C3 (sustainability), C4 (storage), and C5 (cost) criterion does not affect the performance weightings. The reason is the weightings of these criteria are significantly lower than the C1 (safety) and C2 (environmental impact) criteria. The increase of the weighting of C1 (safety) at case II raises the weighting difference between ammonia and hydrogen. The new weightings are 0.547 and 0.454 for ammonia and hydrogen, respectively. It is because ammonia has a higher

performance point than hydrogen at the C1 (safety) criterion due to its safer fuel properties for fuel cell usage. Case III is the case that the weightings of ammonia and hydrogen are the closest to each other with 0.520 and 0.481, respectively. Because hydrogen has a higher performance point than ammonia at the C2 (environmental impact) criterion, the weighting gap between the two fuels is closed. The last case, case VII, is the extreme case that gives the results when all criteria have equal weightings. It is the case that the weighting gap between ammonia and hydrogen is the largest with 0.576 and 0.424, respectively. Although this is the marginal case, it does not affect the order of the fuels which is good for the study. In all cases, ammonia is the most appropriate fuel for the fuel cell on board, and except for the marginal case (case VII), the performance weightings of ammonia and hydrogen remain close to the base case of the study.

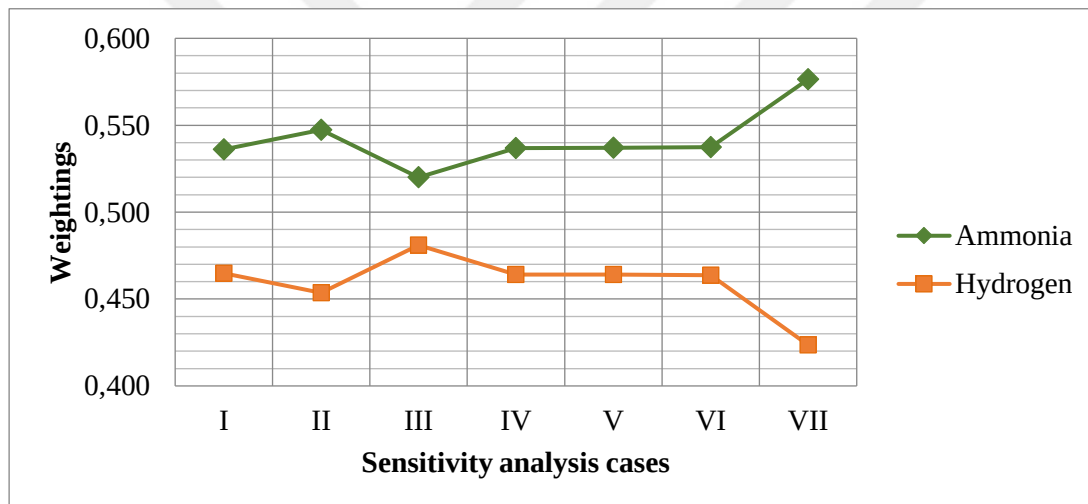


Figure 3.3 : Weightings – sensitivity analysis cases.

Table 3.12 : Performance weightings of ammonia and hydrogen.

	Ammonia						Hydrogen					
	C1	C2	C3	C4	C5	Total	C1	C2	C3	C4	C5	Total
I	0.248	0.183	0.049	0.032	0.024	0.536	0.165	0.230	0.037	0.021	0.012	0.465
II	0.310	0.151	0.040	0.026	0.020	0.547	0.207	0.189	0.030	0.017	0.010	0.454
III	0.204	0.229	0.040	0.026	0.020	0.520	0.136	0.287	0.030	0.017	0.010	0.481
IV	0.242	0.179	0.061	0.031	0.023	0.537	0.161	0.224	0.046	0.021	0.012	0.464
V	0.244	0.181	0.048	0.040	0.024	0.537	0.163	0.226	0.036	0.027	0.012	0.464
VI	0.245	0.182	0.049	0.032	0.030	0.537	0.164	0.227	0.037	0.021	0.015	0.464
VII	0.120	0.089	0.114	0.120	0.133	0.576	0.080	0.111	0.086	0.080	0.067	0.424

3.4 Conclusion

This paper aims to find the most promising and suitable zero-carbon fuel for merchant vessels. The criteria were defined from literature knowledge and ranked using the analytic hierarchy process according to expert points. The explanation for each criterion and performance of the fuels are mainly based on maritime perspective and shipping experiences. Different cases for different importance rates are elaborated thanks to sensitivity analysis, so the reliability of the ranking process is examined. According to the comparison of ammonia and hydrogen, ammonia is safer fuel with lower cost and lower storage issues, and higher sustainability. The only lacking side of ammonia is an environmental impact. Although the difference is low, ammonia has higher well-to-wheel emission than hydrogen that resulting in a higher environmental impact. Finally, in the light of the comparison, it is decided that ammonia is a more suitable fuel than hydrogen for decarbonized shipboard fuel cell applications.

Decarbonization of shipping is the key issue to be resolved and ammonia and hydrogen are two important alternative fuels regarding the future of the shipping industry. It should be noted that in case of a decrease in the cost and with easier storage conditions, hydrogen can play a bigger role. However, today's technological developments give more opportunity to ammonia than hydrogen under maritime conditions in the meaning of sustainable and reliable shipping industry. Both fuels are elaborated with fuel cell systems to achieve the zero-carbon aim, therefore, the power generation step is quite similar for both. Finally, in future works, total system efficiency analysis for a predetermined route and ship can be carried out depending on the different fuels and fuel cell systems. Furthermore, these two fuels may have different behaviors and so different importance rates for alternative ship types. Thus, more specific analysis and different selection parameters can be done case by case according to ship and operation profile.

4. HYBRID POWER AND PROPULSION SYSTEMS FOR SHIPS: CURRENT STATUS AND FUTURE CHALLENGES³

4.1 Introduction

Maritime transportation is one of the economic development promoters for countries by being the major agent of trade between nations for many years. More specifically, 80-90% share of global trade is made by sea transportation (Harrould-Kolieb 2008; Ling-Chin and Roskilly 2016). Being an energy-efficient way compared to road and air transportation is an important reason for the massive use of shipping. As a consequence of this massive use, the biggest fuel consumer in the transportation industry is international shipping (Dere and Deniz 2019). International Maritime Organization (IMO) states that ships approximately consume 300 million tons of fossil fuels annually. The high amount of fossil fuel consumption leads to a high amount of emissions. Although other transportation modes also mainly use fossil fuels, since the content of the fuel is heavy, the amount of GHG emissions in the shipping industry is significant. Ship sourced harmful emissions are mainly caused by the use of fossil fuels. Approximately, 72% of fossil fuel consumption is heavy fuel oil (HFO), 26% is marine diesel oil (MDO), and 2% is liquefied natural gas (LNG) (Gray et al. 2021). Despite the LNG shows better performance of higher energy efficiency and lower GHG emission compared to HFO and MDO, disadvantages like methane slip, and difficulties onboard storage weakened the position in the market (El-Houjeiri et al. 2019). For instance, a study on the comparison of LNG with HFO concludes that LNG may reduce SO_x, NO_x, and CO₂ emissions by 98%, 86%, 11%, respectively (Elgohary, Seddiek, and Salem 2015).

Amount of consumed fuel directly causes well-known climate-changing air polluting greenhouse gases (GHGs), and regulated emissions like nitrogen oxides

³ Inal, O.B., Charpentier, J-F., Deniz C. 2022. Hybrid Power and Propulsion Systems for Ships: Current Status and Future Challenges, Renewable and Sustainable Energy Reviews, Volume 156, 2022, 111965. <https://doi.org/10.1016/j.rser.2021.111965>

(NO_x), sulfur oxides (SO_x), the volatile organic compound (VOC), carbon monoxide (CO), carbon dioxide (CO₂) and particulate matter (PM). According to the Fourth IMO GHG Study 2020, total shipping (international, domestic, and fishing) emitted 1,076 million tons of greenhouse gas (including CO₂, CH₄, and N₂O) which means a 9.6% increase compared to emissions in 2012. According to European Energy Agency (EEA), maritime transportation was responsible for 1.94% of carbon monoxide (CO), 20.98% of nitrogen oxide (NO_x), 11.80% of sulfur oxide (SO_x), 4.63% of particulate matter (PM₁₀), and 8.57% of particulate matter (PM_{2.5}) emission in 2019. Maritime transportation is responsible for around 3.1% of the total CO₂ emissions worldwide, and which corresponds to the sixth most CO₂ emitter country in the world (Balcombe et al. 2019). Furthermore, the share in the global anthropogenic emissions of shipping increased from 2.76% in 2012 to 2.89% in 2018. If any measure is not taken for mitigating shipping emissions, it is expected to increase by 150-250% of emissions by 2050 (Bouman et al. 2017). By the way, CO₂ reduction is an important research area not only for shipping but also for other industries by using different capturing techniques or renewable fuels (Al-Juboori et al. 2020; Cuce et al. 2019; Yin et al. 2020).

Mitigating harmful exhaust gas emissions of shipping is still a challenge for the industry. In this perspective, the International Maritime Organization (IMO), the rule-maker of the industry, is bringing more rigorous regulations for the future of shipping (Livanos, Theotokatos, and Pagonis 2014; Tse et al. 2011) in the framework of the International Convention for the Prevention of Pollution from Ships (MARPOL). The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) are key modifications to MARPOL ANNEX VI which fix some limitations to the air polluting emissions (Gilbert et al. 2018). The harmful emissions are inevitable in the current situation, which still sees the use of fossil fuels such as Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO) as a primary energy source (Inal and Deniz 2021). Therefore, more efficient and alternative solutions to internal combustion engines should be found for the future of the maritime industry. At this point, the maritime industry has mainly three different approaches to eliminate or reduce airborne emissions such as using new emissions abatement technologies, marine alternative fuels, and lastly, electrification of the propulsion with the possible use of hybrid power systems (HPS) (Bennabi et al. 2016). This last solution is the main scope of this paper.

The first approach, emission abatement technologies include many different techniques. Internal engine modifications (IEM), exhaust gas recirculation (EGR) (Kökkülünk et al. 2014; Kyriakidis et al. 2017; Qureshi, Ali, and Sher 2021), fuel water emissions (FWE), waste heat recovery system(WHR) (Boscarato et al. 2015; Nielsen, Haglind, and Larsen 2014), sulfur scrubbers (Jiang, Kronbak, and Christensen 2014), and selective catalytic reduction (SCR) (Choi et al. 2015) are the significant technologies developed to cope with ship sourced GHG emissions. It is obvious that these new technologies are effective in reducing GHG and regulated emissions however, they require additional installation, operation, and maintenance processes that increase the capital and operational expenditures and procedures (Bilgili 2021; Yang et al. 2012).

The second approach is the marine alternative fuels. Currently, methanol, biodiesel, ammonia, biogas, hydrogen, and LPG can be accepted as promising marine alternative fuels owing to their energy capacity (Bilgili 2021; Chiong et al. 2021; Inal, Zincir, and Deniz 2021; Zincir and Deniz 2018). Methanol as being the simplest alcohol can be obtained from natural gas, coal, and different agricultural products (Zincir and Deniz 2021). High flammability and 20,000 MJ/t calorific value are promising but still challenging due to high toxicity (Gilbert et al. 2018). Methanol is under investigation to be used in internal combustion engines to reduce CO₂ emissions (Zincir, Deniz, and Tunér 2019). Hydrogen and ammonia are also important alternative fuels for shipping with their zero-carbon structure. Using renewable energy to produce hydrogen and ammonia is the greenest way instead of separating from fossil fuels like HFO or coal (Sher et al. 2020). Hence, biogas is obtained from agricultural products and organic waste. Methane is the primary energy carrier and the bio form is the most environmentally friendly version. The approximate CO₂ content of the biogas is determined as 25-45% with a 20,000 MJ/t calorific value (Pérez-Fortes et al. 2016). Biodiesel is the most mature biofuel in terms of the production process and supply chain. Biodiesels can be obtained by converting oils and fats into chemicals called Fatty Acid Methyl Ester (FAME) with an esterification process. They have similar properties to diesel fuels by producing low SO_x emissions. LPG is another alternative marine fuel but being explosive and relatively expensive seems like the biggest barrier for ships.

Lastly, the adoption of hybrid-electric for powering the ships both for propulsion and other electrical loads can lead to decrease harmful emissions by reducing fuel

consumption with other advantages as seen in figure 1 (Dedes, Hudson, and Turnock 2016; Fontaras, Pistikopoulos, and Samaras 2008; Nüesch et al. 2014). In this regard, power generation and power storage options have to be well analyzed to find more effective solutions. An optimal and sustainable design according to the ship's operation profile requires a holistic point of view by maritime stakeholders. Hence, the approaches in the literature for the hybridization technologies for ships are generally focused on the use of batteries, supercapacitors, and flywheels as electric storage by combining them with internal combustion engines and fuel cells as power generators (Geertsma et al. 2017; Letafat et al. 2020; Ma et al. 2021; Nuchturee, Li, and Xia 2020). Using a multi-source energy system allows to optimize and improve ship power generation. While the combination of alternative energy sources increases the capital expenditures, thanks to the ability to reach higher efficiencies the operational expenditures decreases.

To be more specific, marine diesel engines are the prominent hybrid combination element with batteries. For instance, diesel-battery hybrid propulsion is investigated for an oceangoing bulk carrier and it is shown that 2% to 3% reduction in fuel consumption and 5% to 7% CO₂ and NO_x emission by increasing the system efficiency can be reached (Dedes, Hudson, and Turnock 2012). Boumann et al. (Bouman et al. 2017) estimate that hybrid power/propulsion can diminish CO₂ emissions by 2-45%. In another research on the diesel-fuel cell hybrid system for an offshore supply vessel, a design is studied to ensure emission regulations (Díaz-de-Baldasano et al. 2014). A study presented by Baccioli et al. (Baccioli et al. 2021) focuses on the hybridization of conventional marine diesel engines with a molten carbonate fuel cell system by using the CO₂ emission of the diesel engine to operate in the fuel cell. According to two different system configurations, 4.9% and 0.8% efficiency gain is reached. Sciberras et al. (Sciberras et al. 2015) studied hybrid propulsion for a Ro-Ro type ship and a 45% reduction in fuel consumption and emission is projected.

On the other hand, various renewable energy resources and non-renewable energy resources should be considered to reach the final multi-energy hybrid solutions according to ship operating modes. Multi-energy hybrid systems are very attractive and promising alternatives for the shipping industry because this kind of configuration allows fuel flexibility and electrical propulsion system integration compared to conventional systems (Yuan et al. 2020). Despite that the hybridization

of energy storage and energy generation technologies makes the system more complex, there are several advantages in terms of efficiency, emissions, maneuverability, maintenance, and fuel consumption (Lhomme and Trovão 2019; Thongam et al. 2013). Therefore, hybridization or electrification of the shipping industry seems like a good option to fit into the predicted IMO framework. It should be noted that the use of hybrid power in ships increases the system complexity, and cost. However, the way on the decarbonization and the new regulations make them viable and necessary. Hybrid propulsion systems are quite new for maritime compared to the automobile industry (Shams-Zahraei et al. 2012; Zahedi, Norum, and Ludvigsen 2014) however, experiences from other industries increase the development speed of hybrid energy solutions in shipping.

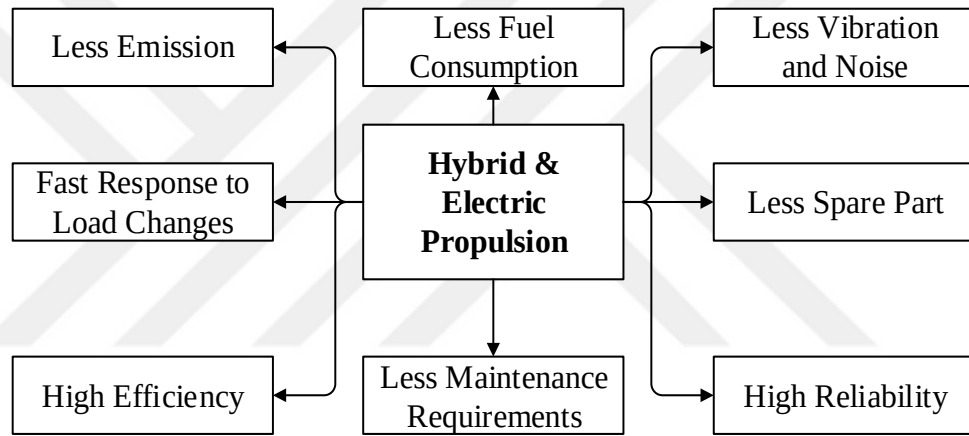


Figure 4.1 : Advantages of electric and hybrid propulsion.

The motivation for this paper is to ensure a comprehensive review of the state of the art of ship hybrid propulsion technologies and the corresponding architectures via presenting strategies and methodologies used for the control and the design of these systems. Additionally, the study develops a generic methodology by defining criteria for hybrid system selection according to ship types and their behaviors. Eight different ship types are selected as the benchmark and possible power generation and energy storage techniques are evaluated for different hybridization topologies. Although there are many ship-based analysis and review papers on hybrid propulsion systems, a state of the art that includes a system selection and classification according to ship types are found as a gap in the literature. Furthermore, an up-to-date review of the current propulsion technologies, energy management systems and optimization techniques are summarized in the same

study by assessing the possible ship types in which the hybrid system can be applied.

In this scope the paper is structured as follows; energy storage and power generation technologies that can be used in ship energy/propulsion systems are presented in sections 2 and 3 via summarizing the most common and promising systems. Hybrid propulsion architecture and energy management systems are presented in sections 4 and 5, respectively. Section 6 discusses the methodologies for system and technology selection and criteria for different ship types. At last, the concluding remarks with the future scope are highlighted in section 7.

4.2 Energy Storage Systems Suitable for Electric and Hybrid Ships

Energy storage systems (ESS) integration is a key point for hybrid ships. On a first hand, integration of ESS allows an internal combustion engine to be operated at the most efficient range to minimize fuel consumption and so harmful emissions. This load-leveling technique is extremely important for the vessels which have an operation profile with transient load variations. Generating the major part of the required power using energy storage systems is necessary and it allows the diesel engine to operate at its high efficiency operating zones instead of low loads where the fuel consumption and emissions increase. ESS choices, combinations, sizing, and global system design and its control should be done in order to respond to operational demands with maximum efficiency considering mission constraints and mission profile. Appropriate roles of ESSs are shown in Figure 4.2.

