

THE ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF ALTERNATIVE MARINE FUELS AND NUCLEAR ENERGY UTILIZATION ON A FLOATING POWER PLANT

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ABSTRACT

The paper aims to investigate the fuel and system options for a floating power plant (FPP) considering economic performance and the decarbonization goals of the International Maritime Organization. Various case studies have been assessed using a reference FPP, encompassing the instant and future retrofitting scenarios. The ready-to-use scenarios involve alternative fuel and organic Rankine cycle-based waste heat recovery system usage. Nuclear energy systems have been evaluated within the reference FPP since they are suitable candidates for achieving zero-carbon objectives and providing low-cost electricity. A simulation framework created in Python has calculated the fuel consumption regarding the power requirement and organized the approaches used in the study. An environmental model comparing the systems has been built to calculate upstream and operational emissions. The cost projection model for 2030 and 2050 has assessed the economic performance. Technique for Order of Preference by Similarity (TOPSIS) one of the multi-criteria decision-making approaches has ranked the systems considering the outcomes of economic and environmental models over the years. Findings demonstrate that the current fuel usage scenario of the FPP is not suitable both environmentally and economically. The other emissions can be near zero and greenhouse gases can be decreased by up to 15.95% using alternative fuels. Nuclear energy is a strong candidate to meet the 2050 targets, but its viability is largely based on economic performance.

Keywords: Floating power plant, alternative marine fuels, nuclear energy, waste heat recovery system, TOPSIS, marine engineering.

NOMENCLATURE

Symbol	Description	Unit	Symbol	Description	Unit
C_f	Carbon Coefficient for Fuels	-	\dot{m}_{ex}	Exhaust gas mass flow rate	kg/s
C_{fs}	Fuel Cost Savings	\$	MCDM	Multi-Criteria Decision-Making	-
C_{fuel}	Operational Fuel Expenses	\$	MeOH	Methanol	-
C_i^*	Relative Closeness Coefficient	-	N_2O	Dinitrogen oxide	-
C_{ORC}	The Cost of ORC System	\$	NO_x	Nitrogen Oxide	-
$C_{o\&m}$	Operation and Maintenance Cost	\$	NoG	Number of Generators	-
C_p	Specific Heat Capacity of The Exhaust	kJ/kgK	ORC	Organic Rankine Cycle	-
C_{plant}	The Installation Cost of The DF Engine	\$	P	Power of One Generator	kW
C_u	Upstream Emission Coefficient	-	PBP	Payback Period	years
CEPCI	Chemical Engineering Plant Cost Index	-	PM	Particulate Matter	-
CH ₄	Methane	-	PS	Power Ship	-
CO ₂	Carbon dioxide	-	r_{ij}	Normalized Decision Matrix	-
CO ₂ -Eq.	Equivalent CO ₂	-	SENELEC	Senegal's Electricity Authority	-
C_e	Electricity Production Cost	\$/kWh	SFC	Specific Fuel Consumption	g/kWh
d_{ij}	Data Point in ith row and jth column	-	S_i^-	Euclidean Distance from	-
DF	Dual Fuel	-	v_j^-	Euclidean Distance from	-
E_o	Operational Emissions	g	S_i^*	Euclidean Distance from	-
E_U	Upstream Emissions	g	v_j^*	Euclidean Distance from	-
EdM	Electricidade de Mozambique	g	SMR	Small Modular Reactors	-
FC	Total Fuel Consumption	g	SO _x	Sulphur Oxide	-
FNPP	Floating Nuclear Power Plants	-	$T_{ex,in}$	Exhaust temperature at inlet	K
FPP	Floating Power Plant	-	$T_{ex,out}$	Exhaust temperature at the outlet	K
HFO	Heavy Fuel Oil	-	t_{op}	Operation Time	h
ICE	Internal Combustion Engine	-	TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution	-
			v_j^-	The Negative Ideal Solution	-

IMO	International Maritime Organization	-	v_j^*	The Positive Ideal Solution	-
LCOE	Levelized Cost of Energy	\$/kWh	V	Weighted Decision Matrix	-
LCV	Lower Calorific Value	kJ/kg	\dot{W}_{net}	Net Power Provided by WHRS	kW
LNG	Liquified Natural Gas	-	WHRS	Waste Heat Recovery System	-
LPG	Liquified Petroleum Gas	-	η_{ORC}	Efficiency of ORC	-

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1. INTRODUCTION

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Millions of individuals still have difficulty accessing electrical energy supplies, despite the continued technological advancements applied in energy production (Ritchie et al. 2024). The global electricity demand is reported as 24,700 TWh in 2021 with an increase of 6% from the year 2020. Although China, the United States, and Europe together constitute 60% of the global energy demand, developing economies like Brazil and India also hold a reasonable share within the remaining 40%. It is predicted that the global electricity demand growth will step up by 24% in 2030 and 77% in 2050 according to 2021 demands (IEA 2022a). Although the resources used for electrical energy production change over time, their fundamental resources are fossil fuels, renewable, and nuclear. To stop climate change and promote environmental awareness within the scope of sustainable development goals, the use of renewable resources has dramatically increased recently (Ritchie et al. 2024).

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All in all, about 300 GW of renewables were taken into operation globally in 2022, while the 1.5 °C pathway suggests the annual deployment of 1000 GW of clean power. The 1.5 °C scenario also suggests shifting the share of fossil fuels in gross electricity production from 62% (2020) to 5% in 2050 since most energy-producing systems use traditional methods causing harmful emissions (Ritchie et al. 2024). In this regard, the share of renewables (28% in 2020) has kept growing globally in recent years (IRENA 2023). The recent investments in the energy sector provide the forecast that the share of renewables on the global energy demand will move up to 38.1% in 2027 by reducing the shares of fossil fuel-based power plants (IEA 2022b). In addition, it is expected that nuclear power which has a share of about 10% in 2020 will also benefit from the climate action due to its ability to provide power with clean, reliable, and cost-competitive properties. However, its share of global energy demand is projected to boost like renewables but remain around 9% (IEA 2023).

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As energy needs increase, it has become more difficult to obtain sufficient, continuous, and reliable energy. Access to energy has not eliminated all problems. Minimizing the environmentally harmful effects of energy production stages and protecting energy supply facilities against external threats has become an important problem. All these factors have paved the way for energy production and providers to work on different alternatives. One of the most important of these alternatives is Floating Power Plants (FPPs). An FPP or Powership is a special ship type built to provide electricity generated onboard to the land. Differing from the stationary offshore energy platforms, they are self-propelled, ready-to-use facilities for developing nations that may be converted from existing ships and connected to national grids as needed (Pamuk et al. 2022). FPPs appear to be a promising solution for regions that need electricity for a certain period. The mobility feature of them is quite valuable in terms of providing electricity close to the coastal area where electricity is needed (Ritchie et al. 2024). The first known FPP system was created by removing all propulsion systems and deck machinery from the cargo ship SS Jacona and installing new boilers and generators. She was used for emergency cases of civilian power service on the New England coast until 1945 (Acuner and Helvacioğlu 2017). Later, the energy production options of FPPs diversified to include nuclear and solar energy, and their use became widespread.

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In 2009, the company pioneered the FPP industry by introducing the world's first floating energy fleet, patented as "Powerships" (PS) by Karadeniz Energy in 2017. Distinguishing itself from traditional FPPs, PSs are uniquely equipped with propulsion systems, enabling quick deployment within a few months after the contract agreement. These innovative vessels can be stationed at suitable coastal locations with access to the main grid, eliminating the need for extensive land acquisition and onshore infrastructure. Power generated by a PS is seamlessly integrated into the main grid through the onboard high-voltage substation. The vessels' high-capacity generators are supplied with fuel via pipelines or bunkering at onshore facilities, offering flexibility in utilizing low sulfur Heavy Fuel Oil (HFO), Liquified Natural

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88 Gas (LNG), and Liquefied Petroleum Gas (LPG) through dual-fuel engine technologies. Notably, after
 89 the contract period concludes, PSs can navigate to the next customer without the need for towing
 90 (KaradenizEnergy 2017). A large PS fleet continues to provide energy in various parts of the world, and
 91 the size of the fleet shown in Table 1 is increasing day by day, both numerically and in capacity. Former
 92 PS projects that are not currently ongoing but were built in the past to provide energy to Iraq, Lebanon,
 93 Guinea, and Indonesia are not included in the table. The complete list of PSs that produce energy with
 94 HFO and LNG is shown in Table 1.

95
 96 **Table 1** Areas and details of the projects (KaradenizEnergy 2024)

Areas	Project Details
Ghana Project	In the Ghana initiative, PS has been delivering 450 MW of energy, operating at the Port of Tema in collaboration with the Ghana Electricity Administration since 2015. Marking the initial African country project and serving as a hub for the West African region, the PS contract for Ghana represents a significant milestone. The electricity purchase agreement for Ghana spans a total of 10 years, structured as a 5-plus 5-year contract. This energy provided by PS corresponds to 23% of Ghana's electricity needs.
Gambia, Africa	In February 2018, Karpowership agreed with the National Water and Electricity Supply Company Ltd. of Gambia to deploy a 36 MW PS. Since 2018, Karpowership has been actively operating in Gambia, meeting 60% of the country's overall electricity requirements. The company's capacity to swiftly enhance energy output when needed has emerged as a crucial element contributing to the nation's energy security and reliability.
Mozambique, Africa	Karpowership agreed with Mozambique's electricity utility company, Electricidade de Mozambique (EdM), to install a 125 MW PS. Operational in Mozambique since 2018, Karpowership collaborates with EdM to transition operations to LNG, marking the initiation of the first LNG-to-Power Project in Sub-Saharan Africa utilizing its FSRU. Karpowership has been contributing to 10% of Mozambique's overall electricity requirements.
Sierra Leone, Africa	In June 2018, Karpowership agreed with Sierra Leone's national utility company, the Electricity Distribution and Supply Authority, along with the Ministry of Energy and Ministry of Finance, to deploy a PS providing 30 MW. Subsequently, an addendum was signed in 2018 to increase the capacity to 50 MW, and in 2020, a third addendum further raised the capacity to 65 MW. Operating in the country since 2018, Karpowership has been instrumental in supplying 80% of Sierra Leone's overall electricity requirements.
Cuba the Caribbean	In October 2018, Karpowership agreed with La Empresa Importadora y Exportadora de Objetivos Electroenergéticos, the state electricity company of Cuba, to deploy three PS totalling 110 MW over 51 months. The operations of Karadeniz PS Barış Bey and Karadeniz PS Esra Sultan commenced in Port de Mariel in June 2019, while Karadeniz PS Ela Sultan started operations in November 2019. By November 2019, the contract capacity was expanded to 144 MW. Subsequently, in November 2021, a new Addendum Agreement was signed, further increasing the capacity to 300 MW, and extending the contract term to 18 years. Currently, Karpowership operates six PSs in Cuba, boasting a combined installed capacity of 420 MW. This marks Karpowership's inaugural project in the Western Hemisphere.
Guinea-Bissau, Africa	In January 2019, Karpowership agreed with Electricidade e Aguas da Guiné-Bissau to deploy a 35 MW PS. Operating in Guinea-Bissau since 2019, Karpowership has played a pivotal role in meeting the entire electricity demand of the country, supplying 100% of Guinea-Bissau's total energy requirements.
Senegal, Africa	In August 2019, Karpowership entered into an LNG-to-Power agreement with Senegal's Electricity Authority (SENELEC) to install a 350 MW PS. Operational in Senegal since 2019, Karpowership has played a crucial role in meeting 15% of the country's overall electricity demands. Additionally, the company is collaborating with SENELEC to transition operations to LNG-to-Power, having already deployed one of its LNG assets, KAMROL LNGT Africa, in Senegal.
Brazil, South America	In November 2021, the company successfully initiated the initial LNG-to-Power agreement in the transatlantic region, specifically with Brazil. The operational power plants in Brazil consist of four PSs and one Floating Storage Regasification Unit (FSRU), collectively generating 560 MW of electricity. The company has been actively operating in Sepetiba Bay since 2022.
South Africa, Africa	In response to South Africa's Risk Mitigation Independent Power Producer Procurement Program tender process in 2021, Karpowership participated in adding a 2000 MW capacity

