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Renewable energy-based electrical microgrid of cold ironing energy supply for berthed ships

Gemiler için sahil elektriği tedarikinde yenilenebilir enerji tabanlı mikro şebeke uygulaması

Türk Denizcilik ve Deniz Bilimleri Dergisi Cilt: 10 Sayı: 1 (2024) 14-26

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ABSTRACT

The importance of ports, which are the gateways between maritime transport and other modes of transport, is growing every day. In addition, the amount of cargo that ports can handle is increasing rapidly every year. At the same time, the need for energy is increasing. Ships hoteling at ports account for a large portion of the power demand at ports. Today, ships hoteling at ports meet their energy needs with their own auxiliary engines running on fossil fuels. In order to achieve decarbonization and zero emissions targets, it is essential to minimize the use of fossil fuels in ports and to increase the use of renewable energy. In this context, meeting the ship's power needs in port through a renewable energy-based microgrid will help reduce emissions. In this study, after determining the energy needs, the scenarios developed with the HOMER program were used to design electrically and economically suitable microgrid systems and to meet the electricity needs of the ships in port using renewable energy.

Keywords: Cold-ironing, HOMER, Port hoteling, Renewable Energy, Ship emission.

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ÖZET

Deniz taşımacılığı ile sanayi ve diğer taşımacılık yöntemlerini birbirine bağlayan bu sebeple de küresel lojistiğin en önemli bileşenlerinden olan limanlara artan ihtiyaçla birlikte liman tesislerinin önemi gün geçtikçe artmaktadır. Bununla birlikte, limanlarda elleçlenen yük miktarı da her yıl hızla artmaktadır. Artan liman kapasiteleri ile yük elleçleme operasyonlarının her aşamasında gerekli olan enerjiye bağımlılık da önemli oranda artmaktadır. Limanlardaki enerji ihtiyacını oluşturan en önemli unsurlardan birisi yük operasyonları amacıyla limanlarda konaklayan gemilerdir. Limanlardaki gemiler günümüzde enerji ihtiyaçlarını fosil yakıtlarla çalışan kendi yardımcı makineleriyle karşılamaktadır. Karbonsuzlaştırma ve sıfır emisyon hedeflerine ulaşabilmek için limanlarda fosil yakıt kullanımının en aza indirilmesi ve buna karşılık yenilenebilir enerji kullanımının artırılması hayati öneme sahiptir. Bu bağlamda, geminin limandaki güç ihtiyacının yenilenebilir enerji tabanlı bir mikro şebeke aracılığıyla karşılanması, emisyonların azaltılmasına yardımcı olacaktır. Bu çalışmada örnek bir liman sahası için enerji ihtiyaçları belirlendikten sonra HOMER programı ile geliştirilen senaryolar kullanılarak elektriksel ve ekonomik olarak uygun mikro şebeke sistemleri tasarlanmış ve limandaki gemilerin elektrik ihtiyaçlarının yenilenebilir enerji kullanılarak karşılanması hedeflenmiştir.

Anahtar sözcükler: Sahil elektriği kullanımı, HOMER, Gemi liman operasyonu, Yenilenebilir Enerji, Gemi emisyonu