The most common ESS used in vessels is batteries. However, different combinations of ESS technologies for onboard usage should be carefully considered as a function of their technical characteristics, costs, weights, and sizes (Hebner et al. 2015). For this reason, batteries, supercapacitors, and flywheels are reviewed in this section according to their different advantageous operational characteristics. A summary of their characteristics is shown in Table 4.2.

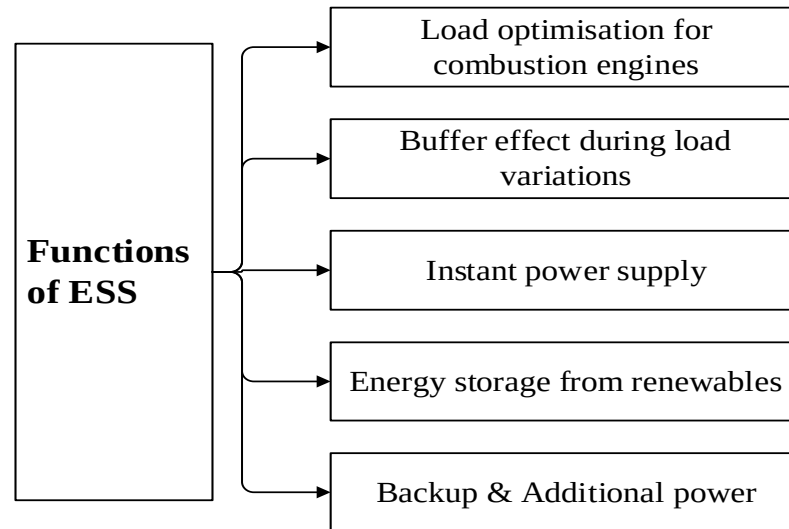


Figure 4.2 : Roles for an ESS on board (adopted from (EMSA 2020)).

4.2.1 Batteries

Batteries are the leading energy storage technology due to their relatively higher energy density, lower cost than other technologies at the same energy level, and already acquired experiences from other transportation sectors. Structurally batteries are formed from electrodes, electrolytes, and separators, while the performance depends on the electrode material (Meng et al. 2017). Since there are various types of batteries that can be commercially applied in the transportation sector, for the maritime industry selection of battery type is an important process for reliable, efficient, and proper application. Even if other kinds of batteries can be used in the future, reviews on the ESS suggest that Li-ion batteries are favorable for shipping considering their high energy densities and high lifetime (cycle) thanks to their industrial maturity level and availability (Chen et al. 2009; Georgescu, Godjevac, and Visser 2018; Luo et al. 2015). Furthermore, the cost of Li-ion batteries is significantly reduced in recent years (DNV-GL 2020). Therefore, the properties of the Li-ion battery are considered for the further steps in the paper as can be noticed in Table 4.1. All battery types have pros and cons, for instance; the most widely used lead-acid batteries are well-known for their low-cost but they suffer from low energy density (Ibrahim, Ilinca, and Perron 2008; Tian et al. 2017); in contrast, nickel-metal hydride batteries can reach to high energy density, however, their self-discharge rate is over 28% (Taheri, Yazdanpour, and Bahrami

2014). The most important and popular battery types for ships are summarized in table 4.1.

Table 4.1 : Characteristics of popular battery types (Al-Zareer, Dincer, and Rosen 2017; Aneke and Wang 2016; Chen et al. 2009; Ma et al. 2021; Nuchtaree et al. 2020).

Battery Type	Energy density (kWh/kg)	Power density (kW/kg)	Efficiency	Lifetime (Cycle)	Capital Cost (\$/kWh)
Lead - Acid	$30-50 \times 10^{-3}$	$75-300 \times 10^{-3}$	70-90%	500-1000	70
Nickel - Cadmium	$50-75 \times 10^{-3}$	$150-300 \times 10^{-3}$	60-65%	2000-2500	300
Nickel Metal Hydride	$60-100 \times 10^{-3}$	$200-1500 \times 10^{-3}$	65-90%	750	300-500
Lithium – Ion	$100-200 \times 10^{-3}$	$80-2000 \times 10^{-3}$	85-90%	600-2000	200-700

Since the batteries offer a great hybridization solution for ships, many analyses were carried out with multiple different strategies. As an example, the hybridization of Li-ion batteries with PEMFC is analyzed for a coastal ship in terms of feasibility and benefit while taking into account several constraints such as power and energy density, lifetime, and cost (Wu and Bucknall, 2020). A proposal on the identification of parameters to estimate the state of charge and capacity of the battery in use onboard ship is studied in (Misyris et al. 2017). The effect of a hybrid battery-diesel electric propulsion system on the exhaust gas emissions for the global dry bulk carrier fleet is analyzed and a potential of 14% reduction of GHG emission is found (Dedes et al. 2012). Alternatively, different configurations of hybrid battery-diesel generators have different effects on emissions. The analysis on the arrangement according to diesel-battery power distribution is studied and specific configurations adapted to mission profile can achieve better results in terms of emission reduction (Vieira et al. 2017). On the other hand, all-electric ship propulsion projects with full batteries are also under investigation. For instance, MF Ampere is an important project and considered as a milestone on the way through

zero-emission fully electric ships, see Figure 4.3 (URL-2). The vessel is the world's first all-electric car ferry and has been operating in Norway since 2015. The 80 m long vessel is equipped with 10 tons of lithium nickel manganese cobalt oxide (NMC) battery, a subtype of li-ion battery, with an energy capacity of 1 MWh. Recharging is done from shore connection during short breaks of unloading and loading at the port and overnight (Karimi, Zadeh, and Suul 2020). The results of the project were fascinating by reducing 1 million liter diesel so more than 8 thousand tons of CO₂ since the ferry has been put into service in 2020 (EMSA 2020).



Figure 4.3 : World first all-electric car ferry “MF Ampere”.

4.2.2 Supercapacitors

Supercapacitors are technologically developed versions of conventional capacitors in the meaning of higher capacitance, higher power density, and cycling capability due to higher electrode surface area and thinner dielectrics. The rapid charging and discharging ability of supercapacitors make them a good option for buffering the load fluctuations in the power system (Zhou et al. 2013). In contrast, limited energy density shows up as an important disadvantage, and so this kind of solution requires another ESS or power generation system for a long-term sustainable operation. Meanwhile, in case of the need short time for power deliverance, power density gains importance, so supercapacitors and to a lesser degree flywheel emerge as solutions compared to batteries (Hebner et al. 2015). Therefore, supercapacitors can have a key role to optimize the hybridization of a ship power system according to operation profile. For instance, Nebb et al. showed a reduction in fuel consumption for an offshore supply vessel for different operation profiles and supply the load changes with a hybrid supercapacitor-battery energy storage system (Nebb et al.

2012). In another study on the techno-economic analysis and optimization of the use of supercapacitor for an electric ferry is elaborated and a 6% decrease in cost is reachable compared to the conventional design with an estimated lifetime of 20 years (Trieste et al. 2015).



Figure 4.4 : “Ar Vag Tredan” supercapacitor driven ferry.

A commercial application on the usage of supercapacitors as an energy storage device for fully electric propulsion has been implemented on the passenger ship Ar Vag Tredan (Figure 4.4) (URL-3). The 22m catamaran ferry serves as a short transportation trip in the Bay of Lorient in France at a maximum speed of 10 knots and it is recharged from shore connection during the passenger loading and unloading (RAE, 2013).

4.2.3 Flywheels

Flywheels are electromechanical devices that store energy in the kinetic energy form by a spinning rotor. The rotating speed of a flywheel is related to an energy-storing capacity. The kinetic energy amount for a flywheel is expressed with the formula (1), where I is the moment of inertia and ω is the rotational velocity (Bolund, Bernhoff, and Leijon 2007).

$$E = \frac{1}{2} I \omega^2 \quad (4.1)$$

If the rotating object is a disc, the stored energy can be expressed with formula (2), where the m is the mass of the disc, and r is the radius of the disc (Bolund et al. 2007).

$$E = \frac{1}{4} mr^2 \omega^2 \quad (4.2)$$

Flywheels are offering an average solution using a trade-off by providing higher energy density than batteries and higher power density than supercapacitors as given in table 2 (Bolund et al. 2007; Hou, Sun, and Hofmann 2018). Although the power density is higher than other ESSs, energy density is lower (Farhadi and Mohammed 2016), therefore the main usage area of flywheels is for tempering load fluctuations such as uninterruptible power supplies (UPS) (Park, Kalev, and Hofmann 2008; Zhou et al. 2013). The friction losses are the main disadvantages; however, magnetic bearings are substantial developments that significantly reduced the friction and the system efficiency can reach more than 90% (Aneke and Wang 2016). Flywheels offer a longer lifetime compared to batteries thanks to their very high cycling capabilities in a wider temperature range without capacity and performance degradation (Bolund et al. 2007; Hou et al. 2018). Furthermore, flywheels are scalable technology with short recharge time and using environmentally friendly materials.

Table 4.2: Comparison table of energy storage options (Nuchturee et al. 2020).

ESS	Energy Density (kWh/kg)	Power Density (kW/kg)	Capacity (kW)	Efficiency	Cycle Life
Battery (Li-Ion)	75-200×10 ⁻³	200- 315×10 ⁻³	Up to 100	85-90%	1000- 10,000+
Supercap- acitor	2.5-15×10 ⁻³	500- 5000×10 ⁻³	Up to 300	90-95%	100,000 +
Flywheels	10-30×10 ⁻³	400- 1500×10 ⁻³	Up to 2500	93-95%	20,000+

Optimization of long-term operation of flywheels is still under investigation to use in vehicles (Luo et al. 2015). However, safety reasons can limit their implementation in ships but still, they can be used to supply pulsed load in military ships (Mutarraf et al. 2018). Indeed, due to high-speed disk velocity, specific protecting housing is necessary, and specific qualifications are required for ship

operating engineers (Inal, Dere, et al. 2021). The common energy storage methods; batteries, supercapacitors, and flywheels are explained and details are given in this section. The power generation technologies will be the third section.

4.3 Power Generation Technologies

Onboard power generation technology choices for the shipping industry are limited. Although the devastating majority is Internal combustion Engines (and particularly marine diesel engines), fuel cells and renewable energy sources also have several examples thanks to their clean energy generation capacities and global environmental concerns. As an advantage, hybrid systems are more flexible than conventional propulsion systems due to their multiple powering options, so, in this section commonly used power generation technologies in hybrid systems are reviewed.

4.3.1 Internal combustion engines

The most conventional and most common way to generate power on board for propulsion and electric loads are the internal combustion engines. Over the 19th and 20th centuries, the driving engines for ships are switched to diesel engines from steam engines and steam turbines (Geertsma et al. 2017). But also, there are several examples of gas turbines instead of diesel engines, especially for warships and very high-power generation. However, from an economical perspective, diesel engines are the major driving engines currently used in vessels. The leading driver of using marine diesel engines is higher efficiency compared to high-pressure steam turbines which can reach 35-37% where diesel engines operate around 48-52% (Nguyen et al. 2020; Provataris et al. 2017). The major advantages of marine diesel engines are being well-experienced, and so, their well-known operational procedures, highly accessible spare parts, and also advanced global fuel bunkering nets put them at the top of the market of marine power sources. However, especially environmental concerns start to shake their power in the market in recent years. Harmful emissions from diesel engines are tried to be controlled by IMO but, it seems difficult to stay below limits using today's technology and diesel fuels.

Although diesel engines' CO₂ emissions are lower than Otto cycle engines thanks to their higher efficiency, they have higher NO_x emissions due to their higher

compression ratio and higher burning temperatures (Dere and Deniz 2020; Özgül and Bedir 2019). Moreover, on the purpose of reducing CO₂, NO_x, SO_x, and PM emissions, liquefied natural gas (LNG) is a very promising solution for LNG carriers by adopting dual-fuel diesel engines (DFDE) using the boil-off gas which occurs in pressurized tanks due to the heat transfer of cryogenic storage. The DFDE operates with both classical fuels; marine diesel oil (MDO) and heavy fuel oil (HFO), and relatively new fuel LNG. The possibility of LNG for shipping is highly in demand after revision of the regulations on NO_x, and SO_x limits in MARPOL Annex IV by the IMO Marine Environment Protection Committee (MEPC). As can be noticed, just by calculating the carbon conversion factor - the equivalent of the emitted CO₂ per mass of the consumed fuel of LNG approximately 14% reduction of CO₂ can be reached in comparison to diesel fuel, as seen in Table 4.3. For instance, an Energy Efficiency Design Index (EEDI) analysis for LNG carriers is made by (Ekanem Attah and Bucknall 2015) considering unburned methane. In another paper economic analysis of LNG using dual-fuel engines is studied according to the cost-effectiveness of different projects (Ge and Wang 2016). However, there are still some problems for LNG usage other than LNG carriers, such as the high cost of onboard storage tanks and safety risks (Wang and Notteboom 2014). Meanwhile, five dimensions are identified as environmental, social, infrastructure/technology, economic price, and maritime demand for marine transportation market development of LNG as fuel (Thomson, Corbett, and Winebrake 2015).

On the other hand, biofuels are significantly effective in the transition to clean energy for the shipping industry (Mofor, Nuttall, and Newell 2015). The main and the major driving advantage of biofuels is the availability of current ship infrastructures like marine diesel oil or heavy fuel oils (Tandekar 2019). Considering the emission reduction, biofuels have a substantially lower impact on the environment compared to fossil fuels like marine diesel oil or heavy fuel oil (Chuah et al. 2017). Although, there are several options to control and eliminate harmful emissions such as; scrubbers, exhaust gas recirculation system, selective catalytic reduction, variable injection timing, and exhaust gas cleaning systems (Lee et al. 2020) high investment cost regarding ship lifetime and limited fossil fuels prepare the alternative fuels and hybrid propulsion to the stage as attractive solutions (Deniz and Zincir 2016; Hansson et al. 2019; Zincir et al. 2019).

Table 4.3 : Conversion factor between fuel consumption and CO₂ emission (IMO 2018).

Fuel Type	Reference	Carbon Content	Conversion Factor
Diesel / Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
Liquefied Natural Gas (LNG)	-	0.75	2.750

However, marine diesel engines have an important role in the hybridization of propulsion systems thanks to their advantages at the cost of fuel oil and higher reliability (Bassam 2017). Marine diesel engines are inefficient during partial loads operations so, their fuel consumption and emissions increase. In terms of satisfying emission limitations and keeping competitiveness at sea trade, minimizing fuel consumption is the major objective. By the way, as fundamental operating characteristics of the diesel engines; most of the engine builders recommend operating their engines above 60% load of the maximum continuous ratio (Nguyen et al. 2020). However, engine loads frequently change particularly during berthing, maneuvering, and departing operations. Therefore, this led to the emergence of the technique of providing the demanded power with energy storage systems such as batteries and supercapacitors which allows the operation of diesel engines at more efficient loads.

4.3.2 Fuel cells

Fuel cells directly convert the chemical energy of the fuel into DC electricity which is fed into the cell unit (Barbir 2005). Since there is only one step of energy conversion by eliminating combustion processes of internal combustion engines, total efficiency is relatively higher than marine diesel engines (Bicer and Dincer

2018). Fuel cells use often hydrogen as a primary fuel option and so they can operate more cleanly than diesel engines (Han, Charpentier, and Tang 2012). In this manner, regarding strict emission regulations, fuel cells are very promising with their low environmental impact for powering future ships (Yan et al. 2020). The major difference between fuel cells from other energy storage systems is their ability to operate without any need for recharging, so they can generate electricity as long as the fuel is supplied.

Fuel cells are classified according to the type of the used electrolyte and commercially five types of the fuel cell are available in the market: Proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). The most popular type is the PEMFC due to its high technological maturity and widespread applications both in maritime and other energy applications (De-Troya et al. 2016). Technological maturity comes with an advantage on the cost side, and also in operational experience. However, as a major drawback, the PEMFC needs hydrogen in high purity, otherwise, the cell unit stops working due to poisoning from carbon monoxide (Baschuk and Li 2001).

The main changes in the operation properties of different fuel cell types arise from the working temperatures; the high and low temperature working fuel cells show different characteristics. MCFC, PAFC, and SOFC are the high-temperature types. By the way, there is also a high-temperature version of PEMFC (HT-PEMFC); switching the membrane material perfluorosulfonic acid (Nafion) with polybenzimidazole (PBI) allows to operate at higher temperatures (Rosli et al. 2017). The HT-PEMFC addresses some problems of PEMFC like water management at the cathode side and high sensitivity to fuel impurities (Tronstad et al. 2017). The high-temperature fuel cells are less sensitive to fuel content and much more flexible in fuel selection; for instance, both hydrogen and hydrocarbons such as diesel oil, methanol, and LNG are the fuel options for SOFC and MCFC via a reforming process (Díaz-de-Baldasano et al. 2014). Besides the fuel flexibility, increase in the power capacity, and efficiency are the direct results of high operating temperatures.

Fuel cells are modular so, their physical properties such as weight or size change according to required power by the system. In general, power output capacity is in kW levels, however, for high-temperature versions, MW levels are also reachable

(van Biert et al. 2016). Indeed, exhaust gases from high temperatures can be used with a combined turbine system so the total system efficiency and power output increase (Inal and Deniz 2020). Selecting the most promising fuel cell type for hybridization is highly dependent on the operation profile of the ship. However, from the handled projects, it seems that PEMFC, MCFC, and SOFC show better performances compared to other types. They have different advantageous specifications; if the power requirement is high, and difficulty at the onboard storage of hydrogen occurs, SOFC and MCFC are preferable. Though, from the emission side, high power density, and technological maturity are the strong sides of the PEMFC. However, the need for high purity hydrogen as a fuel is still not economical for long seas. Therefore, zero-emission is achievable with PEMFC if the case is inland and/or short sea shipping with limited propulsion power requirements.

Various research and development projects have been investigated for different types of fuel cells in shipping. One of the pilot projects; FellowSHIP aimed to investigate the use of hybrid and separated battery-fuel cell technology on an Offshore Supply Vessel (OSV) “Viking Lady”. This ship is shown in figure 4.5 (URL-4). The project is carried out from 2003 to 2018. The main focus of the project was the on-board testing and measurement of the fuel cell by the installation of a 320 kW LNG fueled MCFC system for the auxiliary power needs of the ship. The system is operated for 18500 h at constant load without emitting NO_x, SO_x, or PM (Inal and Deniz 2018).



Figure 4.5 : “Viking Lady” OSV in FellowSHIP project.