	to the country's grid. The company's successful bids, totalling 1,220 MW for LNG-to-Power, were declared as the winning proposals for three projects. Karpowership is set to commence operations in South Africa shortly, contributing to supplying over 5% of the country's total electricity requirements.
Ivory Coast, Africa	In January 2022, Karpowership inked an agreement with the State of Ivory Coast to produce 100 MW of electricity. Operating in Abidjan since 2022, It has been instrumental in fulfilling 7.5% of Ivory Coast's overall electricity requirements.
New Caledonia, Oceania	In February 2022, Karpowership established its inaugural agreement with a private entity, SLN-Eramet, the leading global ferronickel producer. This project marks Karpowership's first venture in an EU overseas territory. Operating with a 200 MW installed capacity, Karpowership has been fulfilling 15% of the country's electricity requirements.
Dominican Republic, Caribbean	In the final quarter of 2022, Karpowership secured its inaugural project in the Dominican Republic, aimed at producing 180 MW of electricity. Operational in Azua since 2023, the company has established its presence in the region. It is very difficult to establish such a large energy facility in a region that has a large tourism capacity and earns a significant portion of its income from tourism.

97

98 Sustainability and decarbonization goals are getting closer to being achieved with the stringent
99 regulations of the International Maritime Organization (IMO) (IMO 2023). In this regard, it is important
100 to be ready for the upcoming and current regulatory environment for the FPP industry. Still, there is too
101 much room on the path to minimize negative environmental impacts and minimize emissions in energy
102 production. To achieve this, energy efficiency should be increased by eliminating losses in the
103 production stages and cleaner energy production should be aimed at alternative energy sources.
104 Methanol (MeOH), ammonia, hydrogen, and LNG show great prospects among the environment-
105 friendly alternatives of marine fuels to reduce the HFO and diesel oil domination in the energy mix
106 although there are still a few environmental issues to be considered, e.g., dinitrogen oxide (N₂O)
107 formation by burning ammonia and methane slip through onboard LNG/LPG storage tanks (Pedersen et
108 al. 2023). Dual-fuel engines are offered as cost-effective solutions that enable retrofitting the alternative
109 fuel systems to existing marine vessels. In addition, excessive amounts of waste heat emitted from large-
110 scale internal combustion engines make it feasible to utilize waste heat recovery systems onboard
111 (Konur et al. 2022a).

112

113 The global decarbonization actions pushed nuclear energy to one step forward in the global energy mix
114 as a clean energy option recently although safety, security, and legal considerations still suppress its
115 widespread utilization. The FPP concept is currently utilized for cheaper electricity costs, short-term
116 establishment duration, and affordable installation costs in rural areas (Pamik et al. 2022). Combining
117 maritime and nuclear frameworks as floating nuclear power plants (FNPPs) has also been experienced
118 since Akademik Lomonosov was commissioned for commercial operation in the Far East of Russia in
119 2020 (Gual et al. 2023). There is a rising interest in deploying small modular reactors (SMRs) on floating
120 platforms or barges, aiming to generate clean electricity and heat in distant coastal areas. This
121 technology is foreseen as a potential solution for decarbonizing offshore activities in sectors like oil and
122 gas or mining, and it may also offer a scalable option for grid-scale electricity production, leading to
123 cost reductions. Various countries, including Canada, China, Denmark, South Korea, Russia, and the
124 USA, are actively engaged in developing marine SMR designs, with some projects in advanced stages
125 of development. The International Atomic Energy Agency held the first international symposium on
126 FNPPs in November 2023, where FNPPs have been discussed as a reliable supply of energy for rural
127 areas (Ashton 2023).

128

129 Several studies have examined the safety and legalization issues related to FNPPs integrated with several
130 alternative energy systems. Lysenko M et al., (2019) discussed the legal and practical aspects of FNPPs
131 in terms of international legal regulations. They indicated that the utilization of FNPPs shows a large
132 conformity with the existing rules of International Law. However, some gaps and grey areas exist in the
133 case of an export that can be overcome with intergovernmental agreements on a bilateral or multilateral
134 level regarding the safety of transport through international waters. It was also concluded that the
135 political stability of the importing country and the region should be carefully weighed. The safety issues
136 for utilizing FNPPs have critical importance before their wide-range use for clean energy production.

137 The focus on the safety of utilizing FNPPs was gathered around many aspects, such as the severe
138 accidents on reactor equipment (Qiu et al. 2020), core instability cases (Guo et al. 2017), safety standards
139 for heating, ventilating and air conditioning systems designs of FNPPs for different climate conditions
140 (Han et al. 2021), hazard analysis for ship collision with a FNPP (Xiao et al. 2023), passive cooling for
141 the safety of FNPP under the rolling effect (Wei et al. 2023). Wang et al. (2023) performed an overall
142 risk and solution approach for the FNPPs in the marine environment. They assessed the regulatory
143 framework and marine-specific challenges of FNPPs.

144
145 On the other hand, some studies have included energy-based analyses of FNPPs and FPPs. Temiz &
146 Dincer, (2022) proposed integrating an offshore-based FNPP into an on-shore solar energy and hydrogen
147 production system in Canada to address the insufficient energy infrastructure for the initial instalment
148 of the land-based system by energizing the initial installation and the low demand of the communities
149 such as the Arctic. Thermodynamic analyses were carried out for a 150 MW_{th} offshore-based FNPP,
150 25 MW_p photovoltaic system, and 15 MW fuel cell unit with an electrolyzer system. Energy and exergy
151 efficiencies of the cogeneration system were calculated as 24.5% and 19.7% for the FNPP's connected
152 case, respectively. The energy and exergy efficiencies during the FNPP's disconnected period are
153 obtained as 39.9% and 46.0%, respectively. Pamik et al. (2022) examined the "Power Ship" concept and
154 assessed the perspectives of the maritime sector on the idea. They outlined advantages factors like fuel
155 availability, preventing power cuts, and supplying energy to required areas while highlighting the
156 security, safety, and social perspective issues.

157
158 The literature review shows that the decarbonization actions pave the way for the transition to cleaner
159 fuels and the FPP industry has started to adapt their power generation systems with dual-fuel engines
160 and nuclear power generation systems. MeOH is also in consideration in worldwide shipping as it is
161 relatively easy to retrofit to dual-fuel engines using LNG fuel systems. Although power ships are
162 operated mainly in coastal regions, a literature gap exists in assessing their air pollution impacts on the
163 electricity-supplied region. Comparative techno-economic and environmental analyses of HFO, LNG,
164 and MeOH utilization for electricity generation on FPPs, including possible carbon tax projections
165 shortly and effects of waste heat recovery system utilization, are not assessed in the literature. The
166 primary objective of this study is to scrutinize the range of fuel and system alternatives pertinent to an
167 FPP within the framework of economic evaluations and in alignment with the decarbonization objectives
168 set forth by the IMO. The study has differentiated from the literature by following aspects:

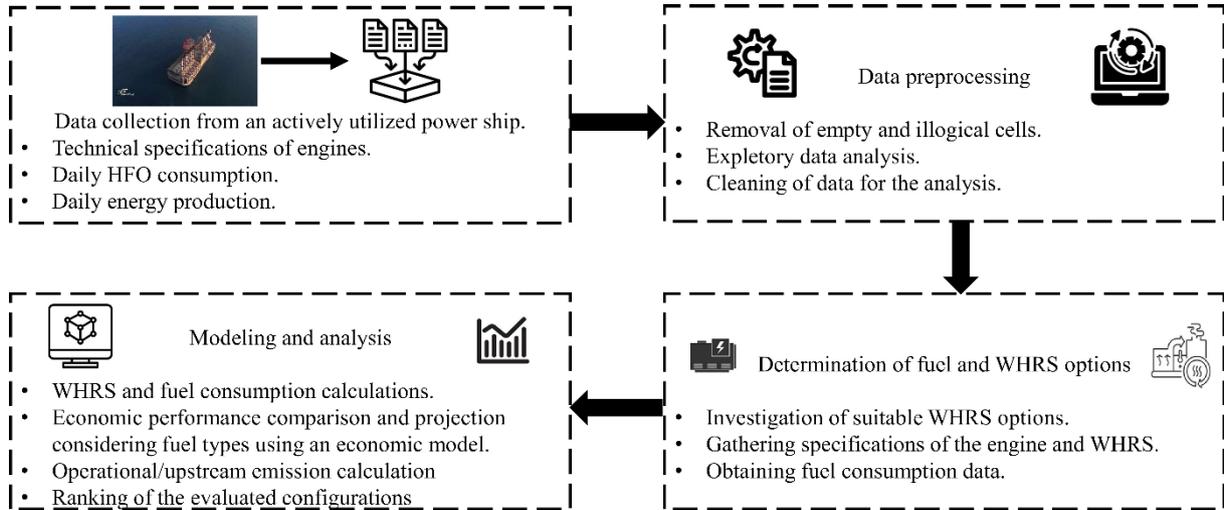
- 169 • Economic and environmental investigation involving different marine fuels and nuclear energy
170 for the FPPs.
- 171 • Providing scenario-based cost-benefit analysis for 2024, 2030 and 2050.
- 172 • An integrated assessment considering the economic performance, upstream and operational
173 emissions for short-term and long-term decarbonization objectives.
- 174 • The feasibility assessment of nuclear energy as a potential avenue for future applications of the
175 FPP.
- 176

177
178 For the analysis, data collection has been conducted from the reference FPP, and various case studies
179 involving three distinct fuels have been formulated. The evaluation encompasses the assessment of
180 installing an organic Rankine cycle (ORC)--based waste heat recovery system (WHRS) on the plant,
181 introduced as supplementary scenarios. Furthermore, a nuclear FPP scenario has been examined as the
182 seventh distinct case study. The determination of economic performance for the years 2030 and 2050
183 has relied significantly on a cost projection methodology for fuel and carbon prices. Additionally, the
184 environmental model has been utilized to compute both upstream and operational emissions across the
185 cases. Finally, a multi-criteria decision-making (MCDM) methodology has been employed to rank the
186 cases based on these comprehensive analyses.