1. INTRODUCTION

Ports are essential intermediaries that connect maritime transport with other forms of transportation, serving as pivotal hubs for global trade and economic activity. As the volume of cargo transported by ports continues to grow annually, so does the demand for energy (Buonomano *et al*., 2023; Sifakis and Tsoutsos, 2021). One major factor contributing to the energy demand at ports is the power required by ships during their berthed period, also known as "hoteling" (Canepa *et al*., 2023). Currently, ships meeting their energy needs at ports rely heavily on auxiliary engines powered by fossil fuels (Kumar *et al*., 2019). However, reducing the use of fossil fuels in ports and increasing the utilization of renewable energy sources has become imperative due to the growing emphasis on decarbonization and achieving zero emissions targets (Grzelakowski *et al*., 2022; Höhne *et al*., 2021). The maritime industry is actively engaged in implementing various regulations and measures to reduce greenhouse gas (GHG) emissions and improve the environmental performance of ships (Lu *et al*., 2023). Four key initiatives that play a crucial role in this regard are EEDI (Energy Efficiency Design Index), EEXI (Energy Efficiency Existing Ship Index), SEEMP (Ship Energy Efficiency Management Plan), and CII (Carbon Intensity Indicator) (Bayraktar and Yuksel, 2023). The EEDI is a regulatory measure that sets energy efficiency standards for new ships, aiming to promote the design and construction of more fuel-efficient vessels. It establishes a limit on the amount of CO_2 emissions allowed per ton-mile for different ship types and sizes (Lindstad and Bø, 2018). On the other hand, the EEXI focuses on existing ships and assesses their energy efficiency against the minimum requirements set by the International Maritime Organization (IMO). This index aims to encourage shipowners to adopt energy-saving measures, such as retrofitting, to improve the fuel efficiency of their fleet (Ivanova, 2021). SEEMP is a management plan that outlines specific energy-saving measures for ships to enhance their operational efficiency. Ship operators implement these measures as part of their overall strategy to reduce fuel consumption, improve energy management, and minimize GHG emissions. Lastly, the CII is a performance indicator under development by the IMO. It measures a ship's carbon emissions per transported cargo and determines its efficiency level. The CII will help identify areas for improvement and enable ships to track and reduce their carbon intensity over time (Wang *et al*., 2021).

In this context, the adoption of renewable energy-based microgrid systems to meet the power requirements of ships in port holds significant promise. Such systems offer an opportunity to decrease emissions and contribute to the overall decarbonization efforts. By utilizing renewable energy sources, ports can minimize their reliance on fossil fuels and make substantial progress towards sustainable and environmentally friendly operations (Sadek and Elgohary, 2020).

The research methodology involves determining the energy requirements of ships in port, followed by the development of scenarios using the Hybrid Optimization Model for Electric Renewable (HOMER) software. Through simulations and optimization, the study aims to identify the most suitable microgrid configurations that align with the specific electrical and economic requirements. Cold ironing, also known as shore power or alternative maritime power (AMP), refers to the practice of supplying electrical power to ships at port from onshore sources (Seyhan *et al*., 2022). The proposed microgrid system harnesses renewable energy sources such as solar, wind, and tidal power, along with energy storage systems, to provide a reliable and environmentally friendly alternative to conventional hotelling practices.

This study aims to address the energy needs of ships in port by designing electrically and economically suitable microgrid systems, powered by renewable energy sources. To achieve this, the HOMER program, a comprehensive software tool for renewable energy system analysis, is employed. These configurations would allow for the effective utilization of renewable energy sources to meet the power demands of ships in port.

2. LITERATURE REVIEW

The need to lower pollution emissions and meet the growing energy demand in port regions have prompted the development of renewable energy-based polygeneration systems, which can produce numerous energy types from sustainable sources (Elnajjar *et al*., 2021). A considerable amount of research has been done on the design, development, and operation of renewable energy-based systems and energy efficiency in port environments (Alamoush *et al*., 2020; Iris and Lam, 2019). Decarbonization of the maritime sector is heavily influenced by the interaction between ships and ports (Halim *et al*., 2018). Important services and infrastructure that facilitate the use of technology on ships can be provided in ports (Acciaro *et al*., 2020; Yau *et al*., 2020).

The ship-port interaction of the future will contribute to the decrease of other pollutants and greenhouse gas emissions from maritime activities (Hoang *et al*., 2022). Although the use of cold ironing in ports reduces emissions from auxiliary engines with help of grid electricity, it does not reduce emissions in all countries (Stolz *et al*., 2021) and is far from achieving the net-zero emissions target (Sifakis and Tsoutsos, 2021). Therefore, it is essential to use renewable energy technologies in ports to achieve the targets (Parhamfar *et al*., 2023; Sadiq *et al*., 2021).

When it comes to the environmental impact of berthing ships, ports may profit greatly from the combination of various renewable energy sources (Yigit and Acarkan, 2018). Studies involving renewable energy technologies have been carried out in many ports (Agostinelli *et al*., 2022; Philipp *et al*., 2021). In these studies, there are also examples benefiting from the HOMER program (Sifakis *et al*., 2022; Vichos *et al*., 2022). However, fully supplying cold ironing with renewable energy to meet its high electricity demand is a huge problem that requires further research (Bakar *et al*., 2023).