4.3.3 Renewable energy sources and other carbon-free sources

The design and strategy of renewable energy sources (RESs) apply to both conventional and hybrid-electric propulsion ships. Technological improvements and readily available solutions call the shipping industry's attention to RESs on the way to zero-emission and carbon-free ship transportation. RESs for the shipping industry is mainly focused on solar energy (Karatuğ and Durmuşoğlu 2020; Wang et al. 2019), wind energy (Fagiano et al. 2012; Kim and Park 2010; Leloup et al. 2014; Talluri, Nalianda, and Giuliani 2018), wave energy (Alujević et al. 2019) and biofuels (Hansson et al. 2019) are carried out in hybrid systems (Tang, Wu, and Li 2018).

The purpose of photovoltaic cells is to supply additional electric energy for the propulsion system or electrical loads of the ship. Solar energy is beneficial considering the auxiliary power demand of the ship, but considering the driving system, the output power is very limited because it is directly related to the available surface where the PV can be implemented and a low power level by the square meter (a few hundred W/m²). The power production depends on the atmospheric and geographical conditions such as the latitude, angle, solar radiation, convection-conduction heat losses, or position of PV panels (Strušnik et al. 2020). This causes power fluctuations whereas it is a necessity to supply stable power to the system. For these reasons solar energy needs an energy storage device and it is generally discussed as a complementary element of a hybrid system for ships. For instance, the design of a combination hybrid PV, diesel, and battery system is elaborated by Lan et al., to optimize the size of the system and maximize the energy efficiency of diesel engines by considering environmental effects (Lan et al. 2015). Furthermore, the ship's physical movements are also affecting the hybrid PV-ESS system efficiency, for instance, the swinging effect is studied by Wen et al. (Wen et al. 2016). Stable power generation is hard for PV panels under maritime conditions. Environmental disturbances such as salt spray and seawater are heavily affecting their efficiency. The combined effect of both can cause to 6% power reduction is found by Zhang and Yuan (Zhang and Yuan 2021). The limited capacity of solar panels and high cleaning requirements for efficiency restrict the consideration for ship application to auxiliary and complementary power sources.

On the other hand, wind energy has various forms to assist the propulsion power by reducing the load of the main engine. Typical techniques to convert the kinetic energy of the wind are Flettner rotors, kites, wind turbines, and wing sails. Flettner rotors' invention dates back to the 1920s. Theoretically, it uses the Magnus effect and when the wind passes across the rotor a thrust force is produced perpendicular to the wind direction (De Marco et al. 2016). The Flettner rotors can generate power even ship speed is greater than the wind speed and it is affected by wind direction rather than speed. Also, the simulation results show that Flettner rotors can diminish fuel consumption by up to 20% (Talluri et al. 2016). A recent application of the rotors is studied at the E-Ship1 project was built in 2010 and the vessel is equipped with two 3.5 MW diesel and four Flettner rotors, the produced energy by this hybrid system allows the ship to sail 17.5 knots (Lu and Ringsberg 2020) as seen in figure 4.6 (URL-5). In contrast, soft sails and kites are simple seem as much more historical by direct use of wind power. Mainly, the performance is related to wind power and direction while the system applies to almost all vessel types without the need for any extra space. Figure 4.7 shows an application of kite usage for an oceangoing vessel (Groot and Wessels 2012). The gain of the kite system can reach 50% at Beaufort 7 depending on the air and sea state (Leloup et al. 2016). Another option is the wind turbine, and a very detailed analysis according to the horizontal and vertical configuration of the wind turbine's axis is done by (Talluri et al. 2016). Vertical axis wind turbines have various advantages compared to horizontal ones such as less complex structure, lower operational and capital costs, ease of installation on a ship in the meaning of stability thanks to lower mass center. Although these advantages for the marine industry, horizontal axis turbines have higher efficiency with higher power production capacity.



Figure 4.6 : “E-Ship 1” with 4 Flettner rotors.



Figure 4.7 : Kite assists to propulsion.

In conclusion, it should be noted that wind and solar-assisted propulsion applicability for ships is limited. By the way, solar and wind energy usage requires some structural changes on the shipboard, and specifically, solar panels require a large surface for installation. On the other hand, the relative immaturity for ships and very high dependence on environmental conditions make it difficult for RES to be the main power source. Also, their low power density makes them a complementary power source.

It can be also noted that nuclear microreactors are under study for high power ship application. These kinds of sources have been developed for military ships; for example, nuclear submarines and aircraft carriers and some particular civilian ships as icebreakers (Carlton, Smart, and Jenkins 2014; Gabbar, Adham, and Abdussami 2021; Gravina et al. 2012; Hirdaris et al. 2014). They can also be associated with RE sources and ESS in hybrid configurations (Gabbar et al. 2021). Even if some study investigates the possibility to use these systems for civilian ships and underlines their high performance and carbon-free energy production potential, safety, integration, social acceptability, and ethics (nuclear dissemination) constraints limit their application in merchant ship context (Carlton et al. 2014; Gabbar et al. 2021; Gravina et al. 2012; Hirdaris et al. 2014).

4.4 Hybrid Propulsion System Architectures

In hybrid energy configuration, the energy distribution is mainly done using electric systems. Hybrid propulsion systems for the ship can be classified under three different configurations depending on the energy distribution from the energy

sources to the propeller; serial, parallel, and combined serial-parallel architectures according to the power transmission technique which is used for propulsion power. The majority of the shipping industry uses an AC grid with fixed frequency for all-electric ship systems (Zahedi et al. 2014). However, the development in power electronics and higher system stability allow DC systems to spread (Balsamo, Lauria, and Mottola 2019; Butcher, Maltby, and Parvin 2009). This is why the DC distribution grid is considered for illustrating the topologies in this paper. Generally, a hybrid power supply consists of a combination of several power sources and energy storage systems from the ones which are described in previous sections of this paper. The different architecture topologies are presented in the following sections, and methodology according to the selection of the system and their comparison are given at last.

4.4.1 Serial configuration

The serial configuration of the hybrid propulsion for ships is relatively mature compared to other configurations (Geertsma 2019). In this system, all power generators like fuel cells, renewable energy sources (RES), or diesel generators and energy storage sources (ESS) like batteries or supercapacitors and the corresponding converters are connected to a main electrical grid, as shown in figure 4.8 (blue rectangle). The propellers are driven with variable frequency supplied AC motors so, connected to DC main electrical bus bar by a DC/AC drive while the battery and fuel cell are connected through a DC/DC converter and can be used directly in the DC bus. The other distributed electric power consumers such as air-conditioning, hotel loads, navigation equipment, and other systems are also connected to the main grid. Many combinations of power sources and energy storage systems can be used with this configuration and depend on the specifications of the ship. In this paper, all applicable options are illustrated to show different alternatives which can be used during the design process.

The major advantage of the serial configuration is sourced from having various operation modes. Since the total electrical energy of the system is collected and uses a common bus bar for distribution of the energy (Lashway, Elsayed, and Mohammed 2016), multiple working modes can be used especially by using just one (e.g. only battery power) or a combination of power supply (e.g. fuel cell-battery, ICE-supercapacitor, or other adapted combinations to the ship and the

operating point). On the other hand, the other energy sources on the system like ESS, FC, or RES allow diesel engines to work in their range of high-efficiency operation zone by assisting at the low load region where the diesel engine suffers from the low efficiency (Bayindir, Gözükcük, and Teke 2011).

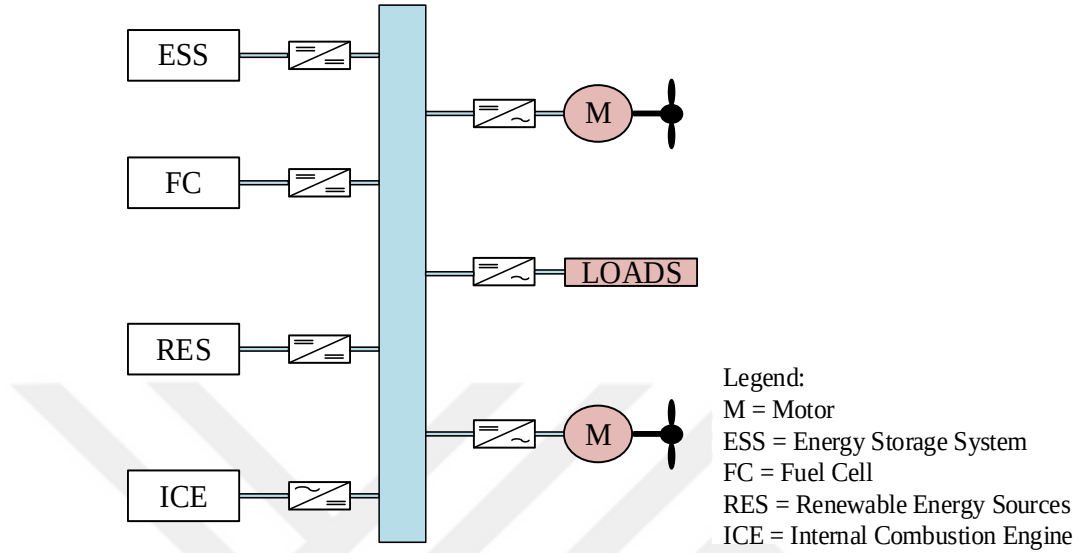


Figure 4.8 : Serial hybrid power topology.

4.4.2 Parallel configuration

The main difference of parallel configuration is the keeping a part of direct mechanical connection between internal combustion engines and propellers. Practically, the electric generation and storage side of the system is very similar to the serial configuration, however, it differs at the propulsion and load side. Thus, the energy storage system, other energy sources, and the additional electric motor which is connected to the gearbox are aiming to improve the performance by assisting the propulsion, as seen in Figure 4.9 (Liu 2020). In another saying, the assisted electric motor reduces the thermal load of the internal combustion engine and so, decreased load causes less fuel consumption and emission.

The major advantage of the parallel configuration is containing both electrical and mechanical propulsion characteristics and their benefits. For instance, limited maneuverability due to mechanical propulsion is removed thanks to electrical propulsion. As another example; the diesel engine can work at the high efficiency and low fuel consumption spectrum without having any trouble due to thermal load thanks to auxiliary electric motor supply. However, the balance between mechanical and electrical links to the propulsion unit should be elaborated on

carefully. Hence, the control strategy for this configuration gains importance and allows to find an optimum point to high efficiency for different power demands (Geertsma et al. 2017). As another advantage, the size of electrical components can be reduced in power capacity thanks to ICE's ability to supply the transient higher power demands.

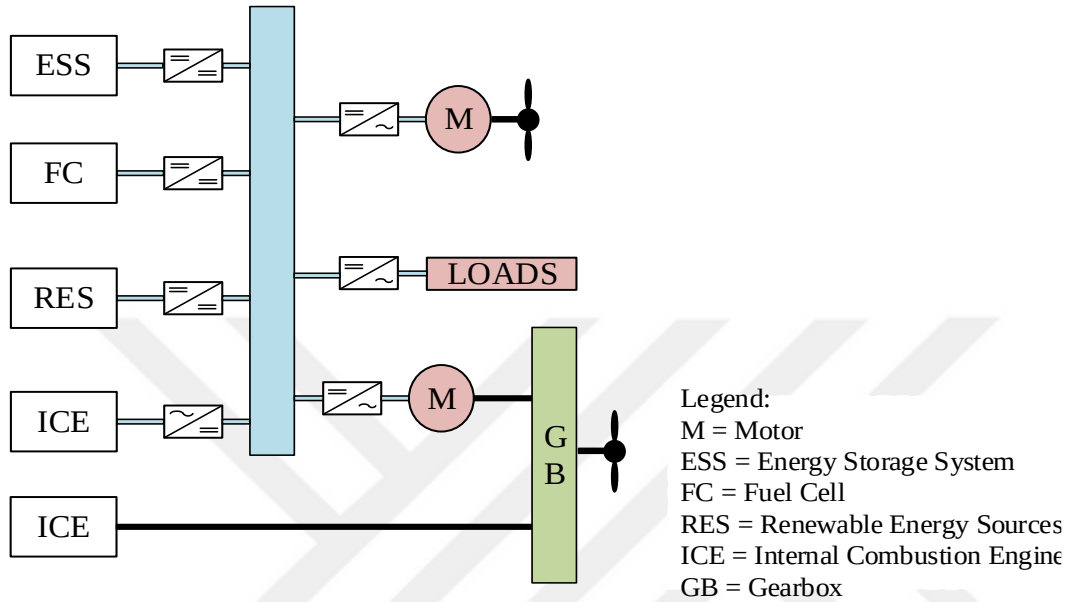


Figure 4.9 : Parallel hybrid power topology.

4.4.3 Serial-parallel configuration

The hybrid serial-parallel propulsion system is a combination of both configurations that support specific features of each system (Dupriez-Robin et al. 2009). This unique configuration allows the system to operate in many different ways; e.g. directly mechanical, fully electric, only serial hybrid, only parallel hybrid, or both. Although the propulsion side is similar to parallel configuration, the mechanical link has another connection with the electrical bus bar via a different gearbox before powering the propeller motor as seen in Figure 4.10. The architecture of the hybrid system is relatively complex compared to other configurations. In return, it consists of advantages from both configurations such as containing different operation modes by using more flexible energy flow controls and optimization of energy consumption (Yuan et al. 2020). A benefits and challenges summary for hybrid propulsion architectures is given in Table 4.4. Both systems have pros and cons and the choice of the configuration should be considered according to ship properties to find the optimum propulsion system.

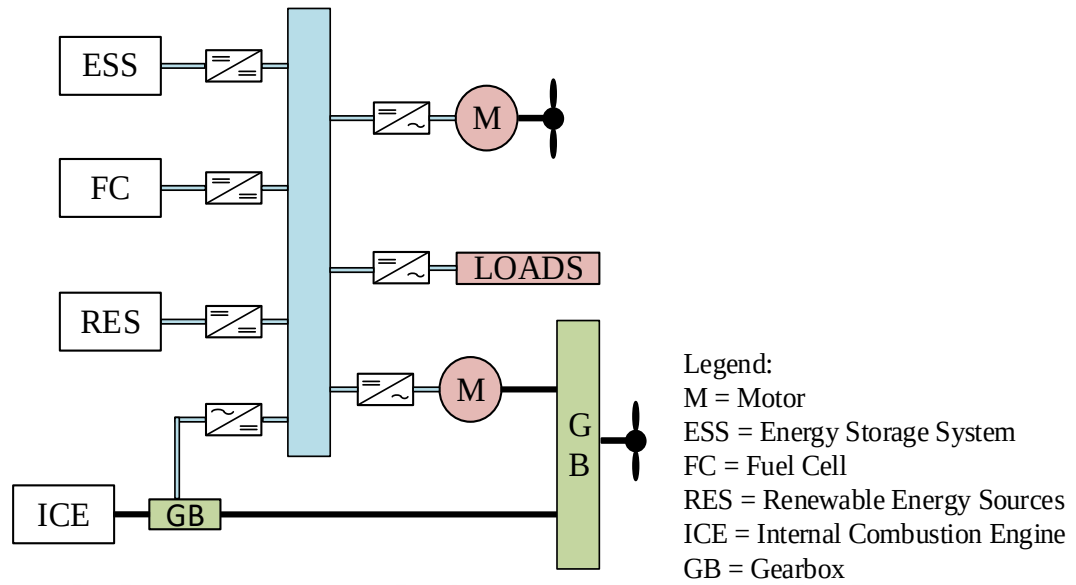


Figure 4.10 : Serial – parallel hybrid power topology.

System suitability is highly dependent on the compromising of CAPEX, OPEX, and other specifications. But from the general perspective, despite its complexity and higher cost, serial-parallel configurations offer better solutions for a great number of ships. The three hybrid propulsion configurations; serial, parallel, and serial parallel are explained in this section. Their advantages and disadvantages are revealed and compared. The next chapter will be about the energy management system and control strategies of hybrid ship propulsion systems.

Table 4.4 : Comparison table of hybrid propulsion system architectures (Bennabi et al. 2016; Geertsma 2019; Geertsma et al. 2017; Ma et al. 2021; Nguyen et al. 2020).

Architecture	Benefits	Challenges
Serial Configuration	• Relatively long operational life • Mature technology, precise control • Engine downsizing and modular system • Zero noise and emission availability • Less fuel consumption and emission	• Multiple energy conversion • Loss of energy during conversions and relatively lesser efficiency • Only electrical propulsion is available

Table 4.4 (continued) : Comparison table of hybrid propulsion system architectures (Bennabi et al. 2016; Geertsma 2019; Geertsma et al. 2017; Ma et al. 2021; Nguyen et al. 2020).

Parallel Configuration	• Zero-emission operation availability • Both mechanical and electrical propulsion availability • ICE can operate at a higher efficiency zone and reduced fuel consumption • Sizing optimization available • Reduced electrical chain and motor size • Relatively flexible control • Increase of DOF in operation modes	• Complex propulsion • Power and torque repartition rules • Additional mechanical links • Hard dynamic switching according to operational need • Need of robust control for higher efficiency
	• Zero-emission operation option • Higher efficiency at lower loads and higher loads • Both mechanical and electrical propulsion availability	• Complex system architecture • Higher cost • Same challenges as for the serial configuration

4.5 Energy Management Strategies

Implementing a real-time energy management smart strategy is extremely important for hybrid-powered and propulsion ships to maintain higher efficiencies of the system and components, and economical, safe, and reliable operations. Since the hybrid power systems contain multi-energy sources and also several consumers, different dynamic characteristics can occur during different kinds of operations. Hence, the energy management system (EMS) should be well organized and applied to give a clear response to changing dynamic requirements of the system to ensure a safe power supply to ship auxiliary loads and propulsion systems. An appropriate EMS can improve energy efficiency and reduce fuel consumption by controlling each power source to achieve optimal operational conditions. In the main, there are two types of EMS that can be reviewed for ships; rule-based, and optimized control strategies (Balsamo et al. 2017; Yuan et al. 2020).

4.5.1 Rule-based control strategy

The rule-based control system is a static control strategy that shows good robustness and strong real-time performance by providing practical control rules which are obtained from previous experiences and expert knowledge, however, optimization capacities are limited because of the weak dynamic response to changes. The rule-based control is commonly used with logic thresholds (Da Rù et al. 2016), and different control strategies with the same approach are proposed for multi-energy hybrid systems. For instance, a hierarchical energy management system for a hybrid system composed of solar panels, wind turbines, batteries, and fuel cell systems is presented by taking into account economic aspects (Torreglosa et al. 2014). In this research, EMS is constituted by master and slave control strategies, where the master defines major and vital reference points to maintain the system efficiency at desired values, and the slave control modifies the subsystems operating points to satisfy the master's commands. The use of cascade control which is composed of PI controllers to generate the master control reference points is an example of how to use logic thresholds in a rule-based control strategy.