187 188 **2. METHOD**

189
190 The method section has been split into two separate subsections which are "System Description" and
191 "Mathematical Modeling". The former has described the data and specifications of the evaluated vessel

192 and engines in the case study while the latter has explained the mathematical background and constraints
 193 of the economic and environmental models used in the study. Fig. 1 indicates the flowchart of the
 194 methodology structure utilized in the analysis.
 195



196
 197 **Fig. 1** The flowchart of the methodology used in the study
 198

199 The technical specifications of plant daily fuel consumption and generated energy have been obtained
 200 for four months from a reference FPP to conduct the analysis. After the data collection, the data have
 201 been cleaned and prepared for analysis. A suitable WHRS has been decided and the fuel savings
 202 regarding each fuel type have been calculated. An economic model that assesses the electricity
 203 production cost (C_e) depending on current prices and projected fuel costs for 2030 and 2050 has been
 204 developed. An environmental analysis has been conducted by considering the operational and upstream
 205 CO₂ of cases. The ranking of the methods has been ensured by an MCDM methodology to highlight
 206 possible shifts over the years. The availability of bunkering operations according to the configuration
 207 has been evaluated and the examined cases have been compared to other feasible plant configurations.
 208

209 **2.1. System Description**
 210

211 The reference power plant has operated in the Dominican Republic during the data collection and Table
 212 2 demonstrates the particulars of the analyzed FPP. The electricity consumption in the Dominican
 213 Republic has nearly doubled over the past two decades, soaring from 8.10 terawatt-hours (TWh) to 17.57
 214 TWh. 15 TWh of this annual electricity production is provided by fossil fuels. Nevertheless, roughly 3
 215 TWh corresponding to %17 rate has been covered by renewable sources in which wind solar, and
 216 hydropower are utilized. The utilization of renewable sources at this rate is insufficient to effectively
 217 contribute to sustainable development goals, particularly in developing countries. Moreover, annual
 218 electricity consumption per person is around 1580 kWh and 550 g of CO₂ emits 1 kWh of energy
 219 production (Ritchie et al. 2024).
 220

221 **Table 2** Specifications of reference FPP (Faber et al. 2022)

Particular	Value/Description	Unit
Gross tonnage (GT)	3,105	-
Deadweight (DWT)	7,445	t
Length overall	91.5	m
Draught	4.3	m
Beam	24.4	m
Built year	2011	-

222
 223 The internal combustion engines (ICEs) used in the power plant are four dual fuel (DF) engines (MAN
 224 18V51/60 DF) that can utilize HFO, LNG, and MeOH. The ICE employed in the powerplant is
 225 analogous to those utilized in cruise ships. The utilization purpose differentiates them from the cruise
 226 diesel-electric propulsion. The stationary floating power plants generally use renewable energy sources

227 such as wind, tidal, and sun however, the reference vessel navigates across the globe and provides a
 228 great amount of electricity in a random place. The alternative energy systems cannot meet solely the
 229 entire load and the current configurations are not equipped with them. The analysis has covered the fuel
 230 conversion scenarios as the instant solution, and nuclear energy as the final solution. The selected
 231 configurations have the potential to meet the whole load. The alternative energy systems can be added
 232 as a supplementary source when the location is known. However, the location-dependent analysis is out
 233 of scope in this study.

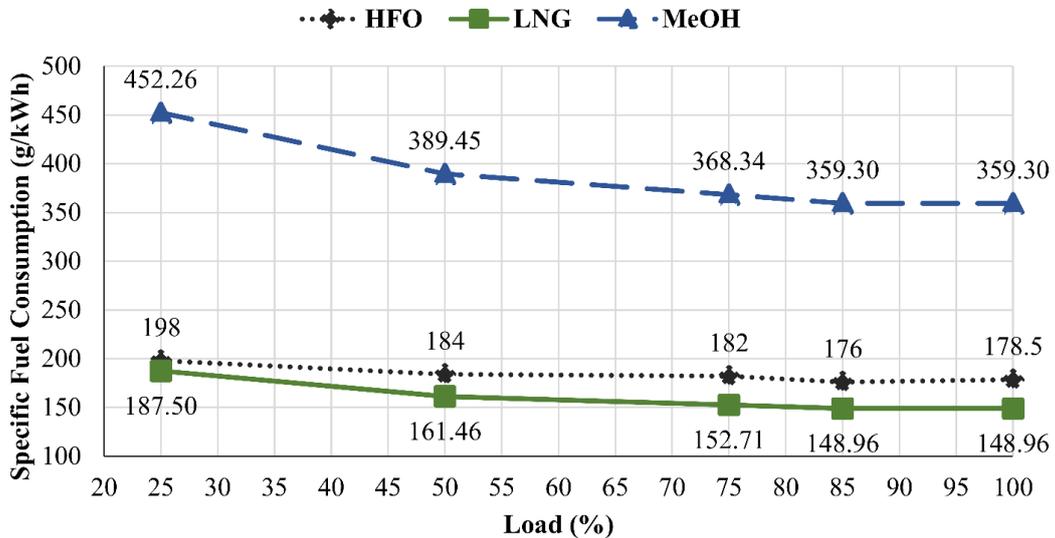
235 During the data collection, the operation was only conducted by using HFO on the plant considered as
 236 the base scenario and denoted as "Case 1". "Case 2" investigates the utilization of LNG as the primary
 237 fuel on the same DF engine configuration. The third case (Case 3) examines the adjustment option for
 238 the current engine for using MeOH as the primary fuel. The addition of the case aims to assess if MeOH
 239 as a marine fuel has potential economic and environmental advantages over LNG. Cases 4 to 6 are the
 240 addition of a WHRS that uses waste heat from the exhaust to support the plant to Cases 1 to 3. The
 241 environmental and economic effects of WHRS usage with different marine fuel modes have been aimed
 242 at examining the FPP. The fuel consumption calculation of DF engines has been ensured by using
 243 energy densities described in the engine data sheet. Table 3 indicates technical details about the current
 244 engine configuration of the FPP.

246 Table 3. Technical details of the investigated engines (MAN 2023)

Specification	Value/Description	Unit
Model	MAN 18V51/60 DF	-
Bore	510	mm
Stroke	600	mm
Frequency	50/60	Hz
Speed	500/514	rpm
Electrical power	17,766	kW

247 The engine output power is 17,766 kW and the specific fuel consumption (SFC) data considering the
 248 different fuel data has been gathered from the engine manufacturer. Fig. 2 shows the SFC of the engine
 249 in different fuel modes.

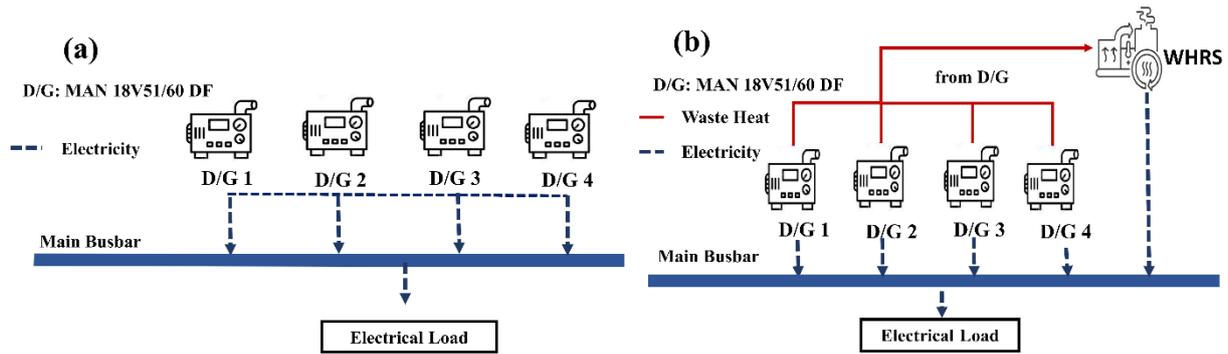
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252 Fig. 2 SFC of each fuel in the engine (MAN 2023)

254 The cases have been formed by fuel type and WHRS utilization so two different system configurations
 255 have been discussed. Fig. 3 illustrates the system schemes of the analyzed configurations. The nuclear
 256 power plant usage scenario has been assessed as "Case 7", and its economic and environmental data has
 257 been obtained from the literature. The utilized fuel and the condition that WHRS is implemented in the
 258 system have been indicated in Table 4 for each case.

260



261
262 **Fig. 3** System schematics of the configurations assessed in the study: (a) base scenarios, (b) WHRS implemented
263 scenarios (adapted from Konur et al. (2023))
264

265 **Table 4** Fuel types and WHRS usages in cases

Case	Plant Power Generator	Primary Fuel	WHRs Usage
1	DF ICE	HFO	No
2		LNG	No
3		MeOH	No
4		HFO	Yes
5		LNG	Yes
6		MeOH	Yes
7	Nuclear Reactor	Uranium	No