3. DATA COLLECTION

The Filyos Port, one of the largest ports in Turkey, is a national investment project located in the Filyos Investment Basin, which Turkey is emphasizing (URL-1, 2023). With the project, it is planned to create new transport corridors, reduce the traffic load of the Istanbul and Çanakkale Straits, increase qualified production, and develop national and international transport and trade. For this purpose, this port has been selected as a sample port since it is designed in accordance with today's technology. Since the port is at the design stage, it is possible to adapt it with cold ironing technology and to utilize renewable energy sources. The location of the port is shown in Figure 1.

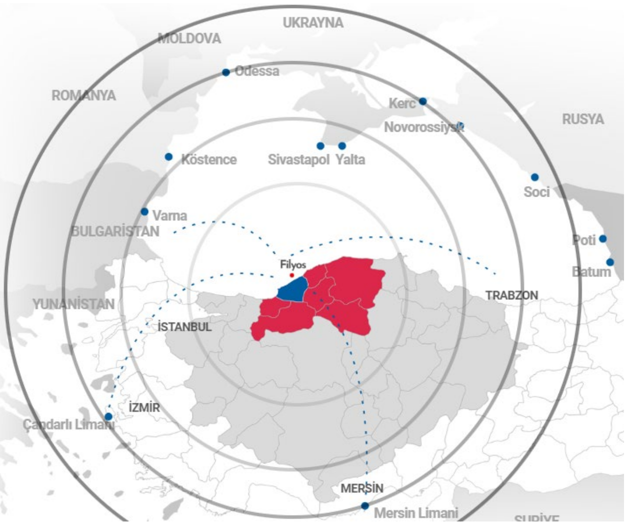

Figure 1. Filyos Port location

In order to produce the energy to meet the demands of the ships, the size of the ships that will stay at the port and the electricity demands of these ships are required. Ship types and sizes included in the port project and the electricity requirements of these sizes are given in the Table 1 (Faber *et al*., 2020; URL-1, 2023).

Table 1. Ship types, quantity and electric demand of port

Ship's Type	Number of Berth by Ship Type	kWh
Container	3	1100
Bulk Carrier	4	110
Ore (Bulk)	4	150
Liquid Cargo	2	800

While planning the energy requirement in this study, the scenario in which all ships are in service at the same time is taken into consideration. The decrease in the use of fossil fuels over the years and the increase in maritime trade require the amount of renewable energy to meet the energy demand. Therefore, it is taken into consideration that the port serves ships by 100% capacity. A bird's eye view of the port and the random berthing patterns of the ships are shown in Figure 2. The hourly distribution of the daily electricity demand of all ships in the port is shown in Figure 3. After the determination of the electrical load, the wind and solar energy potential of the port area gains importance. In this context, wind and solar energy potential is as shown in Figure 4 and Figure 5 respectively.