On the other hand, since the rule-based control strategy highly depends on experience, it becomes hard to find the optimal point for more complex and dynamic systems. Due to the maritime environment having unpredictable conditions and being open to outsourced manipulations like sea and wind effects, the smartest control strategies gain importance when a multi-model and multi-purpose control is required with dynamic time-varying nonlinear problems. The fuzzy logic control is one of the based artificial intelligence control systems and does not require an accurate mathematical model with a tolerable error. A fuzzy-based control method is developed for energy management of the PV, battery, diesel hybrid RORO ship (Yuan et al. 2018). As a result of the research, a decrease in fuel consumption, and emissions by improving the total ship performance are reached by comparing the real ship data and simulation results. Another comparison between fuzzy logic and proportional-integral control-based EMS has been carried for medium voltage DC all-electric ship power systems (Khan, Faruque, and Newaz 2017). Although both EMSs supply the ship power system successfully in different power demands, fuzzy logic control showed better performance on the state of charge management of the batteries by changing charging and discharging rates.

However, establishing the fuzzy rules requires strong expertise in system management and behavior prediction.

The ships are dynamic systems and it is hard to fit into a stable linear mathematical model. Consequently, optimized control strategies are much more effective for multi-energy ships than rule-based control strategies thanks to their sensitivity to different operational aspects and convenience to complex systems (Al-Falahi et al. 2018).

4.5.2 Optimized control strategy

The optimized control strategy can be categorized under two sections; global optimization (GO) and real-time optimization (RTO). Firstly, global optimization uses all system models and conditions with the theoretical basis and accurate mathematical equations to perform offline an overall optimization within a given period. The GO can include dynamic programming algorithm (DPA) (Kanellos, Tsekouras, and Hatziaargyriou 2014), genetic algorithm (GA) (Ancona et al. 2018), artificial neural network (ANN) (Tarelko and Rudzki 2020), particle swarm optimization (PSO) (Divyajot, Kumar, and Fozdar 2018), ant colony optimization algorithm (ACOA) (Xiang and Yang 2021), simulated annealing algorithm (SAA) (Wang et al. 2017), and differential evolution algorithm (DEA) (Wu et al. 2011) or other advanced optimization algorithms. The DPA requires entire information about the optimization problem in advance. In a research on the optimization for the power generation scheduling of an all-electric ship by using DPA, concerning operational constraints like GHG emissions or travel schedule, and while it is assumed that the ship load changes can be forecasted, a decrease in operational costs and GHG emissions is achievable (Kanellos et al. 2014). The GA has good versatility and a wide range of feasible applications with low algorithm complexity. For example, Ancona et al. proposed a GA-based optimization to minimize the fuel consumption by optimizing the load allocation with different energy source configurations for a cruise ship. As a result, hybrid systems showed the best performance among all analyzed parameters, such as economic and environmental (Ancona et al. 2018). Another optimization strategy; the application of ACOA with ECMS on a diesel-electric hybrid ship is analyzed by Xiang and Yang where the aim was to reduce fuel consumption and state of charge fluctuation on the battery (Xiang and Yang 2021). The ACOA based optimized energy management system

almost doubled the rule-based optimization version in fuel consumption by 6.9% to 12.1% reduction, respectively. Another research on the optimal sizing of solar panels, ESS, and diesel generators is conducted by Divyajot et al. using the two different variants of PSO for an oil tanker and it is found that without an ESS, hybrid solar and diesel configuration is not feasible economically (Divyajot et al. 2018).

The second kind of optimized control strategy is RTO. This is an online optimization strategy that focuses on the instantaneous conditions of the energy demand of the system by establishing a real-time model on the energy consumption. Pontryagin Minimum Principle (PMP) and Equivalent Consumption Minimization Strategy (ECMS) are two popular RTO techniques. The PMP uses the strategy of minimizing global optimization problems by separating to local sub-problems to improve response time to the calculations of the system. Although PMP is mostly used for plug-in hybrid electric vehicles (HEV) (Sharma, Onori, and Guezennec 2012), it is rare for shipping. For instance, a real-time PMP application to minimize the fuel consumption for a fuel cell HEV is investigated (Song et al. 2020). Simultaneous updating of energy management function according to unpredicted daily driving cycles such as starting and stopping, dynamic loading, and low or high-power output performed better than rule-based and DPA. The results show that the proposed system has superiority compared to both rule-based and DP-based EMS by improving fuel cell durability. The ECMS aims to calculate optimum power management set points and optimal control formulation to minimize the fuel consumption of the engine (Geertsma 2019). For an unknown operational profile of an HEV, ECMS shows the best performance in fuel consumption compared to various control strategies (Sciarretta et al. 2014). As a result of the demonstration of the ECMS on a hybrid ferry, a reduction of 10% in fuel consumption is reached by optimizing the power balance between power sources (Geertsma et al. 2017).

This section has reviewed the energy management system of hybrid propulsion with control strategies. The next section discusses the methodology for architectural design and hybrid system selection for different ship types.

4.6 Discussion

4.6.1 Methodology of architectural design

The hybrid propulsion system architecture is designed respecting ship specifications and mission profiles since there are a large variety of ships having different routes, missions, and functions. Designing hybrid configuration and corresponding EMS is a multicriteria problem. So, there are many different power supply options to configure the propulsion system of ships. This is why; according to the operation profile of the case ship, the power generation methods and propulsion technique gain importance. Hence, it should be noted that there is no specific type of perfect fit of hybrid propulsion for a specific type of ship. Therefore, engineers need several criteria to assess the most suitable propulsion and power supply system for the ship. For instance, a passenger ship and an oceangoing cargo ship have different power requirement characteristics which constrain the hybridization technologies choices. Therefore, criteria for the assessment of the power trains for ships should take the operation profile into account (Nguyen et al. 2020). The aim should find the optimum solution for the case ship by modeling and simulation the ship's standardized operation (Vu et al. 2015). The methodology for selecting the architectural design is related to various parameters and concerning literature knowledge and systematic assessment, the main criteria and constraints were defined in Table 4.5.

Table 4.5 : Criteria for the HPS selection.

Assessment Criteria	
1. Fuel Consumption	6. Maintenance and Operation
2. Emission	7. Life cycle
3. Maneuverability	8. Efficiency
4. Comfort due to noise and vibration	9. Volume / Weight
5. Cost	10. Bunkering / Cold Ironing

4.6.2 Methodology for system selection

Finding the proper power source and hybrid configuration requires a comprehensive analysis in terms of ship type. The systems depend on the different power demands and integration constraints; hence their architecture is also formed

to ensure their operational characteristics. Therefore, each system has a different role varying from the ship type. As a result of reviewing power generation, energy storage, and propulsion topologies, a ship-specific approach is prepared to provide general guidance on how different energy storage, power generation systems, and propulsion architecture can be useful. Table 4.6 summarizes the systems regarding the ship type and general operation profiles. It should be noted that each ship is characterized by specific operations, so the table gives an overview of availability by generalizing it according to ship types.



Table 4.6 : System assessment according to ship types.

Ship Type	Energy Storage System			Power Generation System			Propulsion Architecture		
	BAT	FW	SC	ICE	FC	REN	S	P	S/P
Tugboat	+++	++	+++	+++	++	+	+++	+++	+++
Ferry	+++	++	++	+++	+++	++	+++	+++	+++
Yacht	+++	++	++	++	++	++	+++	++	++
Fishing Vessel	+++	++	++	++	++	+	+++	++	++
Short Sea Ship	++	++	++	+++	+++	++	++	+++	+++
Oceangoing Ship	++	+	+	+++	++	++	++	++	+++
Cruise Ship	++	+	+	+++	+++	++	++	+++	+++
OSV	+++	+++	+++	+++	+++	++	+++	+++	+++

BAT: Battery, **FW:** Flywheel, **SC:** Supercapacitor, **ICE:** Internal Combustion Engine, **FC:** Fuel Cell, **REN:** Renewable Energy, **S:** Serial, **P:** Parallel, **S/P:** Serial-Parallel, **OSV:** Offshore Supply Vessel, + / ++ / +++: Low / Moderate / High Availability

Tugboats need a high-power density due to their operational characteristics. In general, tugs work at the port area to help during the maneuvering of big vessels. This is why the working frequency of tugs depends on how busy the port is, and so generally tugs mission profile includes repetitive peaks of high power for a short period which correspond to the maneuvering of the helped ship (Kalikatzarakis et al. 2018). Electrical storage is an interesting option for tugboats to shave these peaks of power demands and to maintain a relatively low power of ICE. Reducing the diesel generators and using ESSs would improve the fuel consumption and emissions, furthermore, since their operation location is close to ports, using shore power for electric storage affects positively ship-based emissions. On the one hand, approximately 35% reduction in GHG emissions and fuel consumption can be reached with hybrid and battery-powered industrially proven tugs (Damen 2015). On the other hand, according to an examination on the use of the hybrid diesel-electric concept for a tugboat, charging using a public grid shows much more cost-effective performance in payback time compared to charging with diesel engines (Völker 2015). Hybrid power systems are superior compared to all-electric systems thanks to the flexibility in power generation during critical operations.

Ferries are considered as both passenger and car ferries that can operate at sea and river in this paper. Fully battery-powered or hybrid propulsion has already been practiced since their operations are predictable, short, and determined fixed-route almost for a year. In terms of energy storage, batteries are feasible compared to other alternatives with their higher energy storage capacity. In case of limited battery capacity regarding route else, if the battery cannot provide sufficient range, hybridization is also an option with a diesel engine or fuel cell. Battery and fuel cell combination or all-electric ferries seem like a strong option for zero-emission and 100% fuel savings. Both hybrid topologies are acceptable depending on the total engine room volume and propulsion design. The major challenge for ferries is the limited port stay for charging the batteries. So, for long-range operation hybrid power generation seems preferable instead of relying totally upon an energy storage system. As an industrial example, the MS Color Hybrid ferry is a good representative of using a plug-in diesel-electric hybrid with the ability of full battery power option during parts of its journey with zero-emission (URL-6).

Hybrid and electric power supplies appear very promising for yachting thanks to increasing comfort and reduction in noise and vibration. Yachts are not commercial

ships and so, they do not need to generate income for further operations. Yachts are feasible for hybrid propulsion and power generation but, since they are limiting the total voyage distance, all-electric powering does not seem acceptable for yachting with the current energy storage capability of ESSs. In general, their operation profile does not require high power densities and it is hard to estimate the potential fuel and energy savings. Mainly, they stay at ports and sail at low and economical speeds respecting the sense of yachting. In the meaning of ESS, batteries serve well to yachts but, since the need for high power density is low, SC and FW are not attractive as batteries.

Fishing vessels are potentially viable for electric and hybrid propulsion. The main issue is the size of the vessel, and according to power requirements all-electric with serial configuration is possible, but also, in case of higher power demands hybridization is the stronger option. Regarding the operational profile of the fishing vessels, travel at economic speeds and often auxiliary equipment such as cranes work during the fishing, cargo handling, or preparation procedures. By the way, during the fishing operations, the strategy of supplying energy from ESSs is like in the case of tugboat during maneuvering helping the key approach to reduce emissions and increase energy efficiency. Furthermore, the reduction of radiated noises and vibrations is another important advantage for hybrid and electric propulsion and power generation. The possibility of renewable energy seems weak due to the architectural design and operations of the ship.

Short sea ships are considered as small container vessels, bunker vessels, small tankers, and general cargo vessels sail in national or coastal waters. Short sea shipping has relatively short voyages and more frequent port stays compared to oceangoing shipping. This is why shore connection and ESS charging becomes a useful and attractive solution to use batteries or other energy storage devices for all-electric and hybrid propulsion (Jafarzadeh and Schjølborg 2018). Otherwise, cargo handling equipment (e.g. cranes, high-pressure hydraulic systems) and other electrical loads (navigation, HVAC, etc.) are important consumers regarding total ship power capacity, so, instead of using diesel generators, batteries can supply the demanded power during sailing or at the port. Fuel cells are also feasible for short sea shipping with hybridization ESSs. In this case, zero-emission is achievable especially during inland sailing. Parallel and serial hybrid propulsion configurations are reliable to be used in these vessels.

Energy storage for oceangoing ships is very challenging with current technology and seems not feasible commercially in near future due to long and steady voyages and high-power requirements. However, hybrid power generation and propulsion are feasible for certain operational modes (Dedes et al. 2016). Fuel cells and renewable energy sources are applicable for deep-sea shipping. The capability to use alternative fuels in ICEs and fuel cells or renewable energy are the major drivers for emission reduction. The hybridization of both systems is an attractive solution, specifically for steady-state and fixed-speed voyages. Hybrid and parallel configurations offer a great advantage in the meaning of reliability and alternative propulsion options (e.g. mechanical or electrical drive). Moreover, hybrid and electrical propulsion can increase the maneuvering capacity and efficiency of the ship by offering higher control and fast responses to commands.

Cruise ships are one of the very high energy demanding ship types due to their huge hoteling requirements such as air conditioning, lighting, heating, etc. Moreover, propulsion and auxiliary navigational systems also need high power to enhance the comfort, speed, and maneuvering capability of the ship (Ghenai et al. 2019). Unlike other ship types, the cruise vessels sail towards city centers, so ship sourced emissions are gaining importance, therefore alternative energy sources are under investigation to reduce these emissions for public health. Theoretically, electric storage seems like an option however, as can be noticed, supplying this high energy demand is often not feasible economically. Besides, it is hard to reach a worldwide appropriate voltage, frequency of both ship and shore side (Sulligoi et al. 2015). As a result, hybrid propulsion becomes a pleasing solution with less emission and affordable technology. Besides, diesel-electric propulsion is already proven on cruise ships and hybrid power generation is the further step to optimize the use of diesel generators or minimize the emissions as much as possible. Biofuels are advantageous for cruise ships in diesel engines but other renewable energy sources are difficult to apply on board due to architectural characteristics.

OSVs are highly suitable for electric and hybrid propulsion with hybrid power supply, indeed they have been already proven in numerous projects with batteries and fuel cells. OSVs have critical missions and highly variable load frequency, so any excess power generation happens in their typical operation against any failure risk (Díaz-de-Baldasano et al. 2014). All-electric seems hard for current technology, but hybrid systems are feasible and well-proven in R&D projects

(Tronstad et al. 2017). The diesel-battery and diesel-fuel cell combinations are concluded successfully with lower emission rates by reaching higher efficiencies. The main purpose of electric storage is to supply energy when the power demand is maximized and to allow a diesel engine to work at efficient engine loads. Renewable energy can be used in OSVs to charge ESSs such as batteries, supercapacitors, or flywheels.

4.7 Conclusion

This paper has reviewed the state-of-the-art various energy storage systems, power generation techniques for different topologies of hybrid propelling technologies, and their popular control strategies. HPS is an effective solution considering the environmental concerns and regulative pressures on national and international shipping. HPS is promising to reach higher efficiencies with lower environmental impacts. Emission, noise, vibration, maintenance frequency, and cost reduction can be reached with high efficiency by increasing comfort, so they can be listed as the major advantages offered by HPS. Different levels of hybridization are applicable for ships by setting different topologies and using different ESSs, therefore various options have been investigated in this paper. The main practical approach for hybridization of the ICE is improving the effective working scale by supplying additional energy with other energy sources and ESSs. Therefore, energy storage capacity, efficiency, charging-discharging speed, lifetime, cost, and several other characteristics are critical during the selection and applying the system. In the discussion section, different ESSs, power generation techniques, and propulsion architectures are assessed for different ship types regarding their characteristics, operational profiles, and criteria which are defined before.

It is obvious that ICE is the best option for all types of ships with today's technological maturity for providing the required power. Fuel cells seem also feasible for short sea shipping with hybridization ESSs and then zero-emission is achievable especially during inland sailing. Short sea shipping has relatively short voyages and more frequent port stays compared to oceangoing shipping. Diesel-electric propulsion is already proven on cruise ships and hybrid power generation is the further step to optimize the use of diesel generators or minimize the emissions as much as possible. The limited power capacity, hard maritime conditions, and

high dependence on environmental influences are the biggest obstacles to establishing RES onboard ships in short term. To sum up, power requirements and the mission of the ship have a major influence on the system selection. From the storage point of view, lead-acid batteries haven't been considered for large-scale present and future applications due to limited power and energy density capacity. Indeed, Li-Ion batteries are a reference solution for hybrid ship ESS. Supercapacitors are effective to supply power fluctuations for a limited period. Flywheels are also motivating solutions but technological maturity for shipping applications is relatively weak and additional safety requirements are not elaborated in the literature. On the other hand, limited lifetime compared to conventional ICEs is another demotivating cause for ESSs. For this reason, current researches are separated mainly into two sections for HPS; the first is the optimization of the power management system and the second is the improvement of the storage devices for a fully electric ship for long ranges. The three main HPS; serial, parallel, and serial-parallel are evaluated according to ship type and general operational profile. Although serial-parallel configuration is complex and expensive, having both advantages of two propulsion configurations is safer and zero-emission is achievable with proper ESS and powering systems. Considering intercontinental shipping, HPS or fully electric propulsion still needs additional researches and technological developments, however, for short-range or inland shipping (e.g. passenger ships or ferries) HPS technology is very promising and seems available. Stringent IMO rules and regulations on GHG emissions will increase the transition speed to hybrid and electrical systems. Possible HPS solutions for each type of ship are still under development and it is obvious that technological developments in DC electrical network, power electronics, and smart control systems will be the key feature for the transition to fully electric and low carbon or zero-emission shipping.