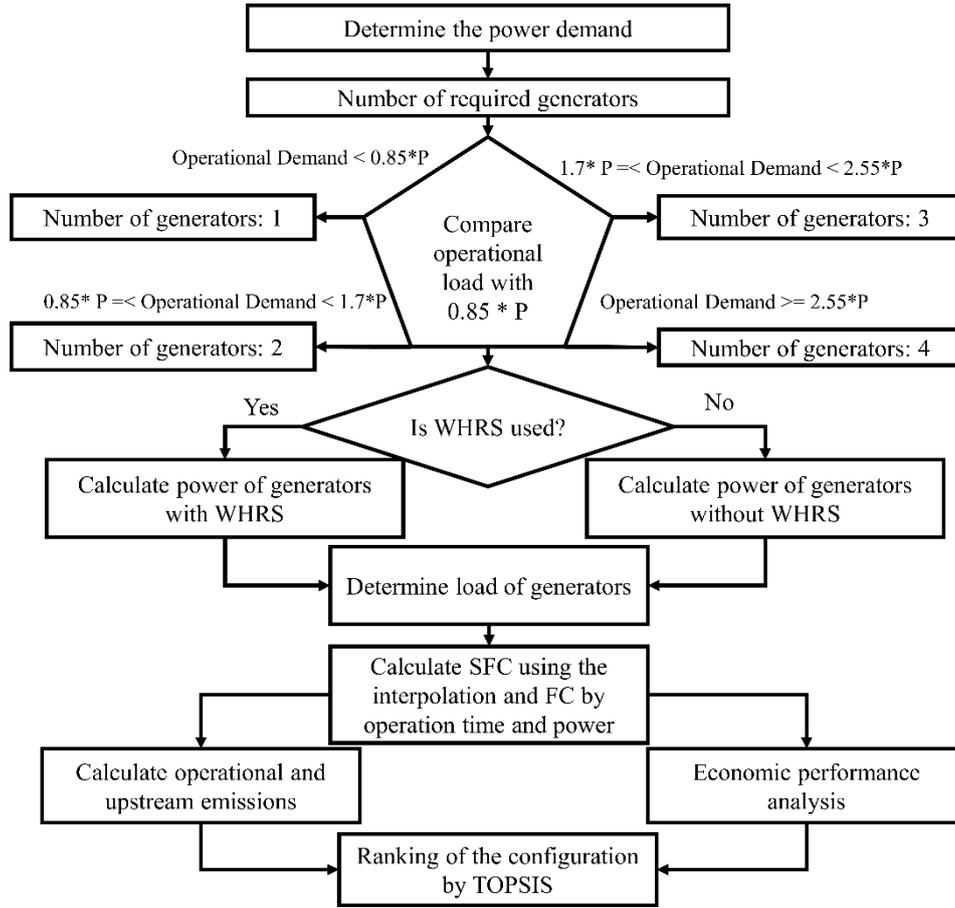
266
267 Fig. 3(a) represents the system schematic for non-WHRs used scenarios while the WHRS-integrated
268 systems' chart has been illustrated in Fig. 3(b) and their respective fuels have been demonstrated in
269 Table 3. The outcomes of these cases have been compared to the nuclear power plant data obtained from
270 the literature.

271
272 **2.2. Mathematical Modeling**

273
274 The section explains the mathematical background of the methodology and logic of the calculation
275 stages. The content of the section is as follows: "Simulation Logic", "Waste Heat Recovery System and
276 Fuel Consumption Calculation", "The Environmental Model", "The Economic Model", and "Technique
277 for Order of Preference by Similarity".

278
279 **2.2.1. Simulation Logic**

280
281 The logic of the algorithm used to conduct the analysis has been illustrated in Fig. 4 as a flowchart, and
282 the mathematical background of the steps has been explained in this chapter.
283
284



285
286 **Fig. 4** The algorithm scheme of the model used in the analysis (adapted from (Konur et al. 2023; Korkmaz et al.
287 2023))
288

289 The model finds the power demand of the respective row from the dataset and then initiates an if-else
290 construct to determine the number of generators (NoG) based on the required electric power and power
291 of one generator (P). If the examined case includes a WHRS, the power supplied by WHRS is calculated,
292 and the remaining load is shared between generators. If the WHRS is not utilized, the load calculation
293 is employed considering that generators meet the whole load demand. After the calculation of generator
294 loads the model computes the SFC by using look-up tables given in Fig. 2 and linear interpolation. In
295 the next step, it determines the total fuel consumption (FC) regarding the operational times (t_{op}) and
296 power demand, then using the FC , the model computes the operational/upstream CO_2 and measures the
297 economic performance. The model has ranked the cases by utilizing the determined MCDM technique
298 at the final stage.
299

300 2.2.2. Waste Heat Recovery System and Fuel Consumption Calculation

301
302 The FC has been calculated by employing Equation (1) (Bayraktar et al. 2023).
303

$$304 \quad FC (g) = SFC \left(\frac{g}{kWh} \right) \times P (kW) \times t_{op} (h) \times NoG \quad (1)$$

305 Equation (2) computes the net power provided by WHRS (\dot{W}_{net}) by performing a constant specific
306 heat-based formula considering different engine loads of the examined cases (Konur et al. 2022b).
307

$$308 \quad \dot{W}_{net} = \dot{m}_{ex} \left(\frac{kg}{s} \right) \times C_p \left(\frac{kJ}{kgK} \right) \times (T_{ex,in} - T_{ex,out}) (K) \times \eta_{ORC} \quad (2)$$

309 The WHRS has been assumed to perform an ORC and the design parameters of the ORC have been
310 taken from Konur et al. (2022). The efficiency of ORC (η_{ORC}) has taken 13.6%, (Konur et al., 2022)

311 and the specific heat capacity of the exhaust (C_p) has assumed at 1.089 kJ/kg·K (Konur et al. 2020).
 312 \dot{m}_{ex} is the mass flow rate of the exhaust and $T_{ex,in}$ represents exhaust temperature entering the WHRS.
 313 They have been taken by the manufacturer's data sheet and determined considering the load of the
 314 generator. The outlet temperature of exhaust from the WHRS is denoted by $T_{ex,out}$ assumed at 363 K
 315 (Konur et al. 2020).

316
 317 **2.2.3. The Environmental Model**

318
 319 Equation (3) calculates the operational CO₂ emissions (E_O) and Equation (4) determines the upstream
 320 emissions (E_U) by using the upstream coefficients (C_u) (Kuzu et al. 2021; Yuksel 2023; Yuksel and
 321 Koseoglu 2023).

$$E_O(t) = FC(t) \times C_f \quad (3)$$

$$E_U(t) = E_O(t) \times C_u \quad (4)$$

322
 323 where C_f is the CO₂ coefficient shown in Table 5 for each fuel. Table 5 also indicates the C_u taken from
 324 the environmental assessment of Gilbert et al. (2018) and the lower calorific value (LCV) of fuels. The
 325 nonrenewable MeOH using conventional production methods has been assessed in the study. The carbon
 326 footprint of the nuclear power plant used in Case 7 has been taken at 50 g/kWh (LSE 2022).
 327
 328

329 **Table 5** LCV C_f and C_u coefficients of fuels (Gilbert et al. 2018; IMO 2018; Pavlenko et al. 2020)

Fuel	C_f	LCV (kJ/kg)	C_u
HFO	3.114	40,200	0.147
LNG	2.75	48,000	0.130
MeOH	1.375	19,900	0.348

330
 331 The other emissions have been calculated by using the operational and upstream emission coefficients
 332 indicated in Table 6. In Equation (3), instead of C_f the relative operational coefficient according to the
 333 type of emission. The remaining upstream emissions apart from CO₂ have been computed by using
 334 Equation (4) when the upstream coefficient of the emission is dependent on the operational emission.
 335 On the other hand, when the unit of coefficient is g/kWh, it is multiplied by the total energy instead of
 336 utilizing Equation 4.

337
 338 **Table 6** Other operational and upstream emission coefficients (Gilbert et al. 2018; Pavlenko et al. 2020; Yuksel
 339 2023)

Emission	Operational (g/kWh)			Upstream (g/kWh or g E_O / g E_U)		
	MeOH	LNG	HFO	MeOH	LNG	HFO
CH ₄	N/A	3.000	0.010	0.752	1.718	0.879
N ₂ O	N/A	0.016	0.027	0.023	0.018	0.004
SO _x	N/A	0.003	3.230	N/A	0.102*	0.771
NO _x	3.050	1.170	15.800	0.153*	0.0158*	0.111*
PM	N/A	0.027	0.720	N/A	0.0274*	N/A

340 *The unit is g E_O / g E_U

341
 342 **2.2.4. The Economic Model**

343
 344 The economic performance of the cases has been compared considering the total operational fuel
 345 expenses (C_{fuel}). The fuel prices have been gathered from ShipandBunker (2024) on 24 January 2024
 346 for Rotterdam port since all fuels are available for bunkering there. Table 7 indicates the gathered fuel
 347 prices used in the economic analysis.
 348

349 **Table 7** Fuel prices (ShipandBunker 2024)

Fuel	Price	Unit
HFO	492.50	\$/t
LNG	613	\$/t

MeOH	302.5	\$/t
------	-------	------

350
351 The projected fuel costs for 2030 and 2050 have been determined according to an economic model
352 described by the study of Helgason et al. (2020). Table 8 indicates the annual fuel price variation ratios
353 regarding low, medium, and high scenarios.

354
355 **Table 8** Yearly fuel price variations (Helgason et al. 2020; Bayraktar et al. 2023; Yuksel 2023; Zou and Yang
356 2023)

Scenario	HFO	LNG	MeOH
Low	+1.80%	-2.04%	+0.08%
Medium	+2.40%	-1.09%	+0.60%
High	+2.90%	+0.57%	+0.70%

357
358 The carbon price has been analyzed using the same scenario-based approach to fuel prices since it has
359 not been strictly determined by maritime administrations (Bayraktar 2023). There are some suggestions
360 for deciding on carbon tax and considering the prices in the literature the low, medium, and high case
361 scenarios have been determined and shown in Table 9.

362
363 **Table 9** Annual carbon tax (EnerData 2023; Francis 2023; Pereda et al. 2023; Bayraktar 2023)

Scenario	2024	2030	2050
Low	56.00	75.00	360.00
Medium	73.00	135.00	250.00
High	100.00	674.00	1285.00

364
365 The cost of carbon has been included in the economic analysis and following MCDM application by
366 employing the carbon tax on the fuel prices that affect the levelized cost of energy (LCOE). The
367 operational and upstream CO₂ equivalents (CO₂ –Eq.) of methane (CH₄) and nitrous oxide (N₂O) have
368 been added to the total CO₂. The cost of sulfur oxides (SO_x), nitrous oxides (NO_x) and particulate matter
369 (PM) has been added the LCOE calculation by utilizing the values depicted in Table 10. Therefore, the
370 cost of other emissions has been included in the MCDM application.