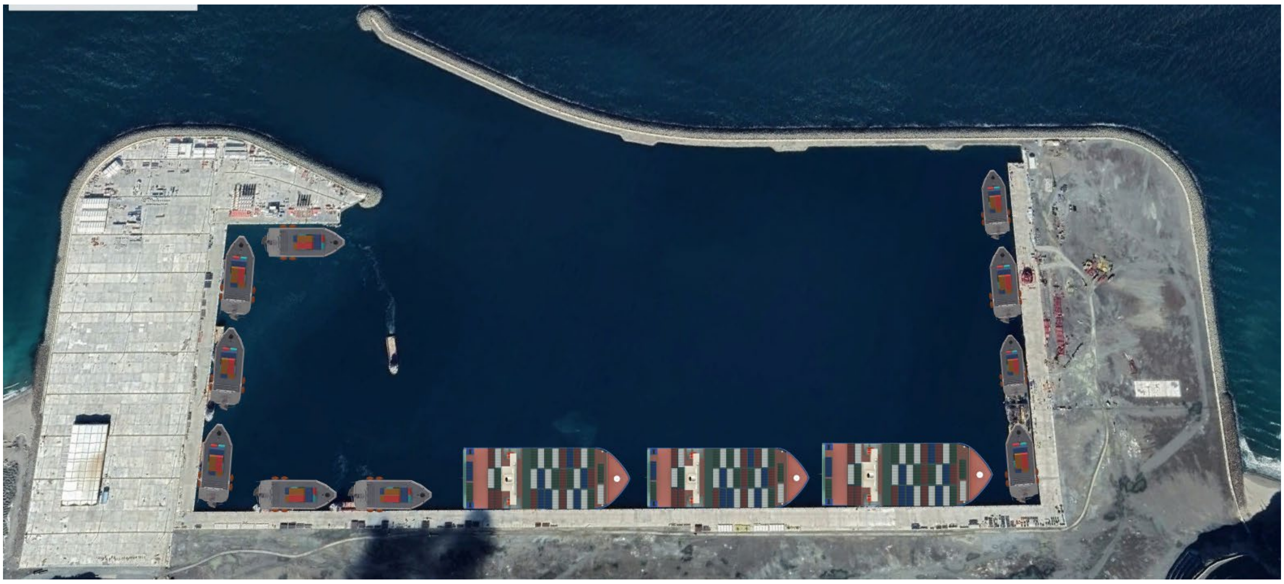

Figure 2. Port with planned ships

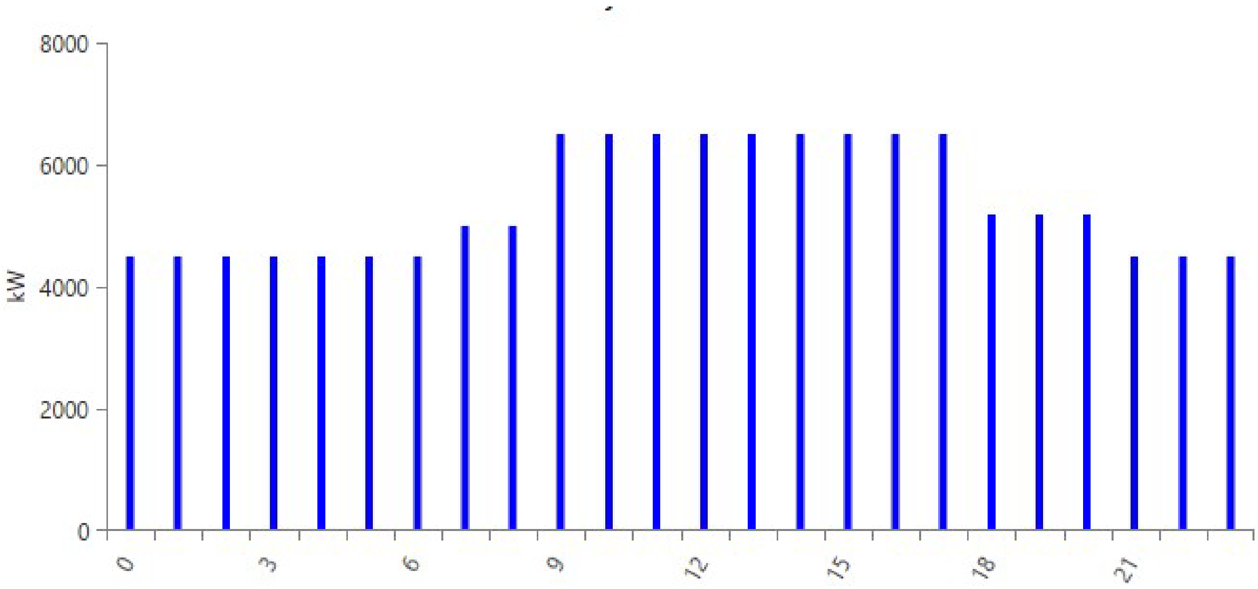

Figure 3. Daily electricity demand of all ships in the port

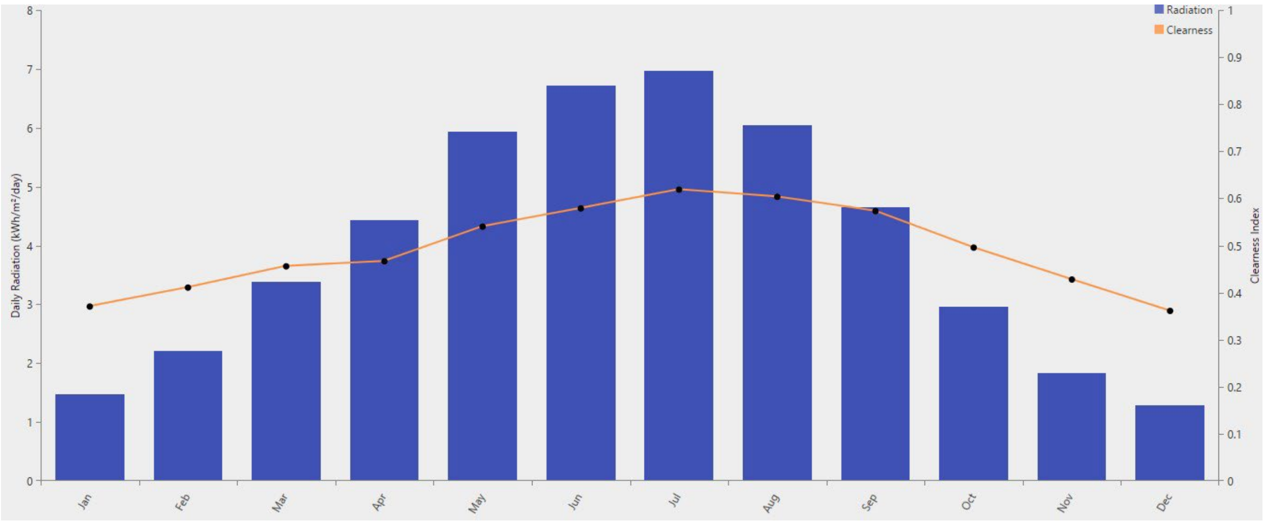

Figure 4. Solar resource of the year in the port

Figure 5. Wind resource of the year in the port

For the optimisation of the system, the costs of the components to be used are also included in the HOMER program. In this context, the cost inputs of the system are shown in Table 2.

Table 2. Costs of component

Component	Costs ($/kW)		
	Capital	Replacement	Operation and Maintenance
Wind	1515	1515	20
PV	830	0	8
Battery	220	200	2
Convertor	325	300	7

4. METHODOLOGY

The HOMER program, a widely used software tool for renewable energy system analysis, was utilized to model and simulate the renewable energy-based electrical microgrid (Baral *et al.*, 2022; Montuori *et al.*, 2014; Restrepo *et al.*, 2018; Shahinzadeh *et al.*, 2016). The program employs optimization algorithms to identify the optimal configuration and operation strategy for the microgrid based on user-defined inputs and constraints (Akarsu and Genç, 2022).

There are studies where the programme offers solutions to a wide variety of electrical needs. The programme can be used for micro-grid installation in areas far from the grid electricity (Amole *et al.*, 2023; Uwineza *et al.*, 2021; Vendoti *et al.*, 2021). In addition, the programme is also used in electrical infrastructure works in the health sector where power outages can have fatal consequences (Aisa *et al.*, 2022; Jahangir *et al.