5. ELECTRIFICATION AND HYBRIDIZATION OF FERRIES: STATE OF THE ART AND CASE STUDY⁴

5.1 Introduction

Transportation is one of the vital elements of world trade. In 2017, the United States Energy Information Administration (EIA) published a study on the energy consumption of the transportation industry, according to the data the transportation sector consumes 110 quadrillions BTU in 2015 and it is estimated that it will rise to 140 quadrillions BTU in 2040. By the way, maritime transportation is responsible for 90% of global transportation with 90% of outer and 40% of inner freight (Deniz & Zincir, 2016; Fan et al., 2018). This high amount of transportation requires an energy source and this causes a huge amount of fuel consumption. The shipping industry mainly uses high sulfur content fossil fuels, and International Maritime Organization (IMO) states that ships approximately consume 300 million tons of fossil fuels annually. This consumption causes to emit greenhouse gases such as NO_x, PM, VOC, and SO_x emissions. Maritime transportation corresponds to 3.1% when the total CO₂ emissions worldwide are considered (Balcombe et al., 2019). In this connection, greenhouse gas emissions are important subjects for the shipping industry in the meaning of long-term commerce and sustainability. The IMO works on radically eliminating ship-sourced emissions by updating and/or establishing new rules and regulations, such as Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP) in the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI (IMO, n.d.). While the main goal of international shipping is to minimize emissions, inland shipping is also highlighting zero-emission transportation for environmental and public health concerns. However, the mentioned emissions are inevitable while the fossil fuels like marine diesel oil and heavy fuel oil are still used in the shipping industry (Inal & Deniz, 2021). For this

⁴Inal, O.B., Charpentier, J-F., Deniz C. In press. Electrification and Hybridization of Ferries: State of The Art and Case Study, Decarbonization of Maritime Transport, Springer Singapore. Eds: B. Zincir, P.C. Shukla, A.K. Agarwal.

reason, more effective solutions or alternative power sources should be found to replace internal combustion engines in the maritime industry. Electric and hybrid propulsion is one of the possible solutions in the way of decarbonized shipping. The United Nations states that today 55% of the world's population lives in cities and this number is expected that to increase to 68% by 2050. Therefore, the emissions of the passenger ships and ferries operating in urban areas gain importance. In this perspective, to reduce ship-sourced emissions, minimization of fossil fuel consumption is the key strategy. At this point, hybrid energy sources are prominent in ships like the automotive industry.

Hybrid propulsion can decrease the fuel consumption of the marine diesel engine by supplying additional power to the system (Bennabi et al., 2017; Dedes et al., 2016; Inal et al., 2022). A classical hybrid propulsion system consists of several different energy storages such as batteries, supercapacitors, and power generation equipment such as diesel engines, and fuel cells. Since the working characteristics of these types of equipment are different, a proper analysis should be carried out according to the operation profile of the ship to find the optimal hybrid design and power management strategy. Sections II and III of this chapter include deeper information about the mentioned equipment and their selection strategies.

This chapter explains the use of hybrid&electric propulsion systems which can be a solution for decarbonized maritime transportation. The chapter contains a description of hybrid propulsion topologies, power management strategies, possible energy sources, and a case study, respectively. Lastly, the chapter's conclusion discusses the role of hybrid&electric propulsion in maritime transportation.

5.2 Hybrid Systems and Power Management Strategies

Hybrid systems mainly consist of two different systems, firstly, energy storage systems (ESS) like batteries, supercapacitors, and flywheels. Secondly, power generation units like fuel cells, marine diesel engines, solar panels, and wind turbines. The components can have various connection topologies (serial or parallel) according to ship architecture and operation profile. On the other hand, power management strategies are another important factor for an effective hybrid system. There are mainly two approaches; rule-based and optimized energy management. This section gives detailed

information about hybrid system components, topologies, and power management strategies.

5.2.1 Hybrid system components

Hybrid system components can be mainly divided into two: energy storage and power generation. On the energy storage side, batteries, and supercapacitors are reviewed. For power generation, marine diesel engines, and fuel cells are the main energy sources.

5.2.1.1 Batteries

Battery technology has been improved significantly in recent years by adopting electrical energy in mobile applications like the automotive industry. Batteries are the major energy storage technology owing to their technological maturity, lower cost, and higher energy density compared to other energy storage devices. Among various types, Li-Ion batteries are the major dominator of the sector thanks to their relatively higher lifetime and considerably lower cost compared to other types. Table 5.1 shows the comparison of the characteristics of the popular battery types.

Table 5.1 : Characteristics of battery types (Aneke & Wang, 2016; Inal et al., 2022; Ma et al., 2021; Nuchturee et al., 2020).

Battery Type	Energy Density (kWh/kg)	Efficiency (%)	Lifetime (Cycle)
Lead-Acid	$30-50 \times 10^{-3}$	70-90	500-1000
Nickel-Cadmium	$50-75 \times 10^{-3}$	60-65	2000-2500
Nickel Metal Hydride	$60-100 \times 10^{-3}$	65-90	750
Li-Ion	$100-200 \times 10^{-3}$	85-90	600-2000

Batteries are mostly popular in the shipping industry by offering great hybridization solutions. More specifically, power density, lifetime, cost, state of charge, and size are the main constraints for batteries to expand their market share for maritime transportation. For this purpose, there are many kinds of research and analyses on the battery-diesel generator and battery-fuel cell hybrid powering systems besides the fully electric ships. For instance, a fuel cell–battery hybrid configuration is analyzed for a coastal ship from many perspectives such as cost, lifetime, power, and energy density. The optimization of the configurations has been carried out to find the most

effective solution (Wu & Bucknall, 2020). Another case study on a dry bulk ship shows that battery–diesel hybrid configuration has the potential to reduce greenhouse gas emissions by 14% by reducing fuel consumption (Dedes et al., 2012). Batteries are not the only hybrid power element but also have an important role for fully electric ships. For example, the world’s first all-electric car ferry, MF Ampere is an important project considered a milestone in electric ship technology and has been working since 2015 in Norway (Karimi et al., 2020).

5.2.1.2 Supercapacitors

Supercapacitors are in demand thanks to their fast charging and discharging abilities although they have a limited energy density. Supercapacitors have higher capacitance, power density, and cycling capacity than conventional ones, their use are relevant when the operation profile of the application requires a high load transition to buffer the system power requirements (Zhou et al., 2013). The operation characteristics of the ship are vital for the selection of the energy storage device. If the system requires the ability of high load transition in a short time, supercapacitors can be beneficial however, if the system requires high energy density with having stabilized power supply, batteries seem more advantageous. Generally, supercapacitors are in use together with batteries to enhance the system’s power supply capacity. For example, for different operation profiles of an offshore supply vessel, a battery-supercapacitor hybrid system reduces fuel consumption and greenhouse gas emissions (Nebb et al., 2012).

5.2.1.3 Diesel engines

Marine diesel engines are the conventional, most experienced, and most common way to generate power for ships. Approximately, marine diesel engines operate at 48-52% efficiency by using heavy fuel oil and marine diesel oil (Dere & Deniz, 2020). The experience level, reachable spare parts, and industrial developments are the greater pros of marine diesel engines. Currently, the major problem with diesel engines is the emissions due to fossil fuel usage. The ship-sourced emission limitations are the leading obstacles that will be faced by these engines. In this aim, alternative fuels and hybrid systems are under investigation. In the scope of this chapter, hybridization opportunities of the diesel engine are mainly reviewed. The cost of fuel, high power capacity, and reliable operational conditions allow a diesel engine to be an important

part of a hybrid ship propulsion system (Bassam, 2017). The hybridization of the marine diesel engine with energy storage systems is the key approach to increasing the total system efficiency. The design characteristics of marine diesel engines are to work above 60-70% load to reach optimal operation points where the fuel consumption is minimized. However, partial and unsteady loads cause inefficient working conditions and an increase in fuel consumption and emissions (Dere & Deniz, 2019). Therefore, the generic power management strategy with diesel engine hybridized systems is to supply the stored electric energy during the operations with load transition like maneuvering or departure by minimizing the load fluctuation of the diesel engine without reducing the load (Huang et al., 2021).

5.2.1.4 Fuel cells

Fuel cells are electrochemical devices that convert the chemical energy of the fuel to electric energy without requiring any additional energy conversion like internal combustion engines (Barbir, 2005; Inal & Deniz, 2020). The direct energy conversion ability allows fuel cells to reach higher overall efficiency. Fuel cells generally use hydrogen but liquefied natural gas, diesel oil, or methanol also can be used after a reforming process. Fuel cells are promising options for the shipping industry owing to their emission-free power generation ability. The main reason for the produced clean energy is that it uses hydrogen as a fuel. In this chapter, fuel cells are considered power generation units due to similar working principles as diesel generators. They can produce power as long as the fuel is supplied and this form the major difference from the batteries.

Fuel cells can be classified according to their electrolyte types. The proton ex-change membrane fuel cells are the leading fuel cell types among five others thanks to their technological maturity and wide application area (De-Troya et al., 2016). Fuel cells' power capacity is at the kW level, but there are several industrial types (high-temperature working types) that can generate power at the MW level (van Biert et al., 2016). Fuel cells are modular, so the physical properties are changeable according to the system's requirements. The selection of the fuel cell type is highly dependent on the ship's physical properties and operation profile. Generally, fuel cells are more suitable for short-sea shipping like inland sea transportation. There are various research projects and analyses for different types of fuel cells in ships. For instance, the FellowSHIP project, one of the pilot projects for the fuel cell application in ships,

was carried out from 2003 to 2018 to investigate the hybrid fuel cell-battery system for an offshore supply vessel (Tronstad et al., 2017). The system worked for 18,500 hours without emitting any NO_x, SO_x, and PM.

5.2.2 Hybrid system topologies

Hybrid systems can be configured under three different topologies. Generally, hybrid systems consist of various energy storage devices and power generation units which are described in the previous section. The difference between configurations is the energy distribution way from the energy sources to the propeller. The serial, parallel, and serial-parallel architectural combinations form the main categories. To simplify the description in this paper electrical sources are considered as DC electric sources connected to a DC grid but the use of an AC grid is also possible.

5.2.2.1 Serial configuration

The serial configuration is the most mature topology for ships compared to other configurations (R. Geertsma, 2019). In this configuration, all energy sources are connected bus bar (or main grid) via converters. An example of this configuration is given in Figure 5.1. In this example, an energy source, a fuel cell, a renewable energy source, and an internal combustion engine are connected to the main bus bar via converters. The propellers are driven with electric motors which receive the required energy from the bar. In addition, other loads such as navigation equipment, HVAC, or lighting are also connected to the main grid.

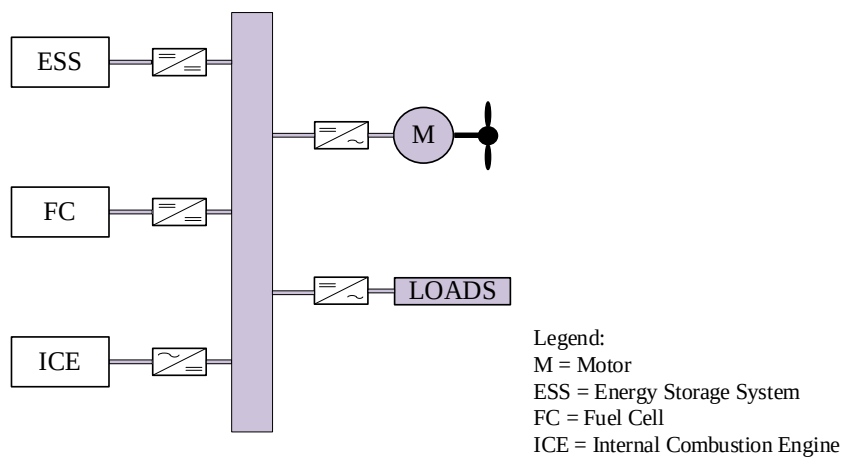


Figure 5.1 : Serial hybrid configuration (Inal et al., 2022).

5.2.2.2 Parallel configuration

Parallel configuration differs from the serial configuration with a direct mechanical link from the diesel engine to the propellers. The electrical components of the hybrid system are similar to the serial configuration. Energy storage devices and other electric generators like fuel cells are connected to the main grid. The major advantage of this configuration is the availability of both electrical and mechanical propulsion. Also, both sizing optimization, zero-emission, and higher efficiency are allowed with this configuration. The weaknesses of the mechanical propulsion like weak maneuvering capacity or diesel engine inefficiency during low loads can be eliminated with a proper power management strategy. On the other hand, the additional mechanical links, and the need for robust control for higher efficiency can be counted as their disadvantages. This configuration is shown in Figure 5.2.

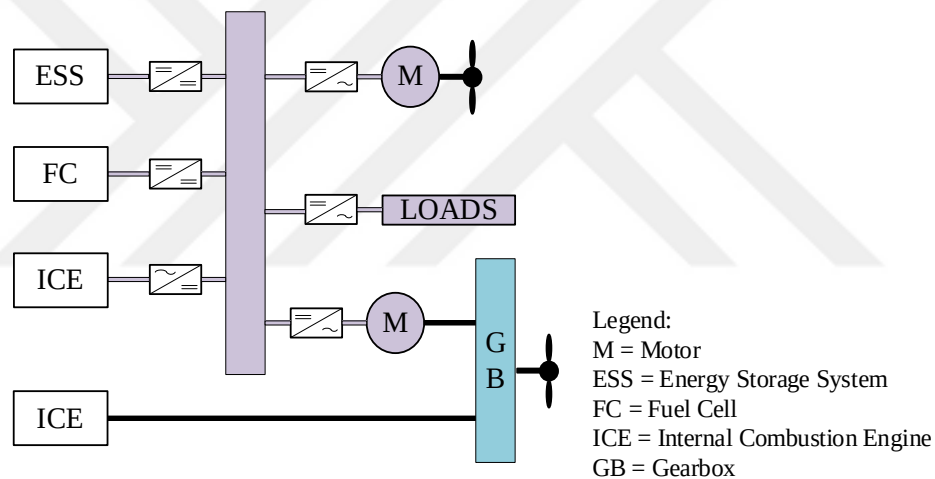


Figure 5.2 : Parallel hybrid configuration (Inal et al., 2022).

5.2.2.3 Serial-parallel configuration

The hybrid (serial-parallel) configuration is the combination of both topologies. In this configuration, the internal combustion engine (generally diesel engines for ships) is connected directly to the propeller via a gearbox. Meanwhile, another gearbox connects the engine to the main electric grid. Therefore, this hybrid system allows the system to work serially and also parallelly. The architecture of the hybrid system is more complex than the other configurations, so, it requires a more detailed energy management strategy but is relatively flexible. The system contains both mechanical and electrical propulsion availability, and it can reach higher efficiency at load

transitions. However, complex system architecture causes higher costs compared to other types. The generic system overview is given in Figure 5.3.

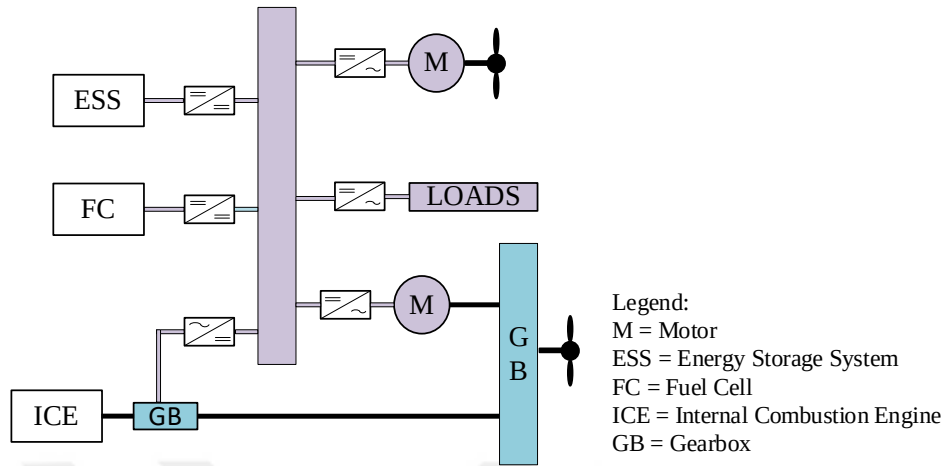


Figure 5.3 : Serial - Parallel hybrid configuration (Inal et al., 2022).

5.2.3 Power management strategies

Hybrid propulsion systems have multiple energy sources and consumers. The elements of the systems have different operational characteristics and, dynamic behaviors during the ship's operations. Therefore, establishing a proper energy management strategy is very important for hybrid propulsion ships to ensure safe and efficient operation. In general, costs, system performance, lifetime, and efficiency are the functions of the established energy management strategy (Garcia et al., 2010). For the same system, two different energy management strategies can have two different results during the operation. According to the aim of the system, an appropriate strategy would give the minimum fuel consumption to minimize the emission at the system's most efficient point. Hence, mainly there are two energy management strategies for hybrid ships; rule-based, and optimized control strategies (Balsamo et al., 2017).

The rule-based control strategy is based on the control parameters from previous experiences. This strategy is static and robust but mostly weak for dynamic systems. The main reason for this weakness is sourced from the hardness of determining the optimal point for changes. The external factors for ships like wind or waves manipulate the expected operation and change the power need of the system dynamically. In this case, depending on the system complexity, smart control strategies like fuzzy logic gain importance for time-varying problems. For instance, in research for an all-electric

ship fuzzy logic showed better performance against a proportional-integral-based energy management strategy at the state of the charge of the batteries (Khan et al., 2017). But, instead of establishing an accurate mathematical model, fuzzy logic rules require expertise in the system behavior and mission profile.

Optimized control strategies show better performance the dynamic systems compared to rule-based energy management strategies. Global and real-time optimizations are the two main categories of the optimized control strategy. Global optimization focuses on the overall optimization during a determined time by using the mathematical equations of the system components. Many different algorithms are used in the literature to optimize the energy management of multi-energy sourced systems. Dynamic programming, genetic algorithm, artificial neural network, ant colony optimization, and particle swarm optimization are the most common techniques to perform global optimization (Ancona et al., 2018; Divyajot et al., 2018; Kanellos et al., 2014; Tarelko & Rudzki, 2020). Real-time optimization is the second type of optimized control strategy for hybrid systems. This strategy differs from global optimization by changing according to the instantaneous conditions of the energy demand by establishing a real-time model of energy consumption. Pontryagin Minimum Principle (PMP) and equivalent consumption minimization strategy (ECMS) are the two common real-time optimization techniques. PMP is rare for ships but it has a wide application for plug-in hybrid electric vehicles. On the other hand, ECMS is used to minimize the fuel consumption of the engine with the optimum power management set points. ECMS shows better performance compared to other techniques in function of fuel consumption. For instance, by using ECMS on a hybrid ferry, a reduction in fuel consumption by 10% is reached (Geertsma et al., 2017).

5.3 Case Study

This section includes an introduction to selected case ship and mathematical models of possible hybridization equipment to analyze the pros and cons of hybrid propulsion.

5.3.1 Case study

To assess the potential advantages of hybrid propulsion, an example ship should be taken as a case. In this chapter, ŞH Beyoglu, a passenger ferry from Istanbul that

operates at the Istanbul Strait between European and Asiatic parts of the city, has been selected. The case study ship parameters are given in Table 5.2.

Table 5.2: Ship properties.