371
372 **Table 10** The environmental and health costs of SO_x, NO_x, and PM (Chang et al. 2017; Kuzu et al. 2021; Canepa
373 et al. 2023)

Emission	Environmental Cost (\$/t)	Health Cost (\$/t)
SO _x	3240	9288
NO _x	9936	10044
PM	15120	56160

374
375 The operational economic performance has been measured by using electricity production costs (C_e)
376 demonstrated in Equation (5) (Shu et al. 2017; Tian et al. 2021). The health/environmental costs of
377 nuclear energy have been calculated at 43.91 \$/MWh (NEA 2020).

$$C_e \left(\frac{\$}{kWh} \right) = \frac{C_{fuel} (\$)}{P_{gen} (kW) \times t_{op} (h)} \quad (5)$$

379
380 The total generated power in kW is denoted as P_{gen} . The C_{fuel} has been computed by multiplying the
381 fuel prices per t and the FC determined by the upper stages. Then the price of an annual carbon tax was
382 calculated by multiplying its price and operational CO₂. The total price taken C_{fuel} and used in the
383 calculations (Bayraktar 2023). The installation of ORC-integrated WHRS has been evaluated by a
384 separate metric called Payback Period (PBP) since it requires an additional investment. Equation (6)
385 indicates the calculation of PBP (Tian et al. 2021).

$$PBP (years) = \frac{C_{ORC} (\$)}{C_{fs} (\$/year)} \quad (6)$$

387

388 PBP has been determined by dividing the installation cost of ORC-integrated WHRS (C_{ORC}) to annual
 389 fuel cost savings (C_{fs}). The C_{ORC} is calculated by using the economic model for the ORC conducted by
 390 Konur et al. (2022) and the Chemical Engineering Plant Cost Index (CEPCI). Equation (7) demonstrates
 391 the computation of the C_{ORC} for 2023 October (the most recent available CEPCI).
 392

$$C_{ORC,2024} = C_{ORC,2022} \times \left(\frac{CEPCI_{2024}}{CEPCI_{2022}} \right) \quad (7)$$

393
 394 The CEPCI value in 2022 is 806.3 (Jenkins 2022; Konur et al. 2022b) and is 790.8 in 2023 October
 395 (Maxwell 2024). To indicate the overall economic performance of each case LCOE has been calculated.
 396 When evaluating the plant-level unit costs of various baseload technologies throughout their operational
 397 lifetimes, the LCOE is the primary instrument of choice (NEA 2020). Equation (8) calculates the LCOE
 398 for each case (Hansen 2019).
 399

$$LCOE \left(\frac{\$}{mWh} \right) = \frac{\sum_{t=1}^n \frac{(C_{plant} + C_{fuel} + C_{o\&m}) (\$)}{(1+r)^t}}{\sum_{t=1}^n \frac{P_{gen} (mW) \times t_{op}(h)}{(1+r)^t}} \quad (8)$$

400
 401 where the installation cost of the DF engine is denoted as C_{plant} calculated at 27,661,146.50 \$ from the
 402 study of Bayraktar et al. (2023) and operation and maintenance costs ($C_{o\&m}$) has taken 1.5% of C_{plant}
 403 (Tian et al. 2021). The discount rate (r) and plant lifetime (t) has assumed at 7% and 25 years respectively
 404 (Shu et al. 2017; NEA 2020). LCOE of a nuclear power plant has been taken at 550 \$/MWh which is
 405 the estimated medium value for a large Artic nuclear power plant by using the ruble dollar exchange
 406 rate on February 13, 2024 (Smolentsev et al. 2018).
 407

408 2.2.5. The Technique for Order of Preference by Similarity to Ideal Solution

409
 410 The sorting of the configurations has been ensured by using The Technique for Order of Preference by
 411 Similarity to Ideal Solution (TOPSIS) which is a commonly used MCDM technique in academic studies.
 412 The method was initiated in 1980, and its main logic depends on positive and negative ideal solutions.
 413 The closest margin to the positive ideal solution (v_j^*) or the farthest extent to the negative ideal solution
 414 (v_j^-) yields the determination of the best rankings. The v_j^* maximizes benefits while minimizing costs
 415 and the v_j^- has the opposite impact. The TOPSIS approach determines the optimal and non-optimal
 416 solutions by computing the distances between the v_j^* and v_j^- . The TOPSIS approach produces easily
 417 comprehensible results and provides optimal solutions using a straightforward methodology (Yuksel
 418 and Koseoglu 2023; Pandey et al. 2023; Li et al. 2024). Creating a decision matrix is the method's initial
 419 step. It is formed by hourly total emissions and C_e values of cases regarding years. Equation (9) indicates
 420 a sample decision matrix and Equation 10 demonstrates its normalization which is the second phase
 421 (Yuksel and Koseoglu 2023; Pandey et al. 2023; Korkmaz et al. 2024; Li et al. 2024).
 422
 423

$$\begin{bmatrix} d_{11} & \dots & d_{1m} \\ \cdot & \cdot & \cdot \\ d_{n1} & \dots & d_{nm} \end{bmatrix} \quad (9)$$

$$r_{ij} = \frac{d_{ij}}{\sqrt{\sum_{k=1}^n d_{kj}^2}} \quad (10)$$

424
 425 The formation of a weighted decision matrix (V) by multiplying the decision matrix and weights is the
 426 third stage of the method. The weights of the columns have been determined according to equal weights
 427 methodology which is one of the objective-weighting techniques. The fourth stage involves deciding v_j^*
 428 and v_j^- ideal values regarding criteria are the beneficial type or not. For a beneficial criterion, the v_j^* is

429 taken as the maximum value while for a cost type is the minimum parameter from the V matrix. The
 430 opposite is valid for the determination of v_j^- . The Euclidean distance from v_j^* and v_j^- denoted as S_i^* and
 431 S_i^- of each value is computed by employing Equations (11) and (12) in the fifth stage. The last stage
 432 determines the relative closeness coefficient (C_i^*) by utilizing Equation (13). The rankings are decided
 433 regarding the C_i^* (Yuksel and Koseoglu 2023; Pandey et al. 2023; Korkmaz et al. 2024; Li et al. 2024).
 434

$$S_i^* = \sqrt{\sum_{j=1}^m (v_{ij} - v_j^*)^2}, i = 1, 2, \dots, n \quad (11)$$

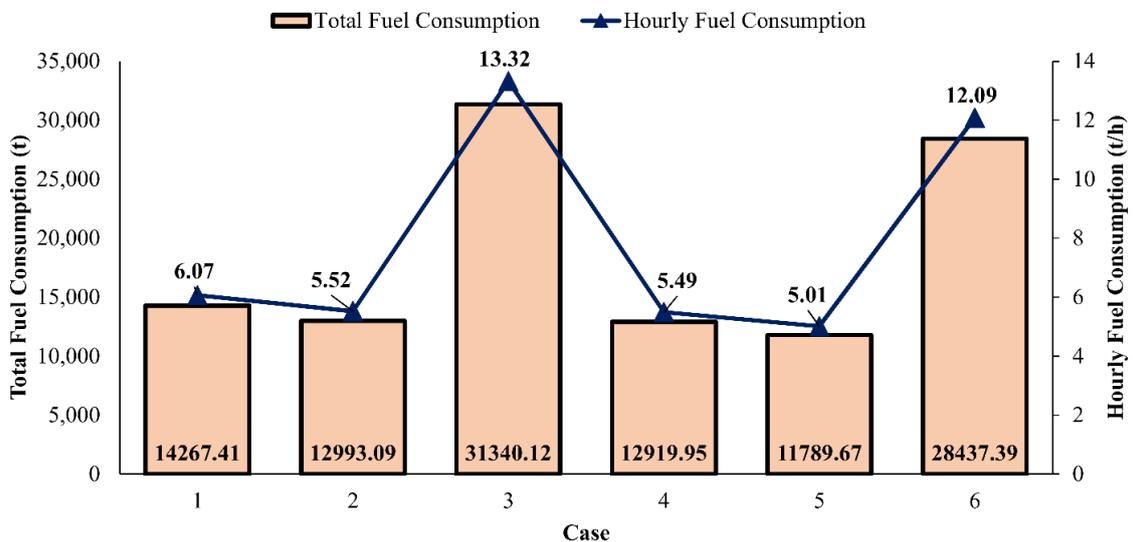
$$S_i^- = \sqrt{\sum_{j=1}^m (v_{ij} - v_j^-)^2}, i = 1, 2, \dots, n \quad (12)$$

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \quad (13)$$

437 The criteria for the analysis have been selected as total (involving both upstream and operational) hourly
 438 CO₂ including equivalent values of N₂O and CH₄, total hourly other emissions (SO_x, NO_x, and PM), and
 439 LCOE.
 440

441 3. RESULTS AND DISCUSSION

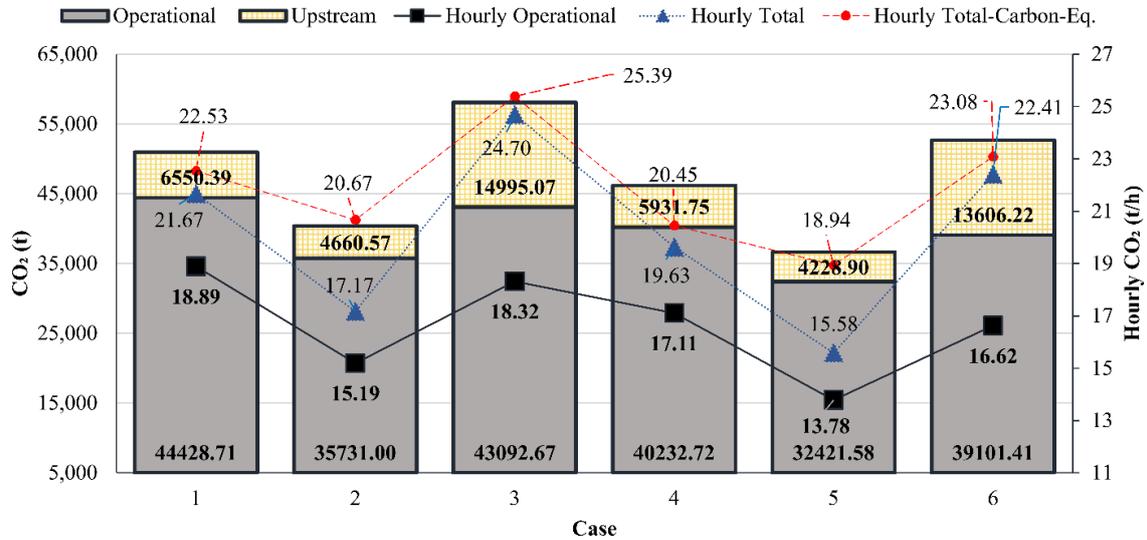
442
 443 The FPP has generated 64,112.1 MWh of electricity during the four months of operation while the
 444 designed ORC integrated WHRS system has supported the system by producing 2,553.07 MWh. Fig. 5
 445 indicates the total (four months) and hourly FC of each case powered by an ICE.
 446
 447



448
 449 **Fig. 5** The fuel consumption of cases

450
 451 The FC reduction between Cases 1 and 4 by utilizing the WHRS has been 1,347.46 t for four months
 452 which equals 0.57 t hourly and 4,042.38 t annual, reduction. The FC of LNG-utilized cases has been
 453 lowered since the LCV of LNG is higher than HFO. The decrease of LNG consumption between cases
 454 2 and 5 by WHRS power supply has been 1203.43 t during the operation leading to a 0.51 t hourly and
 455 a 3610.28 t yearly reduction. The opposite situation about LCV has been valid for MeOH thus the FC
 456 of cases involving MeOH has been found higher. The decrease due to the WHRS utilization has been
 457 calculated at 2902.74 t for four months yielding an annual reduction of 8708.21 t of MeOH which equals

458 1.23 t/h. To observe the environmental impact, the CO₂ emissions have been computed for four months
 459 of operation and illustrated in Fig. (6) for each case.
 460