*, 2021). The programme also offers microgrid solutions to facilities that want to produce clean energy with renewable energy solutions (Çetinbaş *et al.*, 2019; Mehta and Basak, 2020). There are also studies in which the most suitable one for the region or facility is selected among the scenarios with multi-criteria decision-making methods (Jahangiri *et al.*, 2020; Odoi-Yorke *et al.*, 2022; Ullah *et al.*, 2021). In addition to all these studies, there are studies where the programme is used in ports as in our study (Bakar *et al.*, 2022; Buonomano *et al.*, 2023; Elnajjar *et al.*, 2021).

This section describes the methodology employed in the study on the renewable energy-based electrical microgrid of cold ironing energy supply for berthed ships. The primary objective of the study was to assess the feasibility and performance of such a microgrid system, with a specific focus on utilizing the HOMER program for system design and analysis.

HOMER calculates and compares different financial metrics, such as the levelized cost of energy (LCOE) and net present value (NPV), enabling users to evaluate the economic viability of the microgrid system. This comprehensive and user-friendly program empowers researchers, engineers, and policymakers to make informed decisions in achieving sustainable and renewable energy solutions for various applications, including meeting the electricity needs of ships in ports.

The working principle of the HOMER program is as shown in Figure 6.

Figure 6. HOMER framework

In the study, it is planned to meet the electricity demand with 3 different scenarios. These scenarios are as shown in Figures 7, 8 and 9 respectively.