Case Ship Properties	
Propeller Blades	3
Propeller Diameter (mm)	1400
Propelling System	2 x Schottel Twinpropeller
Main Engine (rpm)	1500
Main Engine Power (kW)	4 x 450
Main Engine Model	Volvo Penta D16C-A MG
Ship Length (m)	67.96
Ship Draft (m)	2.95
Ship Gross Ton	747.36
Elec. Motor Voltage (V)	2 x 547

The ship has a diesel-electric powering system for both propulsion and electrical loads. The ship is equipped with 2 contrarotating Schottel Twinpropeller and bow thrusters for propelling and maneuvering. The electrical loads are mainly formed by air conditioning, lighting, and navigational equipment. The generated power by diesel generators is connected to the main bus bar and distributed to the required elements such as propellers, bow thrusters, or electrical loads according to the operation profile. The ship's average voyage is 24 minutes and there are 65 voyages in two ways per day. The case ship's power demand and propulsion behavior change during a voyage. Therefore, a generic operation profile should be determined to understand the route, and operation characteristics. The data according to operation is gathered physically onboard the ship. The power-related data such as energy consumption, equipment cut-in cut-off periods, and power generation fuel consumption are collected from the engine monitoring systems in the engine room. Sailing-related time-based data such as maneuvering time, bow thrusters, and propeller RPMs are gathered at the bridge by an authorized person. Multiple voyages have been completed with ship crew and average data is formed to establish a generic operation profile for the case ship for the same route. Furthermore, the operation profile is divided into four different operating

conditions which are departure, steady-state, arrival, and at the port. Figure 5.4 shows the power-time diagram of the case ship operation profile.

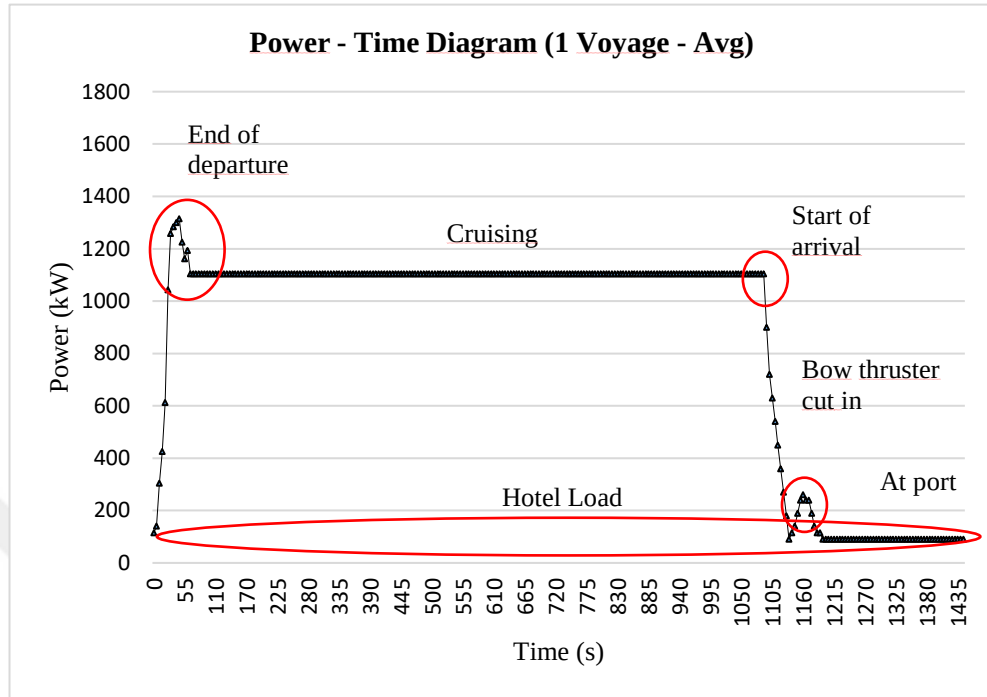


Figure 5.4 : Case ship operation profile with total consumed power (Inal et al., 2022).

The total route takes 24 minutes and the last 4 minutes is “at port” condition where the diesel generators work at the idle load and supply power just for electrical loads. As can be seen in the diagram, the power demand increases during the departure until the constant speed of steady-state sailing conditions is reached. This period covers the ship’s speed increase and the maximum power applied to the propellers to reach the cruising speed. After the ship’s speed exceeds the resistance, the demanded power drops, and the ship passes to the second phase of the operation (steady-state sailing). At the end of the steady-state sailing, the required power diminishes and the ship starts to arrive. The peak during the arrival maneuvering is related to the bow thruster use which serves to berth at the port in a safe, efficient, and rapid way. After completion of the rope tiding, the generators work at the idle load to ensure the hotel loads.

After considering the mission profile, the following part of the paper will study a serial hybrid energy solution combining diesel generators, fuel cells and batteries. This solution allows the minimization of fuel consumption of DG and zero emission modes (using FC and batteries) and fit well with the specification of the case study.

5.3.2 Model examples

To analyze the hybrid system, the system's components should be determined, so, the most common types of equipment for a hybrid ship are listed and approaches for the mathematical modeling are explained.

5.3.2.1 Diesel engine

Due to the case ship having a 4-stroke marine diesel engine, a 2-stroke diesel engine model is not given in this section. A dynamic 4-stroke diesel engine model can be explained with three main elements; a speed governor, an actuator, and the engine. Therefore, they can be modeled with the following transfer functions (Park, 1999).

The speed governor:

$$\frac{T_s + 1}{T_1 s^2 + T_2 s + 1} \quad (5.1)$$

The actuator:

$$\frac{T_3 s + 1}{(T_4 s + 1)(T_5 s + 1)} \quad (5.2)$$

The engine:

$$e^{-T_6 s} \quad (5.3)$$

The T variables are the time constant and can be found in (Park, 1999). Time constants for the speed governor of the studied Diesel Engine T, T1, and T2 are 0.2, 0.0002, and 0.01 seconds, respectively. For the actuator, T3, T4 and T5 are 0.25, 0.009 and 0.0384 seconds, respectively. Lastly, the time delay for the diesel engine is T6= 0.024 seconds.

These representations are taking the time delays into account and allow the system to work dynamically. The result of the engine model would give the generated torque, and the power can be calculated at first order with the multiplication of torque with speed as follows:

$$P_{DG} = T_{DG} \times \omega_{DG} \quad (5.4)$$

5.3.2.2 Battery

Simulink library includes a mathematical dynamic battery model that can simulate different types of batteries based on data commonly found in the datasheet manufacturers. The model makes it possible to model different types of batteries by linking an electrical model composed of a controlled voltage source in series with internal resistance to an electrochemical model, which makes it possible to link the evolution of the electrical parameters to the dynamic evolution of the state of charge of the battery.

Charging or discharging of the battery is calculated as follows:

$$E_{disch} = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} it + A \cdot \exp(-B \cdot it) \quad (5.5)$$

$$E_{charge} = E_0 - K \cdot \frac{Q}{it + 0.1Q} \cdot i^* - K \cdot \frac{Q}{Q - it} it + A \cdot \exp(-B \cdot it) \quad (5.6)$$

Where the E_{disch} and E_{charge} are the discharging and charging voltages, E_0 is the constant voltage, K is the polarization constant, Q is battery capacity and i^* is the low-frequency current, A is the exponential voltage and lastly, B is the exponential capacity.

5.3.2.3 Fuel cell

There are three different approaches to the modeling of fuel cells; analytical, semi-empirical, and mechanistic (Cheddie & Munroe, 2005). Analytical models cover the relation between the input and output of the fuel cell according to experimental data. These types of models are quite easy to understand and do not require a long time for computation. In contrast, mechanistic ones are built respecting to chemical and physical properties of the fuel cell and are much more detailed but require a long computational time. For this reason, semi-empirical models are advantageous by combining both advantages of the other two model classes.

A generic validated fuel cell model can be found in Simulink for different fuel cell types at different power ranges (URL-7). The model example for a fuel cell in Simulink is shown in Figure 5.5.

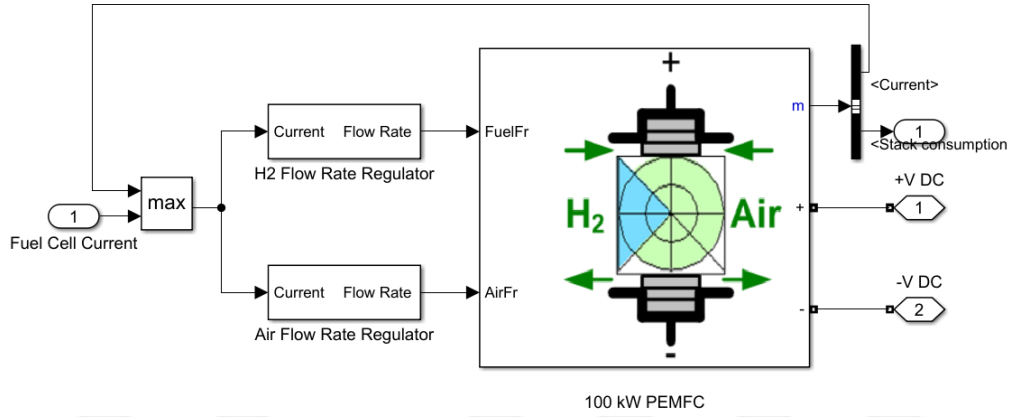


Figure 5.5 : Fuel cell model example.

5.3.2.4 Electric converter

Each power source in the hybrid systems should supply different currents according to components. For this reason, converters should be used to regulate the power source voltage. There are different types of converters, to boost or reduce the voltage but most commonly the equation which describe the converter as a DC/DC tunable transformer (mean value model) can be written as follows where the V is the voltage, I is the current and η is the converter efficiency:

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}} \eta_{conv} \quad (5.7)$$

5.3.2.5 Shaft

The moment of inertia of all rotating elements should be considered while calculating the torque and power transition. Therefore, the mechanical equation of the shaft is given as follows:

$$I \frac{dy}{dt} = T_{RG} - T_P \quad (5.8)$$

Where I is the moment of inertia of the shaft in kg.m^2 and T_{RG} and T_P are the torque of reduction gear (applied in the propeller shaft) and the hydrodynamic torque of the

propeller respectively (these 2 torques are in Nm). The model example in the Simulink platform is shown in figure 5.6.

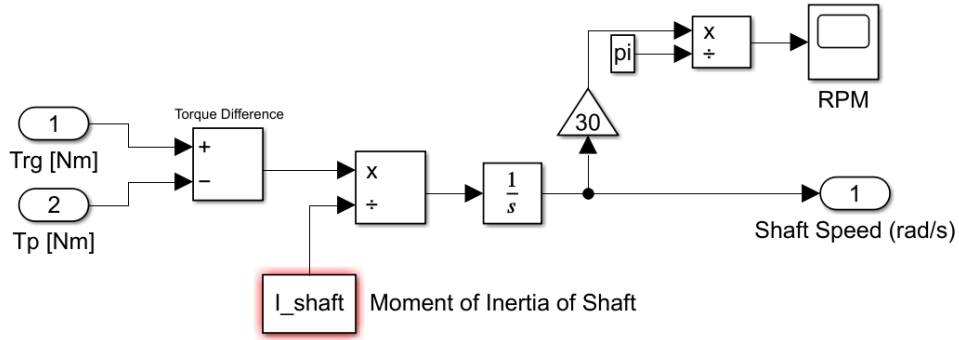


Figure 5.6 : Shaft model example.

5.3.2.6 Reduction gear

The reduction gear is used to adapt the rotational speed between the electric motor and shaft. The main parameter is the reduction ratio (k) which determines the relation between speed and torque transmission. The rotational speed and the torque are inversely proportional. Therefore, the model equation can be used as follows where the ω is rotational velocity and T is the torque:

$$\frac{T_{RG}}{T_M} = \frac{\omega_M}{\omega_{RG}} = k_{RG} \quad (5.9)$$

5.3.2.7 Electric motor

The electric motor converts the electrical power to mechanical power for the propulsion of the ship. In our study, the power requirement of the system is known for each period of the operation, so, the modelling approach is about the torque and rotational speed-based operation limitation of the electric motor. However, the motor limitations should be considered for a more accurate calculation. Therefore, typical limitation curve of the motor is shown in Figure 5.7, where T_m is the motor torque, and ω_m is the motor rotational speed. The equation between the torque, rotational speed, and power (limitation equation) is given below:

$$T_m = \frac{P_m}{\omega_m} \quad (5.10)$$

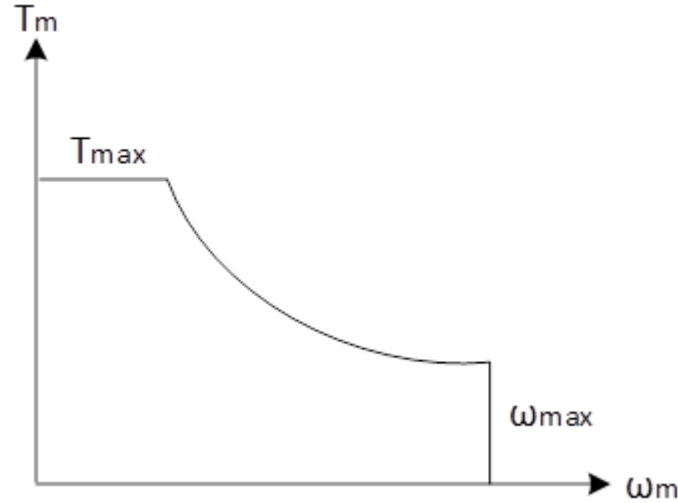


Figure 5.7 : Electric motor working limits.

The model example in the Simulink is shown in Figure 5.8. There the motor parameters are the limitation couple and base speed, and a proportional integrative (PI) control is used in the model (blue rectangle). The selected maximum motor rpm is taken at 2000 RPM.

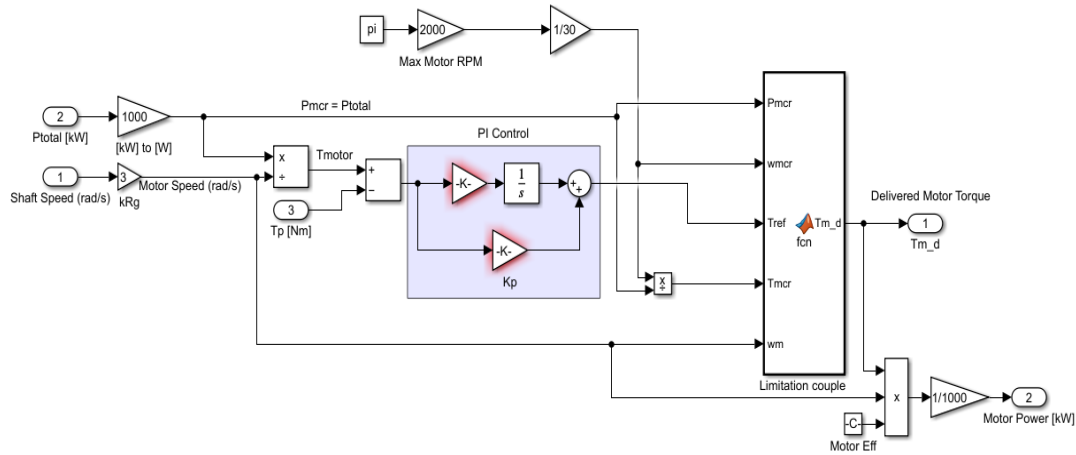


Figure 5.8 : Electric motor model example with PI control.

5.3.2.8 Propeller

The propeller allows to create thrust to reach the required ship speed. The propeller block is shown in Figure 5.9. While the water speed and shaft speed are the input, propeller thrust and torque are the outputs.

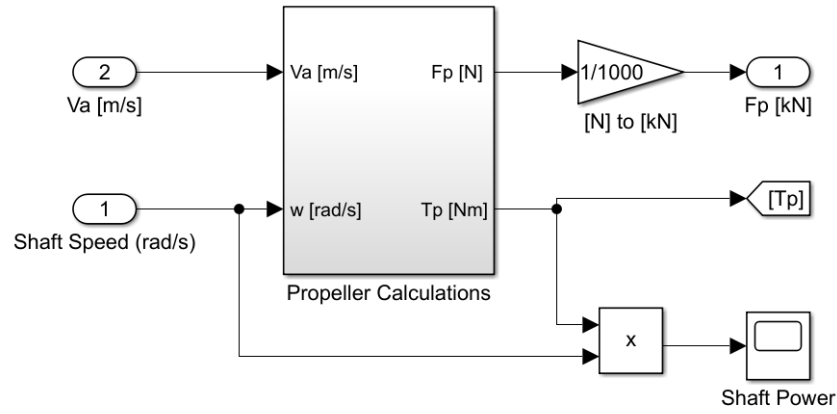


Figure 5.9 : Propulsion system example.

The propeller calculations are using propeller geometrical data as input to calculate thrust (F_p) and torque (T_p) according to the following equations.

$$F_p = K_F \times \rho \times n_p^2 \times D_p^4 \quad (5.11)$$

$$T_p = K_T \times \rho \times n_p^2 \times D_p^5 \quad (5.12)$$

The non-dimensional thrust coefficient (K_F) and torque coefficient (K_T) are calculated using the following equations according to Wageningen data. These data are obtained by test of reduced scale model in basin.

$$K_F = \sum_{n=1}^{39} c_n(J)^{s_n} \left(\frac{P}{D}\right)^{t_n} \left(\frac{A_E}{A_0}\right)^{u_n} (Z)^{v_n} \quad (5.13)$$

$$K_T = \sum_{n=1}^{47} c_n(J)^{s_n} \left(\frac{P}{D}\right)^{t_n} \left(\frac{A_E}{A_0}\right)^{u_n} (Z)^{v_n} \quad (5.14)$$

The advance coefficient J can be calculated by the following equation, where the n is the rotational speed and D is the diameter of the propeller.

$$J = \frac{V_A}{n_p D_p} \quad (5.15)$$

Lastly, thrust force (P_F) and the torque (P_T) of the propeller are calculated as follows:

$$P_F = F_p \times V_A \quad (5.16)$$

$$P_T = 2\pi n_p Q_P J = \frac{V_A}{n_p D_p} \quad (5.17)$$

5.3.2.9 Hull

A proper hull model is vital for a successful hybrid ship simulation. The hull model aims to calculate the interactions between hull resistance, power and speed of the ship. In our case, the parameters of the ship are known, therefore, ship's hydrodynamic resistance can be calculated with Holtrop-Mennen technique (Holtrop & Mennen, 1982). This technique allows to calculate the total resistance and required power for a designed speed of the ship. The equation is given below:

$$R_T = R_F(1 + K_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \quad (5.18)$$

Where the RF frictional resistance according to ITTC-1957, $(1+k)$ is the form factor, RAPP is appendage resistance, RW is wave resistance, RB is additional resistance due to bulb, RTR is the additional pressure resistance due to transom immersion, and lastly, RA is the model-ship correlation resistance. After the total resistance is calculated, the total hull model can be implemented into the general model as shown in figure 5.10. The resistance is dynamically changing according to ship speed and propeller thrust force.