461
 462 **Fig. 6** The operational and upstream CO₂ emissions of cases
 463

464 The operational CO₂ has been found highest for the cases utilizing HFO while for the LNG-used cases,
 465 it has been calculated lowest. Despite having the lowest C_f , the utilization of MeOH in the DF engine
 466 has not outperformed the LNG in terms of operational CO₂ due to the higher FC of MeOH. The lowest
 467 operational CO₂ has been obtained for Case 5 at 27.03% equals 32,421.58 t for four months. Compared
 468 to the base scenario, LNG utilization as the primary fuel in the power plant has decreased the operational
 469 CO₂ by 8,697.71 t which coincides 32,394.53 t (19.58%) annual reduction. The addition of WHRS has
 470 raised this deduction to 44,720.44 t. The lowering of CO₂ has remained at 1,336.05 t and the WHRS
 471 addition has increased it to 5,237.31 t yielding yearly deductions of 4,976.09 t and 19,841.5 t
 472 respectively. The sole WHRS usage on the base case has led to the decrease of CO₂ by 9.44% resulting
 473 in a 4195.99 t during operation and 15627.94 t annual deduction. The upstream emissions have been
 474 computed as lowest for the LNG utilization and the decrease occurred in the operational emission has
 475 led to even lower for Case 5. In Case 2 the upstream CO₂ emissions have been calculated at 4,660.57 t
 476 and the utilization of WHRS has lowered them to 4,228.9 t. Since the upstream emissions are dependent
 477 on the production of the fuel, reducing the consumed fuel triggers the deduction of the upstream CO₂.
 478 On the other hand, the upstream CO₂ has been a concern for the cases using the MeOH due to higher
 479 operational consumption and upstream coefficients. The high FC and upstream emissions have led to
 480 the highest total CO₂ emissions found at 58,087.74 t in Case 3 even the low C_f of MeOH. The
 481 nonrenewable MeOH utilization on the floating plant has increased the total emissions by 13.94% which
 482 equals 7,108.64 t for four months, and 26,476.05 t yearly. The usage of green MeOH would provide
 483 more desirable emission outcomes. The optimized choice considering the total, operational, and
 484 upstream emissions has been detected as the utilization of LNG in terms of fuel choice. The addition of
 485 WHRS has remarkable potential to reduce the FC and emissions for all fuels. The upstream CO₂ of Case
 486 7 has been found at 3205.61 t and operational emission has been zeroed in this case therefore they have
 487 not been shown in Fig. 6. The remaining operational and upstream GHGs and their CO₂-eq. values have
 488 been illustrated in Fig. 7.
 489

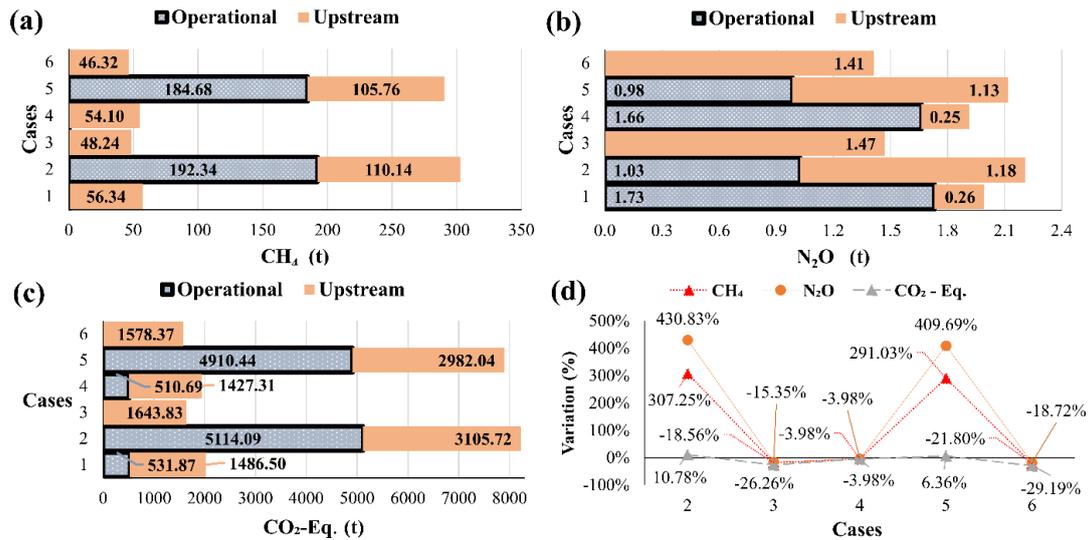


Fig. 7 The secondary operational and upstream GHGs; (a) CH₄, (b) N₂O, (c) CO₂ – eq., (d) variations compared to Case 1

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The LNG utilization on the FPP has resulted in a colossal amount of CH₄ and N₂O emissions during both the operation and production phases. The increase compared to Case 1, which is the current usage scenario of the plant, has been calculated at 430.83% and 307.25% respectively in Case 2. The WHRS has reduced slightly these increments however, the CO₂ reduction by LNG usage shown in Fig. 6 has been impacted negatively due to the increment in other GHGs. The MeOH utilization has ensured the best outcomes in terms of CH₄ and N₂O emissions. The total operational and upstream GHGs have been expressed as hourly total carbon-eq. in Fig. 6. When the comparison has been employed according to this value, the LNG utilization alone has provided an 8.28% reduction, and the addition of WHRS has improved this value up to 15.95%. The WHRS usage in the base scenario expressed as Case 4 has reduced the hourly total carbon-eq. by 9.24% solely. The MeOH utilization on the plant has increased the total CO₂-eq. by 12.71 while the WHRS usage in Case 6 has pulled down the value by 10.28%.

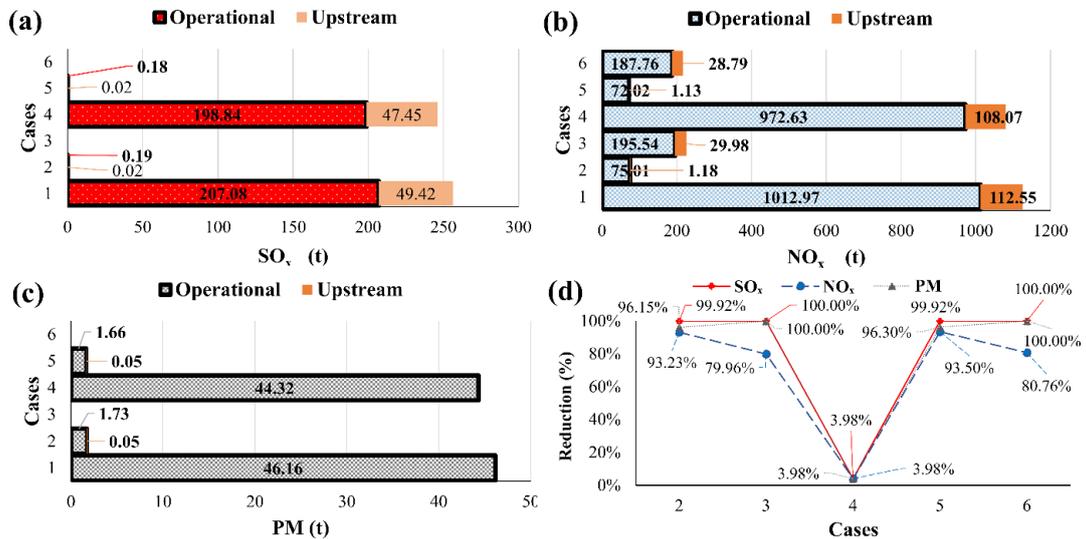


Fig. 8 The other operational and upstream air pollutants: (a) SO_x, (b) NO_x, and (c) PM, (d) reductions compared to Case 1

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The usage of LNG in the plant has decreased SO_x and PM emissions by close to 100% while MeOH has ensured a 100% reduction of these air pollutants. The greatest NO_x drop has been provided by Case 5 and Case 6 has the second highest reduction rate. The sole WHRS usage in the base scenario (Case 4) has reduced the other emissions by 3.98%. The annual fuel costs including the carbon price of cases involving an ICE (Cases 1 to 6) have been illustrated in Fig. 9.

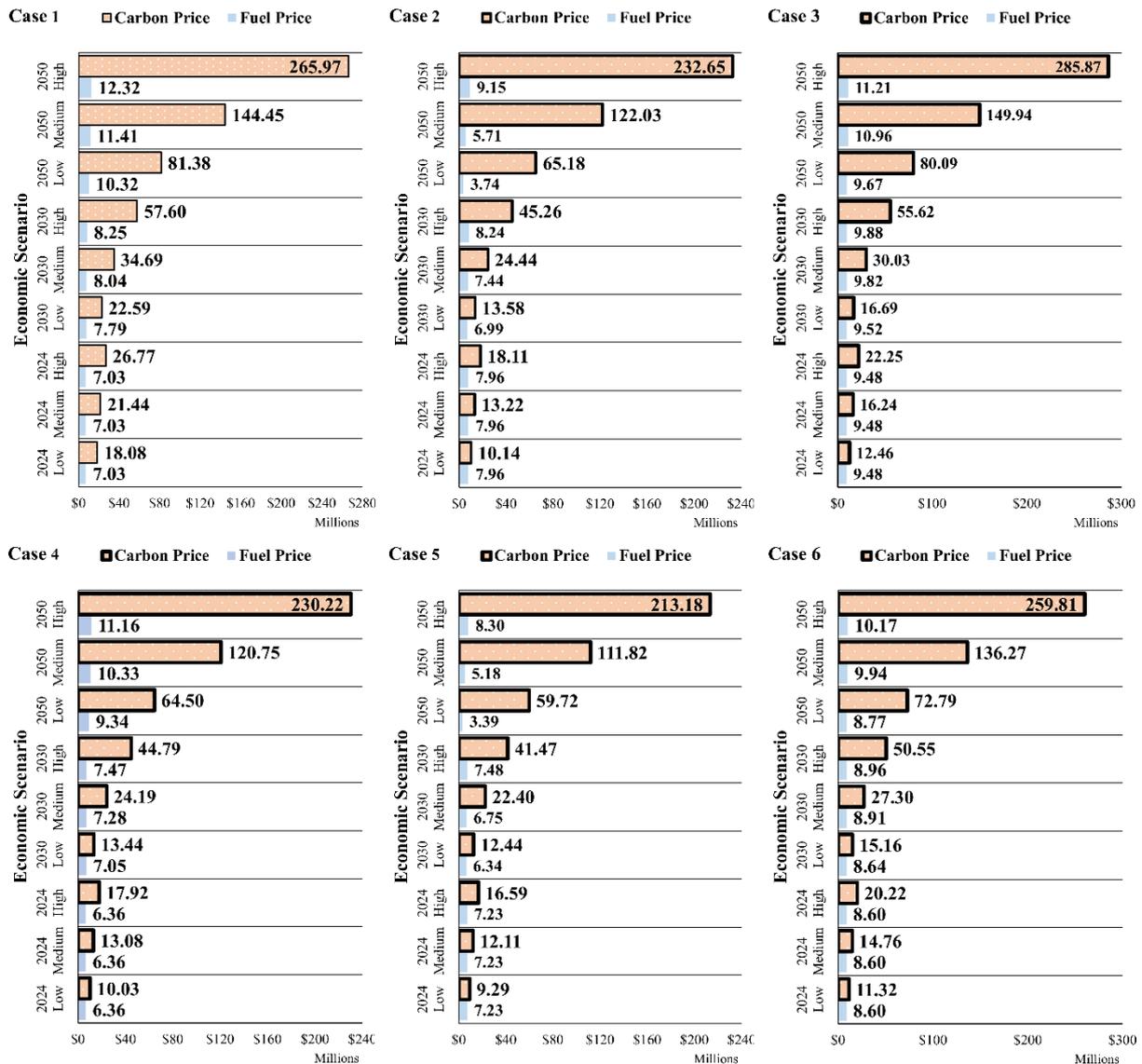
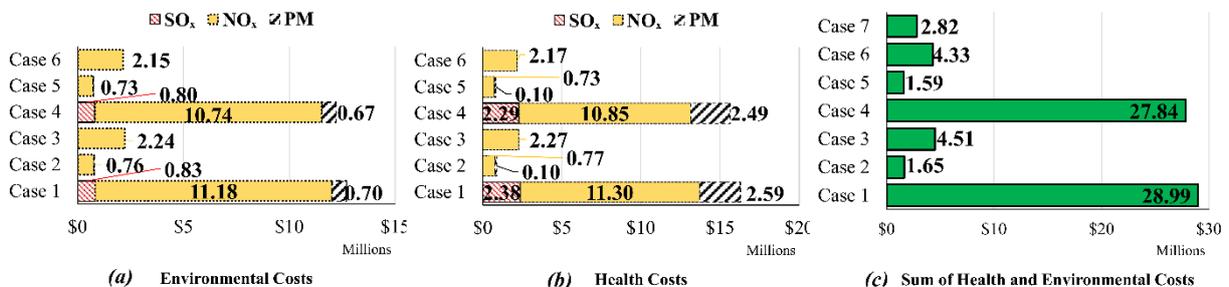