While determining the scenarios, LCOE values, initial investment costs, renewable penetrations included in the systems were taken into consideration.

A. System Energy Production and Storage

When designing power generation from renewable energy sources in system design, the nature of available renewable resources affects the behaviour and economics of renewable energy systems, as it determines the amount of renewable energy generation.

Solar resource data show the amount of Global Solar Radiation (GCR) (the sum of beam radiation-beam radiation directly from the sun and diffuse radiation-diffuse radiation from all parts of the sky) that hits the Earth's surface in a typical year (Shilpa and Sridevi, 2019).

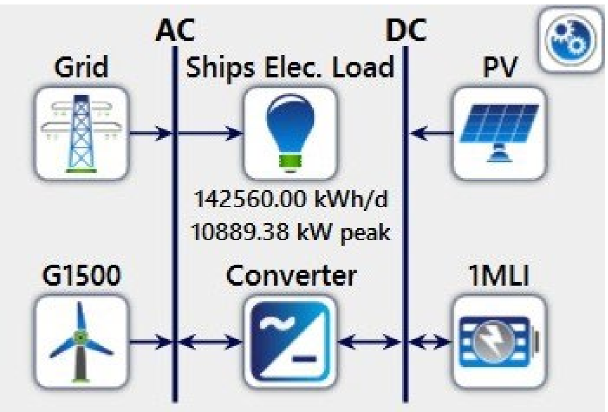

Figure 7. *Scenario 1* includes **wind turbine / photovoltaic (PV) / battery / converter / grid** systems.

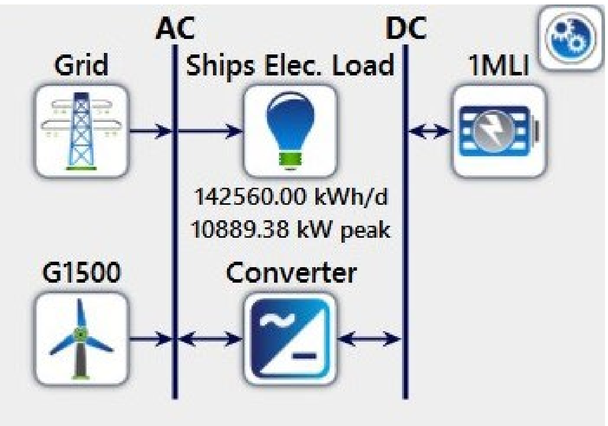

Figure 8. *Scenario 2* includes **wind turbine / battery / converter / grid** systems.

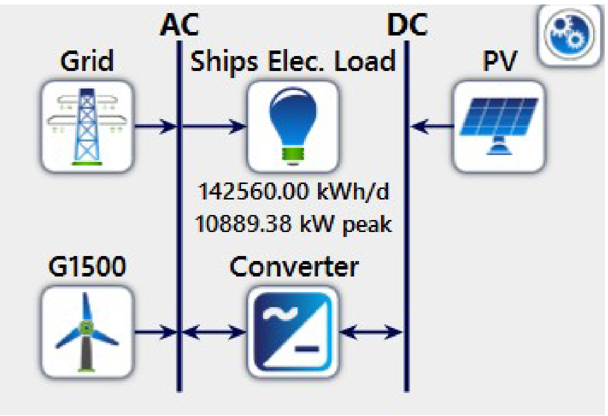

Figure 9. *Scenario 3* includes **wind turbine / PV / converter / grid** systems.

The data can take one of three forms: hourly average global solar radiation on the horizontal surface (kW/m^2), monthly average global solar radiation on the horizontal surface (kWh/m^2 day) or monthly average clearness index (Riayatsyah *et al.*, 2022). The clearness index is the ratio of solar radiation hitting the Earth's surface to solar radiation hitting the top of the atmosphere. The clearness index is a measure of the openness of the atmosphere and is a number between zero (0) and one (1) (Islam *et al.*, 2021). Wind resource to model a system with one or more wind turbines, the program user must provide wind resource data showing the wind speeds that will drive the turbines in a typical year. Whenever possible, wind resource data should be hourly. Otherwise, HOMER can generate synthetic hourly data from 12-month average wind speeds and four additional statistical parameters, such as the Weibull shape factor, the autocorrelation factor, the diurnal pattern strength and the hour of peak wind speed (Nasab and Kilby, 2022).