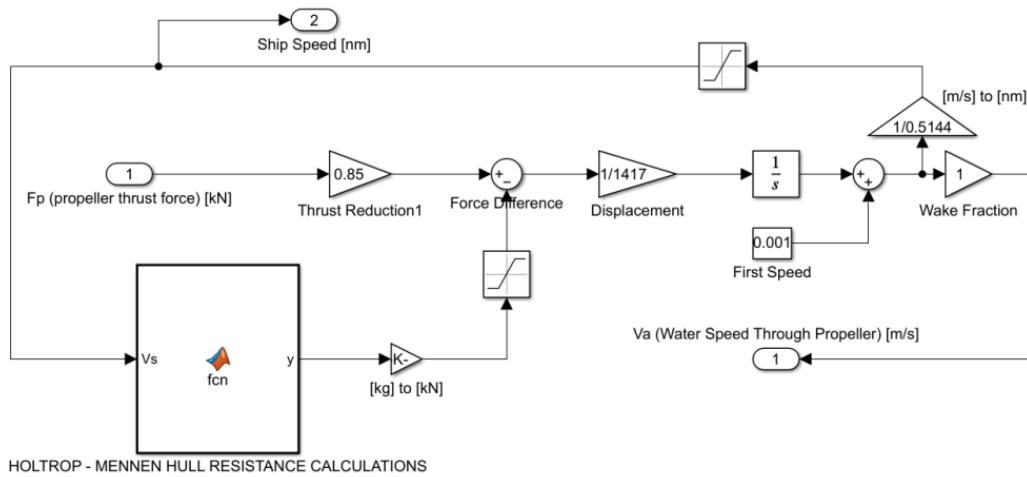


Figure 5.10 : Hull model example.

5.3.2.10 Energy management

Energy management strategy is extremely important for hybrid ships to ensure high efficiency with lower fuel consumption and emission. In the previous section of the chapter most commonly used energy management strategies were reviewed. The key factor to establish a proper strategy is the operation profile and physical properties of the ship. The mass and volume of the ship are important to apply the energy storage devices and their capacities. On the other side, the operation profile is used to determine the main rules and constraints to manage different power sources of the hybrid system.

In our study, according to data collected from the case ship, the average hotel load is determined as 90 kW and is considered as constant during the mission. The reached maximum power load is 1314 kW, and the average steady-state power demand is 1104 kW. Therefore, the new system should have the supply capacity of this required power. The current onboard loaded power capacity is 1800 kW with 4 diesel engines at the maximum power of 450 kW. By using the data from the engine's instruction book, the specific fuel consumption curve is calculated according to the engine load function, where the $f(x)$ is the specific fuel consumption, and x is the engine load:

$$f(x) = 0.0244x^2 - 3.5228x + 317.34 \left[\frac{\text{g}}{\text{kWh}} \right] \quad (5.19)$$

To find the optimal working point of the diesel engines, the specific fuel consumption curve is minimized:

$$f(x) = 190 \left[\frac{\text{g}}{\text{kWh}} \right] \text{ while } x = 72 \quad (5.20)$$

Therefore, the most fuel-efficient working point ($P_{DG,opt}$) of the diesel generators is at 72% load:

$$P_{DG,opt} = 450 \times \frac{72}{100} = 324 \text{ kW} \quad (5.21)$$

The possible diesel generator power is given below;

$$P_{DG,min}(t) < P_{DG}(t) < P_{DG,max}(t) \quad (5.22)$$

Where the $P_{DG,min}$ is 40% of the maximum power ($P_{DG,max}$) (450 kW);

$$P_{DG,min} = 450 \times \frac{40}{100} = 180 \text{ kW} \quad (5.23)$$

There are 2 diesel generators, the total power at optimal operating point can be found;

$$P_{DG,opt,total} = 324 \times 2 = 648 \text{ kW} \quad (5.24)$$

The similar approach can be followed for the fuel cell systems. Four packs of proton exchange membrane fuel cell with the maximum 100 kW power capacity which can be used optimally at 85.5% capacity is used. The corresponding relations for the fuel cells are given in equations (5.24) to (5.26).

$$P_{FC,opt} = 85.5 \text{ kW} \quad (5.25)$$

$$P_{FC,max} = 100 \text{ kW} \quad (5.26)$$

$$0 < P_{FC}(t) < P_{FC,max}(t) \quad (5.27)$$

There are 4 fuel cell units, so the total optimal power of the fuel cells can be found as;

$$P_{FC,opt,total} = 85.5 \times 4 = 342 \text{ kW} \quad (5.28)$$

Where $P_{FC,opt}$, $P_{FC,max}$, P_{FC} , and $P_{FC,opt,total}$ are the optimal power, the maximal power, the current power of one fuel cell unit, and the total optimal power to be provided by the four fuel cell units, respectively.

Table 5.3 : Battery using strategy with respect to state of charge.

20 - 40%	40 - 90%	90 - 100%
MIN	INTER	MAX
Battery is mainly charging (if possible)	Battery is mainly discharging (if possible)	
$SOC_{Min} < SOC_{BAT} < SOC_{Int}$	$SOC_{Int} < SOC_{BAT} < SOC_{Max}$	

The state of charge of the battery is divided into three sections for establishing a proper power management system. Respecting the state of the charge, the role of the battery changes. The selected battery is a Li-Ion type with an energy capacity of 200 kWh. Table 5.3 shows the main strategy for the use of batteries, respecting the state of charge

the battery (SOC). So, the power balance of the ship can be written as follows. The total power load (figure 5.4) power is sum of the generated and stored power from diesel generator, fuel cell and batteries. $P_{BAT,dc}$ symbolizes the discharging position of battery and $P_{BAT,c}$ is the charging position of battery. The battery's lower limit is determined as 20% of charge for a longer lifetime. For both cases, PDG varies according to the load power.

$$P_{LOAD}(t) = P_{DG} + P_{FC} \pm P_{BAT} \quad (5.29)$$

The state of the charge of the battery is the key performance indicator for the power split. So, according to min, inter or max cases of the state of charge the battery, the rule changes. Operational priority is always to maintain the fuel cell system at its optimal operation point given by equation 5.27 due to zero emission compared to diesel engine. In case of emergency, the SOC_{min} can act as SOC_{inter}. The summary of the charging and the discharging operations of the battery is shown in the Figure 5.10. The behavior of the battery changes according to two variables: ship's demand and SOC. The red arrows show the way where the battery SOC moves and areas are numbered respecting the instant operation and state of the charge.

There are three different states have been defined for the battery system as below:

- if $SOC < SOC_{min}$

No 1: Battery charging @ port, arrival and steady-state sailing.

No 3: Neither charging nor discharging @ departure.

- if $SOC_{min} < SOC < SOC_{inter}$

No 1: Battery charging @ port, arrival and steady-state sailing until reaching SOC_{inter}.

No 2: Battery discharging if SOC_{inter} has been reached and power demand is higher than $P_{FC,opt,total}$.

- if $SOC_{inter} < SOC < SOC_{max}$

No 2: Battery discharging for power demand higher than the power which can be provided by fuel cells (battery provides a complementary power, mainly @ departure and steady-state sailing).

No 3: Neither charging nor discharging @ port, arrival and steady-state sailing when the power demand is lower than the power which can be provided optimally by fuel cells.

The number 1 case corresponds to the areas where the battery state of charge is lower than the intermediate position, and when the power demand from the motors are lower than the sum of optimal generated powers ($P_{g,opt} = P_{DG,opt,total} + P_{FC,opt,total}$). In this case, the batteries are charged with the difference between $P_{g,opt}$ and the power demand until they reach their optimal state of charge. So, the system can be used in this state during the ports, steady-state sailing and arrivals for increasing state of charge. The second state corresponds to use of the battery as an electrical source (discharging the battery). When the battery SOC has firstly reached the preferable condition (SOC_{inter}) and the needed power is higher than $P_{FC,total,opt}$ the battery acts as a power source to supply an additional power to the system. In this case, fuel cell units are maintained at their optimal operating points. These cases correspond to power demand is higher than fuel cell's optimal power. In these cases, batteries can be used at desired power (according to power requirement) and DGs are used to complete the required power if needed. The third state is defined for the SOC higher the inter value, the neither charging nor discharging. However, if the SOC is lower than the minimum point, the battery won't act as an additional power source, besides, the system will not charge due to the high-power requirement of the system.

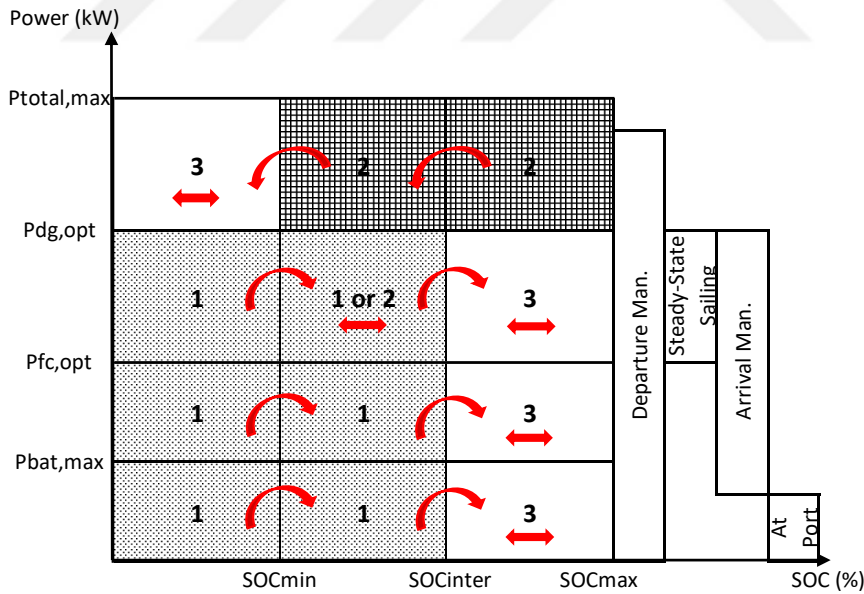


Figure 5.11 : Summary of the operation strategy.

The ramp rate (R) of the power sources is the other important constraint, the equations should be added as follows (Banaei, et al.,2020):

$$\left| \frac{P_{FC}(t) - P_{FC}(t - \Delta t)}{\Delta t} \right| \leq R_{FC,max} f(t) \text{ while} \quad (5.30)$$

$$R_{FC,max} = 10 \text{ kW per second}$$

$$\left| \frac{P_{BAT}(t) - P_{BAT}(t - \Delta t)}{\Delta t} \right| \leq R_{BAT,max}(t) \quad (5.31)$$

$$\text{while } R_{BAT,max} = 50 \text{ kW}$$

$$\left| \frac{P_{DG}(t) - P_{DG}(t - \Delta t)}{\Delta t} \right| \leq R_{DG,max}(t) \quad (5.32)$$

$$\text{while } R_{DG,max} = 150 \text{ kW}$$

The operation profile has been divided into four section; which are departure, steady-state sailing, arrival, and port. The analysis results show that 35% less marine diesel oil is consumed in total, and the reduction in the consumed fuel for each section of the voyage is given in the Figure 5.12 and 5.13.

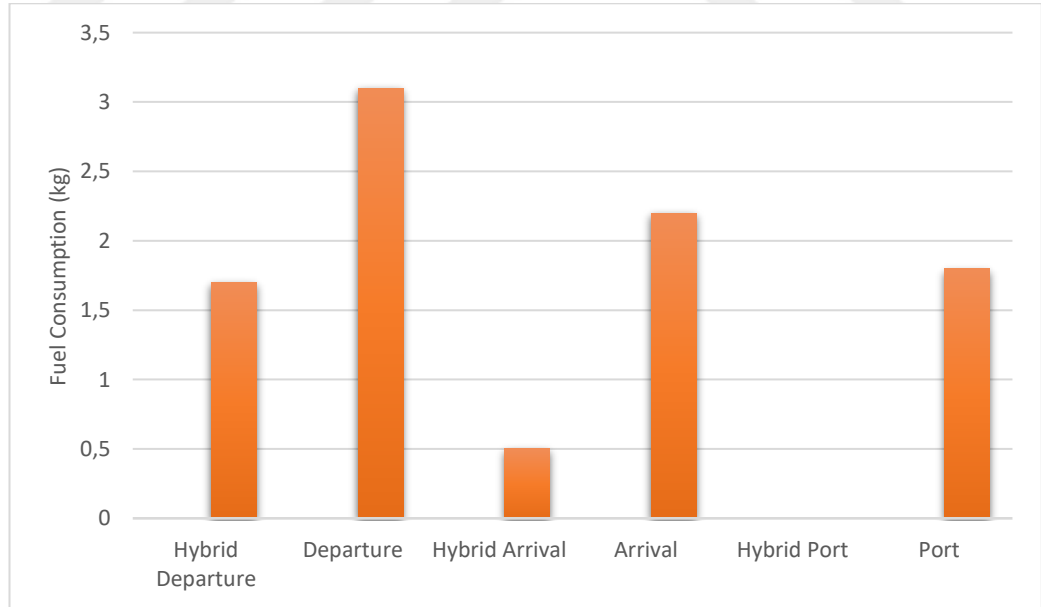


Figure 5.12 : Fuel consumptions for departure, arrival, port and their hybrid versions for 1 voyage.

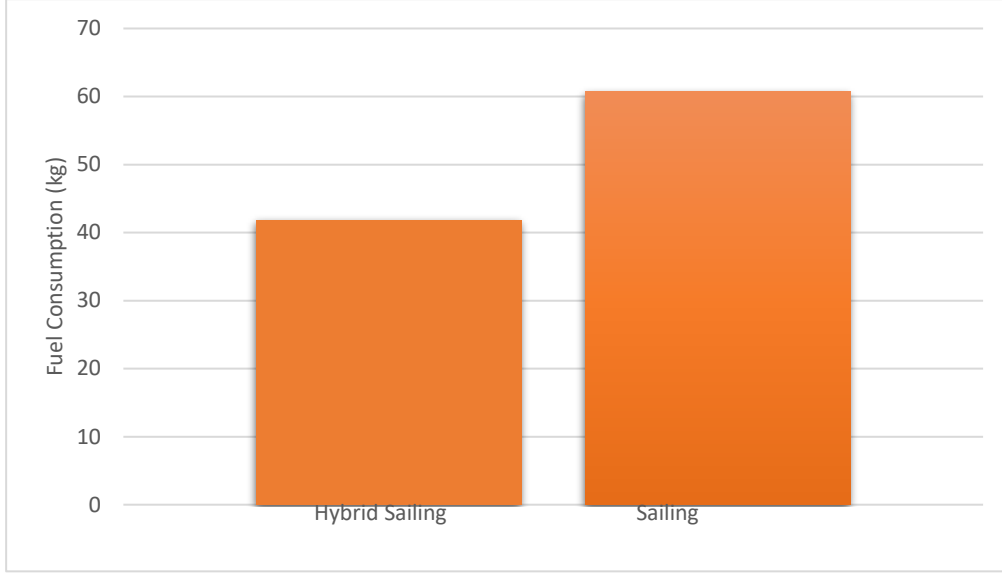


Figure 5.13 : Fuel consumptions of steady sailing and its hybrid version for 1 voyage.

To understand the environmental effect of this less fuel consumption, the harmful emissions such as CO_2 , NO_x and SO_x are calculated by using the following equations:

$$CO_2 = SFC \left[\frac{g}{kWh} \right] \times CF \quad (5.33)$$

$$SO_x = SFC \left[\frac{g}{kWh} \right] \times 2 \times 0.97753 \times 0.005 \quad (5.34)$$

The specific fuel consumption (SFC) is the key factor for both emission types. In equation (3.32), CF symbolizes the carbon factor of the used fuel, in our case it is 3.206, which is marine diesel oil (IMO, 2018). The equation (3.33) is used for SO_x emissions (adopted from Zincir, 2022), where the 0.005 is the maximum allowable sulphur content for the fuel. The last equation (3.34) is for the NO_x emissions, the engine's RPM is shown with n , and since the engines satisfies IMO Tier II limits, it can be calculated as follows:

$$NO_x = SFC \left[\frac{g}{kWh} \right] \times 44 \times n^{(-0.23)} \quad (5.34)$$

According to given properties, and ship's operation profile, the emission reduction potential of the proposed hybrid system is given in the Figure 5.14 and 5.15.

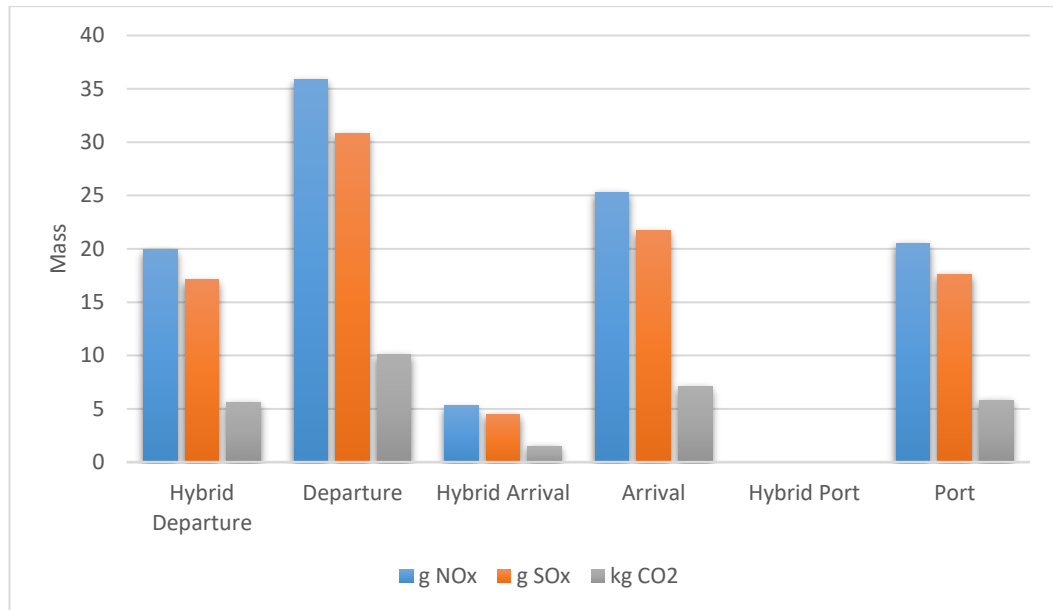


Figure 5.14 : Emissions for departure, arrival and port sections.