Fig. 9 Annual fuel costs involving the carbon prices of cases

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The annual fuel of the cost HFO-utilized cases has increased dramatically due to the climbed-up price of the fuel and carbon tax. The low scenarios of the LNG used cases have been projected to reduce the yearly fuel expenditure remarkably on the other hand, The annual price of MeOH with carbon cost has been estimated with a steadier trend. The WHRS usage has provided considerable cost-saving for the cases including the utilization of MeOH or HFO due to increased fuel prices in the future estimations. Fig. 10 indicates the health and environmental cost of other emissions according to cases.

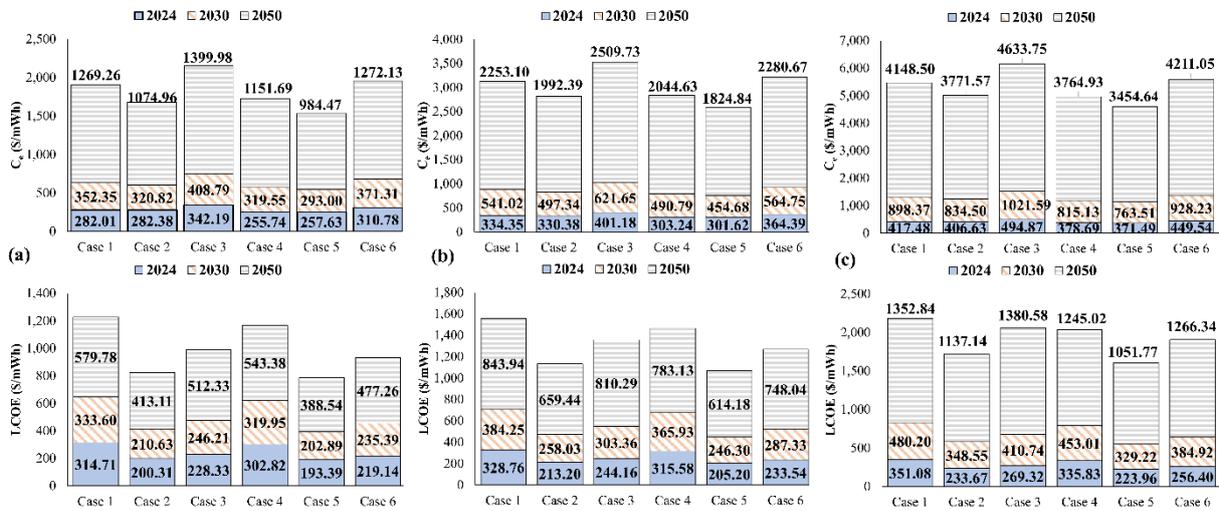


(a) Environmental Costs (b) Health Costs (c) Sum of Health and Environmental Costs
Fig. 10 The (a) environmental, (b) health, and (c) total costs of SO_x, NO_x, and PM emissions.

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The environmental and health costs of other emissions sourced by conventional fuels have been calculated remarkably higher than the alternative fuels since MeOH and LNG have almost eliminated

531 SO_x, NO_x, and PM emissions. The environmental and health-related costs of the nuclear plant have been
 532 computed at around 2.8M \$ which is between LNG and MeOH utilized cases. Fig. 11 demonstrates the
 533 C_e and LCOE of each case which includes the carbon emission-related costs regarding the year and
 534 projection scenario.
 535



536 Fig. 11 C_e and LCOE regarding according to (a) low, (b) medium, and (c) high scenarios.
 537
 538

539 The economic performance of HFO-utilized cases has been projected poorly in both LCOE and C_e while
 540 LNG as a marine fuel has been found a much more suitable option in economic terms. The model has
 541 predicted the economic performance of the cases having LNG as the highest in both terms. The
 542 difference between cases' C_e has higher since the metric only depends on fuel prices. When the
 543 installation costs have been considered along with the discount rate, the cases have performed more
 544 closely. In 2024 and 2030 scenarios the most feasible fuels have been found economically for the FPP
 545 as the LNG and HFO, while MeOH has the highest LCOE and C_e. In 2050, the LNG has the lowest
 546 metrics, and MeOH has come close to HFO. The LCOE of the nuclear power plant has been taken at
 547 550 \$/MWh for floating nuclear plants in the Arctic area for comparative purposes. When the comparison
 548 has been performed using this value, the nuclear power plant has a direct advantage over all
 549 configurations. Fig. 12 depicts the fuel cost savings and PBP of WHRS installation when the plant uses
 550 different fuels considering the fuel price projection scenarios.
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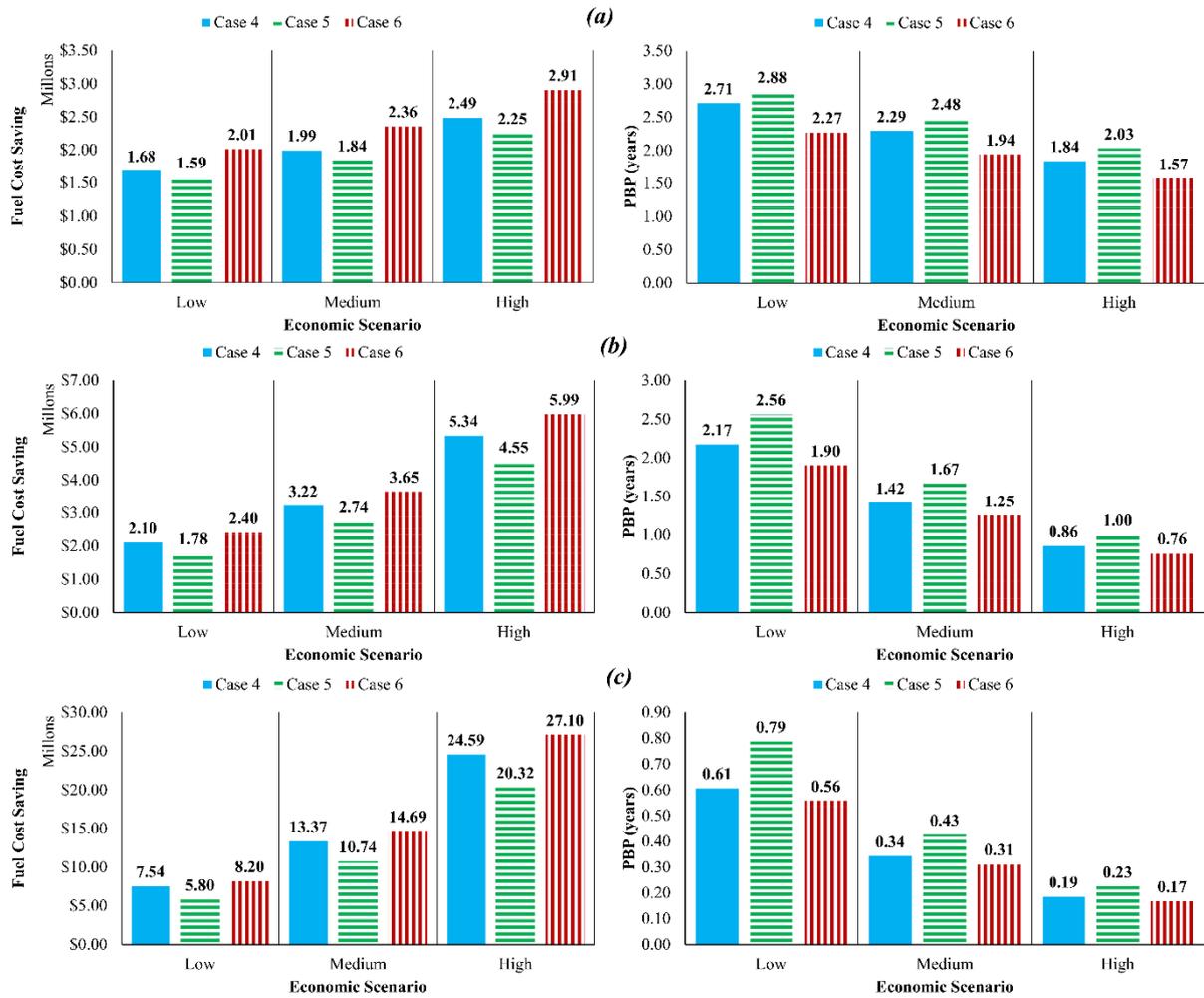


Fig. 12 Fuel cost reductions and PBPs of WHRS installation with the utilization of different fuels in (a) 2024, (b) 2030, and (c) 2050.