The program calculates the power output of the wind turbine for each hour in a four-step process. In the first step, it calculates the average wind speed for that hour based on wind speed source data and anemometer height. In the second step, it determines the wind speed corresponding to the centre of the turbine using the logarithmic law or power law. In the third step, it uses the power curve of the turbine to calculate the power output at the wind speed with reference to the standard air density. In the fourth step, this power output value is multiplied by the air density ratio to obtain the ratio of the actual air density to the standard air density. The program multiplies this power output value by the air density ratio, which is the ratio of actual air density to standard air density (Ahamed *et al.*, 2021).

B. System Economic Background

Economic data is essential for the program to deliver accurate results. In this context, LCOE, one of the program outputs, is calculated with the formula below (Mostafa *et al.*, 2020).

$$LCOE = \frac{C_{ann,tot}}{E_{base} + E_{\sec} + E_{grid,sale}} \tag{1}$$

- EM, Levelised cost of energy
- $C_{ann.,tot}$, total cost (annual)
- E_{base} and $E_{sec.}$, base and secondary loads
- $E_{grid,sale}$, yearly sales to grid

The net present cost (NPC) of each proposed power system is calculated by the computer, which then ranks the systems by NPC in descending order. The NPC is the present value of all the expenses incurred over the life of the system, minus the income and the current value of the system. It is an important measure as it indicates whether or not the overall investment has been successful. The formula below gives the NPC.

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{2}$$

- C_{NPC}, Net Present Cost
- $C_{ann,top}$, total cost (annual)
- CRF, capital recovery factor
- i, real discount rate,
- R_{proj} project lifetime.

Scenario lifetime is determined by the lifetime of the component with the longest lifetime. For this reason, the scenario lifetime is 25 years, which is the lifetime of PVs. Component's capacity, number of components, capital cost, operating and replacement costs, salvage costs used in the scenarios are presented in tables. In addition, the renewable penetration of the scenarios and the cost per kW of electricity generation are also among the results.

5. RESULTS

Scenario lifetime is determined by the lifetime of the component with the longest lifetime. For this reason, the scenario lifetime is 25 years, which is the lifetime of PVs. Component's capacity, number of components, capital cost, operating and replacement costs, salvage costs used in the scenarios are presented in tables. In addition, the renewable penetration of the scenarios and the cost per kW of electricity generation are also among the results.

The costs of the scenario 1, 2 and 3 are given in Table 3, 4 and 5 respectively, where Table 6 shows economic and renewability penetration comparisons of the all scenarios.

Table 3. Costs of *Scenario 1*

Scenario 1	Size	Capital	Operating	Replacement	Salvage	**Total**
Wind	8 x 1.5 MW	$727,200	$240,000	$727,200	-$545,400	**$1.15M**
Battery	1MWh 78 pcs	$686,400	$156,000	$624,000	-$206,272	**$1.26M**
PV	23274 kW	$772,704	$186,194	$0.00	$0.00	**$958,898**
Grid	-	$0.00	$1.33M	$0.00	$0.00	**$1.33M**
Convertor	6401 kW	$83,215	$44,808	$76,814	-$25,605	**$179,233**
System		**$2.27M**	**$1.95M**	**$1.43M**	**-$777,277**	**$4.87M**

Table 4. Costs of *Scenario 2*

Scenario 2	Size	Capital	Operating	Replacement	Salvage	**Total**
Wind	12 x 1.5 MW	$1.09M	$360,000	$1.09M	-$818,100	**$1.72M**
Battery	1MWh 15 pcs	$132,000	$30,000	$120,000	-$40,000	**$242,000**
Grid	-	$0.00	$3.76M	$0.00	$0.00	**$3.76M**
Convertor	2862 kW	$37,200	$20,031	$34,339	-$11,446	**$80,124**
System		**$1.26M**	**$4.17M**	**$1.25M**	**-$869,546**	**$5.80M**