As can be seen in the figure 5.14, hybrid system can reduce the fuel consumption and emissions with different ratios depending on the power demand. The decreases at the emission are 45%, 79% and 100% for departure, arrival and port, respectively. The reason of total emission elimination at port is due to the lower power demand than the optimal fuel cell power ($P_{FC,opt,total}$). In this position, generators and batteries are in stand-by position and hotel load is covered by the fuel cells. The results for the steady-state sailing section are given in the figure 5.15.

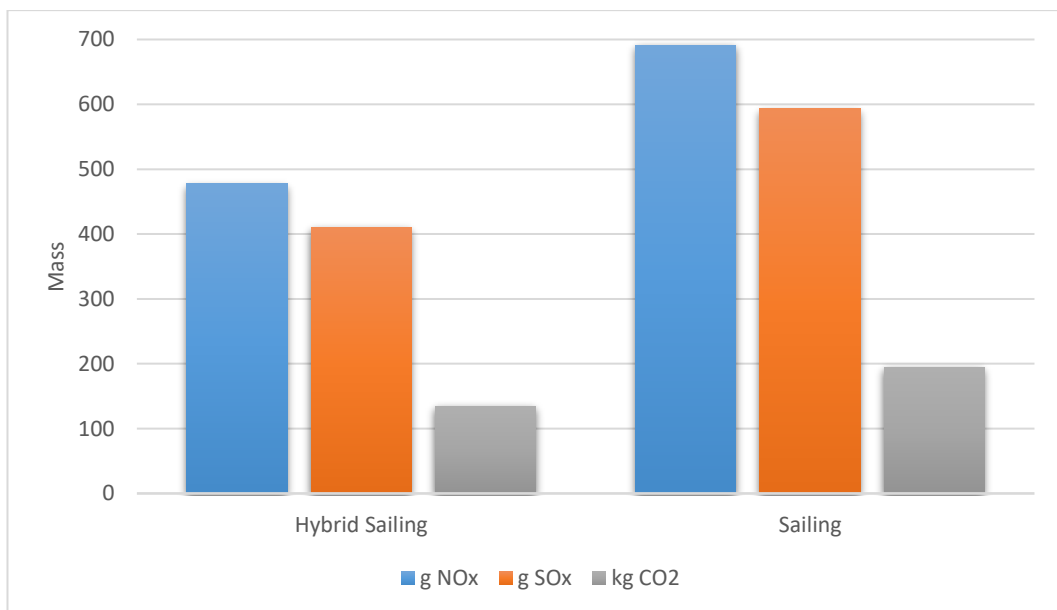


Figure 5.15 : Emissions for steady-state sailing.

As can be noticed in the figure 5.15, the emissions during steady-state sailing have decreased by approximately 31%. The main difference is coming from the eliminating of 2 diesel generators by supplying the required power with fuel cells and batteries. During the steady-state sailing, the fossil fuel has consumed only by two diesel generators instead of four.

Total fuel consumption is about 67.9 kg per voyage but if the system were hybridized, the consumption would drop to 44.2 kg which means a reduction of about 35% per voyage. By respecting the daily and yearly data of the ferries, there are 140 voyages per day, and 51,100 voyages per year (by neglecting the holidays and considering as all ferries are the same). Therefore, if the results are multiplied by 51,100 the yearly saved amount will be found 1,124 tons of diesel oil just for one ferry. The state of charge of the battery is considered as full during the analysis.

5.4 Conclusion

In today's world, greenhouse gas emissions are the main problem for ships. International Maritime Organization strongly works on emission reduction techniques and brings more strict regulations. With this aim, hybrid propulsion systems are one of the major solutions of the industry to reduce emissions. This chapter firstly introduces the hybrid ships and hybridization components with the possible topologies. Batteries, diesel generators, fuel cells, and supercapacitors are reviewed for the energy part of the systems. Serial, parallel, and serial-parallel topologies for the hybrid power systems are shown with diagrams. Then, the most popular energy management strategies are introduced. Thirdly, a case ship with the operation profile and mathematical modeling of equipment are explained. Transfer functions of a 4-stroke diesel engine, battery, and fuel cell dynamic models in the Simulink are discussed. Mathematical models of the converters and DC electric motors and propellers are presented. The mechanical equipment such as reduction gear and the shaft are represented with mathematical models. The hull resistance calculations are given with the Holtrop-Mennen technique and Simulink models are shown for the readers to enhance the clarity of the explained topic. An approach for the energy management strategy is given according to different power sources and power balance equations shown to enlighten future studies on similar topics. Lastly, reduction in fuel consumption and emissions are shown and hybrid system is compared with the

conventional one. The study investigates the combined use of diesel generator, fuel cell and batteries for the case study of an Istanbul ferry. This solution can be a very interesting choice for ferries operating into cities thanks to their zero-emission or reduction at the fuel consumption capabilities.





6. CONCLUSION

6.1 Conclusion

Maritime transportation is one of the key elements of international trade with its high capacity. Besides, the amount of consumed fossil fuel and so, the emitted exhaust gases are other important issues of interest to maritime transportation. Especially, ships operating close to the shoreline or urban transportation are much more dangerous due to harmful emissions to human health. With the rules, regulations, and legislations of IMO, efforts are being made to reduce greenhouse gas-effective emissions in the maritime industry. The most critical emissions are CO₂, NO_x, SO_x, and PM which are under scrutiny by the IMO. Therefore, shipping companies are seeking more energy-efficient propulsion methods to reduce harmful emissions. There are many different options to reduce or eliminate ship-sourced emissions. Improvements in ship design, using alternative fuels, scrubbers, use of renewable energy, electrification of ships, and reducing the speed (required power for the ship propulsion) are some of the leading technologies. However, all these new technological approaches are quite challenging due to the different characteristics of the ships. In this regard, each ship should be studied as a proper case for selecting the best energy efficiency improvement. Selecting the case ship is substantial to establish and analyze the correct propulsion technology. Besides the emission reduction technologies, the powering system can be changed. Electric propulsion is an already proven technology for the automotive industry. The studies on cars are generally depending on the driving methods. Since the city traffic and highway characteristics are different, the engagement of the powering technology varies. Battery hybridized internal combustion method is the most common approach. When the traffic in the city increases, electric driving is activated, on the other hand, the engine is running in high-speed stationary driving. The same point of view can be adapted to ships. If the case vessel works for urban transportation, the electric power can supply the required power. However, for oceangoing vessels, the required propulsion power is relatively higher than for small type ships. Hence, the only option can be used is a marine diesel engine with an electric

supply. This combination would reduce the emission during oceangoing trips. As mentioned in the introduction section, a passenger ferry is selected as a case vessel. So, the expectation from the ship is to minimize the emissions by using electric power. The generation of electric power is also another important issue. Comparing the automotive industry, the energy storage capacities of the batteries are quite weak for the shipping system. So, another way electric production way should be found for the ships. Using renewable energy is a great solution, however, the technological maturity for mobile applications seems far from the commercial application. The examples of wind turbine applications were shown in the previous articles, but the architectural characteristics of the ship changes with this technology. Also, photovoltaic panels can be an option. But the power generating capacity is limited too. At this point, fuel cells are remarkable with carbon-free power generation abilities. There are different types and the correct type should be selected for the ships. The second section of the thesis was analyzing this topic. The other great issue is the used fuel type in fuel cells. Since the main purpose is the decarbonization of shipping, two fuel types are on the scene; ammonia and hydrogen. The details and the selection of the proper fuel type is analyzed in the second article, which forms the third section of this thesis. The following sections were on the hybridization of the fuel cells and diesel generators with batteries. The case vessel possible energy management strategy and the emission reduction potential with the fuel consumption are explained with the mathematical models of the each component.

In this thesis study, the electrification of ship propulsion systems with hybrid power generation and electric storage devices is investigated. The main selection reason for the hybrid system is strongly related to the operation profile of the ship. In the previous sections of this study, it has been shown and explained that electric propulsion systems are much more effective when the load fluctuation is high during the operation. On the other hand, when the ship has a long-time voyage with a constant load, internal combustion engines are still the most affordable and effective way to produce the required propulsion power. However, in our study, a passenger ferry has been chosen as a case ship that works between the Asia and Europe coasts of Istanbul. Then, the hybrid system components have been selected according to the ship's properties and operation profile. The main idea is to reduce the harmful emissions which are directly related to ships' inefficient operations and use of fossil fuel.

In this perspective, in the first part of the thesis study fuel cells are elaborated for shipping applications. The five main commercial types are explained, reviewed, and evaluated. Mainly, fuel cells suffer from low power capacity for maritime applications. Especially, for oceangoing big-size ships have greater power demands than a fuel cell can produce. For this reason, the high-temperature types, molten carbonate, and solid oxide fuel cells seem promising. On the other hand, the high power-producing capacity needs fuel volume which should be stored onboard the ship. The ability to use hydrocarbon fuel for high-temperature working fuel cells is a great advantage compared to low-temperature types that need hydrogen in high purity. Since the industrial experience in hydrogen storage is weak, LNG and marine diesel oil-using ability is gaining importance. Then, ships were categorized according to their architectural characteristics, general operation profiles, power demands, volumes, and safe maritime operations. The criteria are determined to assess the fuel cells with the AHP tool. The offered criteria to experts were safety, cost, fuel types, efficiency, emission, size, power capacity, and lifetime. The importance (weights) of the criteria were calculated by gathering the given points from the experts. Respecting the results safety was the most important was the size brought up the rear. Lastly, according to the parameters of the fuel cell types, proper scoring has been carried out. Diesel oil using molten carbonate fuel cells and proton exchange membrane fuel cells were in the top two. The little difference between them is strongly related to the ship's operation profile and power requirement.

In the second part of the thesis, hydrogen and ammonia fuels were compared to use in proton exchange membrane fuel cells. The PEM fuel cells were found as one of the best fuel cell types for ship applications. They can use hydrogen directly and ammonia after a reforming process. Therefore, ammonia has been accepted as a hydrogen carrier to use in fuel cells. The idea was to determine which fuel is more feasible in the short-term for carbon-free shipping. The criteria were defined to evaluate by using literature knowledge. According to maritime expertise and industrial knowledge, the selected criteria were safety, environmental impact, sustainability, storage, and cost. A sensitivity analysis has also been carried out to the AHP results and ammonia showed a better performance than hydrogen in short-term vision. However, from the environmental perspective, hydrogen was better due to the ammonia's toxicity. On the other hand, ease of storage, and cost were the primary drivers that put the ammonia forward in this comparison. From the short-term perspective ammonia was leading but

in the long-term hydrogen is the ultimate solution. The main disadvantage comes to form the hard storage condition of the hydrogen.

In the third section of the thesis study, hybrid power generation technologies, energy storage components, energy management systems, and hybrid propulsion topologies have been reviewed. Diesel engines, fuel cells, and solar and wind power as renewable energy sources are discussed as power generation units. On the energy storage side, batteries, supercapacitors, and flywheels have been presented and described. Three common hybrid propulsion configurations, serial, parallel, and serial-parallel architectures are detailed with their pros and cons by highlighting commonly used energy management systems and optimization methods. Lastly, criteria for hybrid system selection are defined according to eight different ship types and assessed by providing a generic methodological approach. It has been shown that electrical components and architectural design should be elaborated according to the operational and architectural characteristics of ships. In short term, it is concluded that internal combustion engines are still the major hybridization element with different energy storage systems. New regulations on the mitigation of harmful emissions would accelerate the transition to hybrid power which is an important option for the ultimate zero-carbon shipping goal.

The fourth section of the thesis study especially focuses on the minimizing the impacts of the ships operating in the coastal, harbor, or urban areas which is a key feature considering environmental and human health concerns. Shortly, ferries or passenger ships operating in these areas will face reaching zero-emission constraints. Therefore, using electricity as a main vector of energy is one of the most promising ways to reach these goals. Particularly, full electric or hybrid solution using multi-source energy systems appears to be a very relevant solution. This section is devoted to the study of the electrification and hybridization of passenger ships operating in coastal and urban areas. The first part of the section aimed to review the fully electric and hybrid propulsion topologies and power management strategies that can be used for ferries and passenger ships operating in coastal or urban areas. Particular focus will be on full electric solutions based on batteries, supercapacitors and fuel cells as main energy sources and possible energy management strategies. In the second part of the chapter, a case study is presented based on the specifications and mission profile of the Istanbul Ferries crosses the Bosphorus. A possible technical solution has been studied by giving mathematical models of the equipment respecting the state of the art in the first part.

Mathematical models for each equipment on board ship has been completed, and a rule-based energy management system for the hybrid battery, fuel cell, and diesel engine combination is proposed. The fuel consumption and emission reduction ability has been shown in this section for the selected passenger ship.

At last, the proposed hybrid system has two diesel generators instead of four. The required missing power is supplied by the fuel cells and battery packs. This smaller number of generators has additional advantages as well. The operational requirements and system costs are much more affordable compared to diesel engines. Specifically, less periodical maintenance, less operational expenditures, and lower running times are the most important operational advantages from the diesel engine perspective. Furthermore, at the hybrid system the operation point of the engines are at the high efficiency area compared to conventional system.

6.2 Limitations and Future Studies

The limitations for each section are forming the total for the thesis study. The important factors that faced during the studies can be divided into different parts according to characteristics of the work. For instance; the difficulties are different for the assessment tools in the first two sections, and data gathering for the case ship in the last section.

For the assessment part at the first and second sections, the followings can be listed:

- Finding the experts from the industry for criteria weighting at the topics such as hydrogen, ammonia, hybrid systems and fuel cell topics was very difficult. Also, sometimes their returns to the prepared surveys about the study topics was late.
- AHP tool is quite subjective, and very depended on the experts' ideas. Although each survey in this study were conducted with more than 15 people, adding and combining some other decision-making tools could be more effective. For this reason, sensitivity analysis has been added to the results at the second section. This helps to test the reliability of the result.
- The alternative fuel, alternative energy sources, and power generation literature is weak to assess the gaseous fuels such as hydrogen that is studied in the articles in this thesis. Hydrogen storage and bunkering opportunities are also not sufficient compared to diesel oil fuels.

For the modelling and case study parts at the third and fourth sections, the followings can be listed:

- The hull model of the case ship is calculated with Holtrop-Mennen technique although the data gathering period was physically onboard ship. The required documents about the architectural characteristics of the ships were missing.
- Each equipment is mathematically modeled in the Simulink environment. However, since there is no validation opportunity, fuel cells and battery models are used as in the generic models of the software.
- The electric converters are modelled statically, dynamic boost or buck-boost converter could be used for improved results.
- The operational data is collected with under summertime conditions, and without an additional Bosphorus traffic. Alternative weather and sea conditions can be added to the simulations.
- Rule-based energy management is used for hybrid system. Optimized energy management strategies can be used with different algorithm by comparing the results for the same ship and operation.
- Different level of modelling and equipment can be used for hybrid system. In this study, fuel cell, diesel generator and battery combination has been carried out for emission analysis. However, supercapacitors and renewable energy sources may give remarkable results.
- The study can be enlarged by considering hydrogen fueling station from the ports and/or onboard production. However, this should to investigate economic and technical feasibility more deeply. Also supplying the port energy requirements by hydrogen fuel cells and batteries can enlighten the way to the zero-emission urban transportation.
- Future studies may also focus on heat recovery systems for fuel cell outputs. Organic Rankine cycle can be an attractive proposal to reach the higher efficiencies.

To sum up, hydrogen fuel cells are promising solutions to reduce the emissions in urban sea transportation by hybridizing with batteries and diesel engines. Zero emission can also be achieved with fuel cells as clean power sources. Hydrogen storage costs and fuel cell technologies are the major obstacles to its use as a transportation technology, but it is certain that it is only a matter of time.

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EDUCATION

- **B.Sc.** : 2017, Istanbul Technical University, Maritime Faculty, Marine Engineering.
- **M.Sc.** : 2019, Istanbul Technical University, Graduate School, Maritime Transportation Engineering.

PROFESSIONAL EXPERIENCE AND REWARDS:

Professional Experience

- **2017 – 2017** : Piri Reis University, Maritime Faculty, Marine Engineering Department – Research Assistant
- **2018 – 2018** : Chemfleet – Oceangoing Marine Engineer
- **2018 – ongoing** : İstanbul Technical University, Maritime Faculty, Marine Engineering Department – Research Assistant

Rewards

- 2nd Place in Unmanned Surface Vehicle Competition (Arduino controlled wireless communication) Turkish Naval Academy - May 2016, TR.
- Mansion Reward in Port Innovation Contest / YILPORT, 2019, TR. “Hybridized Port Vehicles with Hydrogen Fuel Cells”.
- PhD Student Bursary, 2020 / Institute of Marine Engineering Science and Technology (IMAREST), UK.
- 1st Place in “Woman in Maritime Lab Ideathon” by “SeaCode” Project with SheFarers Team, UK, 2020. (Org. by Shell, Hafnia Group and BW&LNG)

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Inal, O.B.,** Zincir, B., Deniz, C. (2022). “Investigation on the Decarbonization of Shipping: An Approach to Hydrogen and Ammonia”, *International Journal of Hydrogen Energy*.
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- **Inal, O.B.**, Zincir, B., Deniz, C. (2021). “Comparison of hydrogen and ammonia for the decarbonization of shipping”, *5th International Hydrogen Technologies Congress (IHTEC-2021)*, 26-28 May 2021, Online.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

Articles

- Dere, C., Zincir, B., **Inal O.B.**, Deniz, C. (2022). “Investigation of the Adverse Effects of Slow Steaming Operations for Ships”, *Proceeding of the Institution of Mechanical Engineers, Part M: Journal of the Maritime Environment*.
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- **Inal, O.B.**, Dere, C., Zincir, B. (2022). “Hydrogen as Maritime Transportation Fuel: A Pathway for Decarbonization”, in book: *Greener and Scalable E-fuels for Decarbonization of Transport*, Springer.

Conference Papers

- Tekeli, M.M., Akyuz E., Gulen, M.F., **Inal O.B.** “Numerical analysis of tank coating selection in chemical tanker ships”, *International Symposium on Energy Management and Sustainability (ISEMAS-2022)*, 06-08 April 2022, Online.
- Gulen, M.F., Kadioglu, M., Arslan, O., Tekeli, M.M., **Inal O.B.** (2022). “A bow-tie analysis for navigational safety and environmental sustainability on the 1915 Çanakkale Bridge”, *International Symposium on Energy Management and Sustainability (ISEMAS-2022)*, 06-08 April 2022, Online.
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Projects

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