Due to the higher carbon taxes, fuel prices have been estimated to increase which has resulted in a great deal of fuel cost savings with a low PBP for all scenarios through the years. In Case 6, this trend can be observed more clearly since the price of HFO has been calculated as the highest among the examined fuels in 2050. Even in 2024, if the application of carbon tax happens in the maritime sector, the WHRS installation will be a feasible option in power plants. Fig. 13 illustrates the ranking of algorithms by utilizing the TOPSIS technique in 2024, 2030, and 2050 considering the economic scenarios.

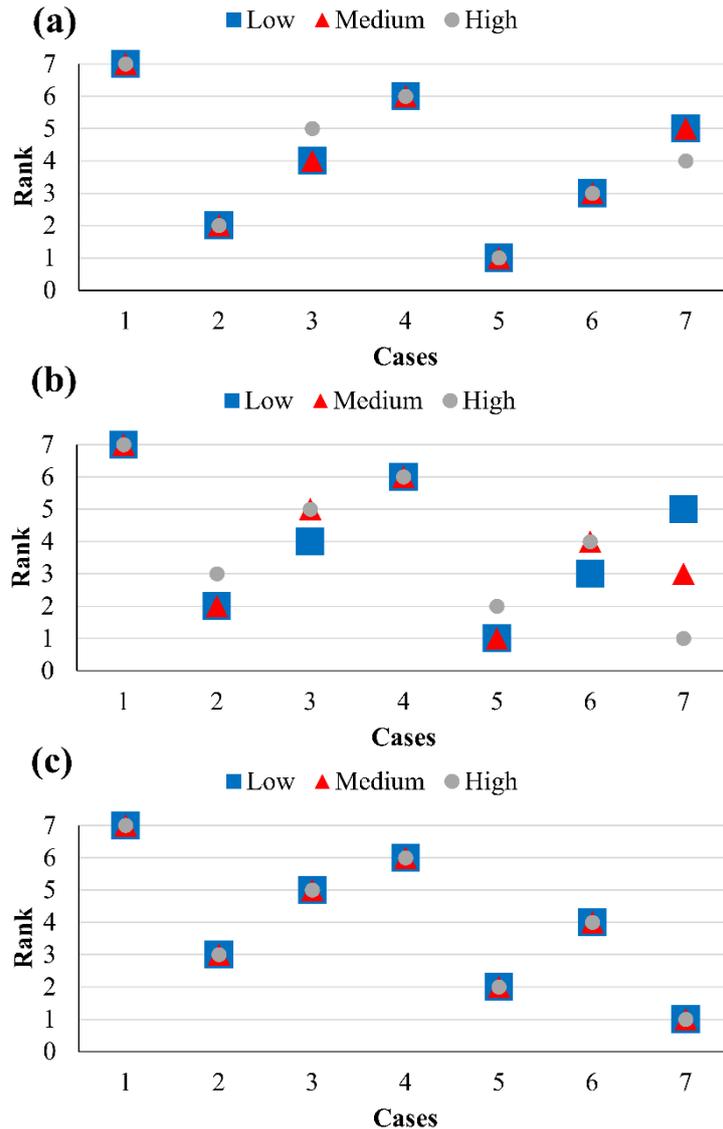


Fig. 13 Rankings of cases according to economic scenarios in (a) 2024, (b) 2030, and (c) 2050.

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The ranking of cases has been ensured by TOPSIS methodology with the criteria of LCOE, total hourly CO₂ including equivalent values from CH₄ and N₂O, and total hourly other emissions. The weights have been distributed equally to consider the importance of environmental impact. The current HFO utilization case has been detected as the worst in all economic scenarios and years. The addition of WHRS to the base scenario (Case 4) has improved it to the sixth place. The usage of MeOH has impacted an improvement to fourth place while the addition of WHRS to this scenario (Case 6) has held the rank at third place in 2024, by 2030 third according to low and high, or fourth place in the medium scenario. In 2050 this case has been found at fourth place in every scenario. In 2024, the first and second spots have been determined as the utilization of LNG – WHRS and LNG alone respectively. The nuclear power plant has been ranked fourth in the high scenario and fifth in the low and medium scenarios. In 2030, the nuclear power plant has climbed up to the third spot in the medium scenario, and the first rank in the high scenario. Case 5 involving the WHRS and LNG utilization on the plant has been first placed in low and medium scenarios in the estimations. By 2050, when the LCOE of the plant can remain stable, the nuclear power plant has been detected as the most feasible option in all scenarios. If the LCOE of the FNPP is selected at a higher threshold like 1,100 \$/kWh (twice of current value) the rank of Case 7 reaches the first spot in 2050 medium and high scenarios. Especially these outcomes become more prominent since the remaining cases cannot meet the decarbonization targets of 2050 set by IMO.

591 Although the FNPP is a suitable option for the examined case theoretically, some serious concerns
592 should be considered when an investment like this is planned (Bayraktar and Yuksel 2023a). The safety
593 issues on board should be considered more carefully due to the harsh operational conditions and the
594 level of safety in nuclear energy technology has been insufficient for maritime operations (Adumene et
595 al. 2022). The most prominent safety hazard can be considered as the storms thus, the FNPP must stand
596 with a certain level of pitch/roll and heave movements. The protection of the reactor must be ensured
597 by multiple hulls while the watertight radiation areas must be provided to protect the plant from floods.
598 The overpressure and overheating of the plant have been well-known additional hazards that affect the
599 safety levels of the plant. Security is also an important issue considering the pirate activities and cyber-
600 attacks on the plant which must be considered during the design and operation (Buongiorno et al., 2017).
601 Due to the possibility of radioactive waste or nuclear leakage, FNPPs have the potential to impact the
602 marine environment and ecology when they are in operation or during transit (Standring et al., 2009;
603 Wang et al., 2023). Even though the plant involves a zero-discharge design which stores all waste on
604 board, during the maintenance or operation accidents resulting in a leakage are a huge concern for the
605 environment (Standring et al., 2009). The perception of the public is a crucial issue in such applications
606 and the approach to nuclear energy is not in a good place in terms of social perspective. The economic
607 performance of the FNPP has been found prominent in the analysis, and when the capacity of the plant
608 is larger it can be more economically viable (Ondir Freire and de Andrade 2019). The installation costs
609 of these require a colossal amount of money and a small mistake can yield economic uncertainties in
610 addition to environmental risks. The operational costs of the FPPs utilizing nuclear energy can be much
611 more than the estimated values which can lead to less efficient economic performance compared to other
612 options (Smolentsev et al. 2018).

613
614 Switching alternative fuels is the most viable option for achieving short-term goals on the other hand,
615 for the long-term goals carbon-free fuels should be considered. In addition, The conversion of these
616 fuel-using plants to fuel-free plants may result from the system installations incorporating these fuels
617 (Yuksel 2023; Jeong and Yun 2023). The LNG has been found as the most feasible option in terms of
618 economic and environmental aspects. The bunkering options for LNG fuel have increased in recent
619 years but depending on the operation area of the plant, the fuel delivery would be problematic (Islam
620 Rony et al. 2023). The biggest concerns about the LNG are a remarkable increment of other GHGs and
621 the failure to meet 2050 decarbonization goals (Islam Rony et al. 2023; Rochussen et al. 2023). Even
622 though having a higher LCV, and more accessible bunkering options, the increased CH₄ and N₂O have
623 been found as more compared to theoretical calculations in practical areas using LNG which shifted the
624 interest of the maritime sector to MeOH (Bayraktar and Yuksel 2023b; Bayraktar et al. 2023). In the
625 analysis, the MeOH conversion has not been detected as a beneficial option environmentally due to the
626 upstream emissions. This problem can be resolved with green production methodologies (Wang et al.
627 2021). The transition to MeOH and LNG can guarantee both regulatory compliance and meeting the
628 short-term emission goals in an economically viable manner because the systems operating on carbon-
629 free fuels produced by green techniques are not yet fully prepared for use on board (Tunagur 2023;
630 Yuksel 2023). Additionally, because the operating and storage principles of the analyzed systems and
631 ammonia or bio-MeOH consumption on DF engines are similar, retrofitting or adaptation of LNG or
632 MeOH DF systems to these fuels may be easy (Duong et al. 2023).

633 634 **4. CONCLUSION**

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636 The study assessed the economic and environmental feasibility of various configurations using different
637 fuels on an FPP. The installation of a WHRS on ICE-utilized systems was evaluated by adding the
638 options as additional case studies. The seven different cases were ranked according to environmental
639 impact covering the upstream/operational emissions and economic performance based on three different
640 fuel-carbon price projections in the current year, and target years determined by IMO. The main findings
641 derived from the study can be listed as follows:

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643 • The utilization of the proposed ORC-WHRS on the FPP was found feasible for all analyzed fuel
644 types.

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- The case that represents the current operational state using HFO was detected as unsuitable in terms of environmental impact.
 - Due to the planned carbon price applications and fuel cost projections, the usage of HFO on the plant was determined disadvantageous economically in future scenarios.
 - The conversion to the MeOH was not found beneficial for the current and future decarbonization targets for the analyzed floating power plant.
 - To achieve short-term emission reduction goals and satisfactory economic performance, LNG was determined as the most suitable option for the plant, even with the increased CH₄ and N₂O emissions.
 - LNG utilization can be thought of as a short-term solution for the plant and can also be available in many bunker points however, it does not comply with the 2050 emission reduction targets.
 - The feasibility of an FNPP is heavily dependent on the LCOE which is assumed at a medium level estimation. Even if the LCOE was taken higher, it was the most suitable option to succeed in the 2050 goals.
 - The safety and waste management of the FNPP will be a critical issue in applying the configuration in a practical field.

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662 Limitations of this study can be listed as follows:

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- The environmental impact has been assessed by utilizing the current emission factors gathered from the literature. In the comparisons involving the future projection scenarios, the conversion factors have been taken constant.
 - The economic metrics depending on the price of WHRS and DF engines have been calculated by using the current prices.

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The paper contributed to the literature by conducting a comprehensive analysis of the current trending alternative marine fuels that can be utilized on the FPP and benchmarking with a nuclear system configuration that can ensure the decarbonization targets of the maritime sector. The study can be beneficial for academics who work on similar subjects, and maritime sector stakeholders interested in the floating power plants. Future studies may involve the operational and environmental risk assessment of FNPP, or the investigation of different fuels and system retrofit options to achieve a greater economic and environmental performance on the plant.

677

678 **Author contributions** All authors contributed to the manuscript writing. Methodology and data analysis was designed and performed by Onur Yüksel. Data collection was performed by Murat Pamık. Literature review and conceptualization were performed by Olgun Konur, Murat Pamık and Murat Bayraktar. Review & editing was carried out by Olgun Konur. All authors read and approved the final manuscript.

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686 **Declarations**

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692 **Consent for publication** Not applicable.

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