Table 5. Costs of *Scenario 3*

Scenario 3	Size	Capital	Operating	Replacement	Salvage	**Total**
Wind	8 x 1.5 MW	$727,200	$240,000	$727,200	-$545,400	**$1.15M**
PV	11885 kW	$394,588	$95,081	$0.00	$0.00	**$489,669**
Converter	5625 kW	$73,122	$39,373	$67,497	-$22,499	**$157,494**
Grid	-	$0.00	$3.68M	$0.00	$0.00	**$3.68M**
System		**$1.19M**	**$4.06M**	**$794,697**	**-$567,899**	**$5.48M**

Table 6. Economics and renewable fraction of Scenarios

Scenarios	CAPEX	OPEX	NPC	LCOE	Renewable Fraction
1 (W/B/C/G/PV)	$56.7M	$2.60M	$122M	$0.0855	%84
2 (W/B/G)	$31.5M	$4.54M	$145M	$0.0946	%57.7
3 (W/PV/G)	$29.9M	$4.28M	$137M	$0.0883	%59.1

Scenario 1, which has the highest initial investment cost with the highest number of components, has the highest percentage of renewability. Scenario 2 and Scenario 3 are scenarios with close renewability fractions and initial costs. In addition, LCOE values are close to each other.

6. DISCUSSION

In this study, it is aimed to meet the energy demand of ships while they are at the dock with cold ironing technology. In addition, as mentioned in the literature, it is also emphasised that electricity generation can be met by scenarios involving renewable resources and the national grid (Tawfik *et al.*, 2023; Vakili and Ölçer, 2023). Filyos port, which is newly built, and its hinterland is open to innovation, has been chosen as the location, and it is foreseen that it can provide a place for renewable energies while reaching the port capacity.

When we analyse the scenarios economically, although the CAPEX values of *Scenario 2* and

Scenario 3 seem favourable, the OPEX values ensure that the LCOE values are close to each other in the long term in all scenarios. This situation requires decision makers to decide whether to make investments in the first place or to spread them over the long term. In addition, offering electricity service to ships for a charge will further reduce the cost of electricity generated.

Ports will be more motivated in this regard if they receive support from the government for this investment. In addition, the increase in the number of ships with shore power system will positively affect such investments.

As can be seen in Table 6, *Scenario 1* is superior to the other scenarios in terms of renewable fraction. The reason is that it includes both solar and wind energy and at the same time battery to use the generated energy more efficiently. Scenarios with higher renewability rates can be created, but this will both increase the cost and create problems in high energy needs (Bakar *et al*., 2023).

7. CONCLUSION

In conclusion, ports play a very important role in the global transport network but also contribute significantly to greenhouse gas emissions. To address this issue, the study presents suitable scenarios for renewable energy based microgrid systems in ports. While determining the scenarios, our study aims to accurately determine the energy needs of ships in ports. With the HOMER program, microgrid systems are designed to meet energy needs efficiently and economically.

However, this paper is not without limitations. The limitations of the study include the policy of selling electricity to the ship, not including the installation fee of shore power to the port in the system, and not including the areas where renewable energy systems will be installed in the port in the scenarios.

Scenario 1 is the most suitable scenario both economically and in terms of renewable fraction. As the rate of renewable fraction increases, emissions in the port area will also decrease. This will also contribute positively to the maritime industry, which needs emission reductions. The disadvantage of *Scenario 1* compared to other scenarios is the high initial investment cost.

Scenario 2 and *Scenario 3* have lower initial investment costs since they have fewer components. However, renewable fractions are also low compared to Scenario 1. Another disadvantage is the high operational costs as it is supplied more from the national grid.

The maritime industry adopts emission reduction as a priority strategy. In order to implement this strategy, ships are subjected to emission measures in a continuously tightening manner. Investments in ports are valuable to achieve the zero-emission target.

Future studies will include increasing the number of scenarios, ports selling electricity to ships or offering discounts in port fees so that ships using shore power in the competitive market will prefer such ports.

AUTHORSHIP CONTRIBUTION STATEMENT

Yunus Emre ŞENOL: Conceptualization, Writing - Original Draft, Writing-Review and Editing, Data Curation, Visualization.

Alper SEYHAN: Methodology, Validation, Formal Analysis, Resources, Software.

CONFLICT OF INTERESTS

The author declares that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

Author declares that this study was conducted in accordance with Ethics Committee of Social Sciences, Science and Engineering Sciences Research.

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