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Advancing Sustainable Marine Transportation: Operational Feasibility of Offshore Floating Charging Stations

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ABSTRACT

The feasibility analysis of offshore floating charging stations (FCS) incorporating renewable energy sources (RES) in India and around the world presents a promising and pioneering solution to meet the emerging demands of maritime transport systems for sustainable development. The global shift towards sustainable transportation supports the increasing adoption of electric vessels (E-vessel), which forces the inclusion of innovative solutions for their reliable operation. This study includes a feasibility analysis of FCS combined with an energy management system for reliable operation. A real-time analysis was conducted at an offshore location in the Arabian Sea, near Gujrat, India, to assess the operational and implementation possibilities of FCSs in India, especially in the Exclusive Economic Zone (EEZ). An appropriate energy management system in the FCS tackles E-vessel demand changes, real-time variations in RES, and energy flow balance with reduced reliance on backup energy systems. The findings demonstrated a reduction of 88% in the backup energy requirement for the FCS, and the energy management system ensured that the FCS had an immense improvement in excess RES support to meet additional E-vessel demands. This paper also included a comparative analysis between an offshore location in India and one in Europe. This study highlights the potential of FCS to improve the adoption of E-vessels in India's and global marine transportation.

Keywords

Electric vessels;
Energy management systems;
Maritime transport;
Offshore floating charging stations;
Renewable energy integration;
Sustainability.

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1. Introduction

Recently, there have been significant developments in electric vehicle technologies and clean energy solutions substantiate the progress of sustainable developments in the transportation sector. In a similar way, marine transportation sustainability is also gaining so much importance, especially considering the Sustainable Development Goals (SDGs) [1]. The sustained progression of electrification in transportation necessitates the development of charging technology. Charging stations for electric vessels (E-vessels) are an essential part of marine electric transportation.

Recent reports about charging facilities for electric vessels set up at ports and shoreside by various maritime companies uphold the development possibilities of E-vessel deployment on a large scale [2, 3]. The innovative solution of offshore floating charging stations (FCS) on sea routes can effectively handle the recharging needs of E-vessels during sea voyages, surpassing the limitations of portside charging facilities. Through the utilisation of renewable energy sources (RES), especially wind, solar, and ocean energy systems, the offshore FCS can assist in the sustainable recharging of e-vessels. The FCS can tackle the main challenges offered by the onshore charging infrastructure with the implementation of quick charging technologies [2, 4].

The FCS system can effectively reduce greenhouse gas emissions by utilizing RES with minimum reliance on fossil fuel-based energy generation, thus reducing environmental impact and climate variations [5]. FCS can support the onshore port charging facilities by minimizing vessel interruptions, congestion, and the system's effective operation [4]. Thus, FCS can support the widespread

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Abbreviations

FCS	Floating Charging Stations;
RES	Renewable Energy Sources;
E-vessel	Electric Vessels;
EEZ	Exclusive Economic Zone;
SDGs	Sustainable Development Goals;
EMS	Energy Management System;
EM	Energy Management;
NREL	National Renewable Energy Laboratory;
NIWE	National Institute of Wind Energy;
ESS	Energy Storage System;
IEA	International Energy Agency;
BES	Backup Energy Source;
F-NPPs	Floating nuclear power plants;
OTEC	Ocean Thermal Energy Conversion;
MNRE	Ministry of New and Renewable Energy;
IRENA	International Renewable Energy Agency;
FOWIND	Facilitating Offshore Wind in India;
GWEC	Global Wind Energy Council;
AIS	Automatic Identification System.

deployment of E-vessels globally, supporting sustainable developments in the marine sector considering the growing demand [6]. The FCS can also provide new job openings, which can, in effect, support economic growth and development [2]. The FCS system's operation and management can be effectively enhanced by using AI predictive analytics, remote monitoring, operational management strategies, and automated systems [7, 8]. As marine transportation drives towards cleaner and greener transformations, offshore FCS offers innovative and sustainable development solutions for the marine industry [9].

The scope of the study comprises assessing the operational feasibility of FCS, including site-specific seasonal variations, at an offshore site near Gujarat, India. It focuses on the operation and real-time energy management for FCS deployment in the specific geographic site. The operational feasibility of FCS using real-time data, considering seasonal variations, is analysed in the work. Location-specific studies are necessary for FCS deployment. This work incorporates an innovative exercise in appropriate real-time energy management, taking into account the practical operational and implementation feasibility for a geographic location in India. The FCS operation at the Indian offshore location near Gujrat, with proper energy flow balance, shows effective management and surveillance of the system with real-time data. This work's novelty pertains to the investigation of implementation and operational feasibility with a real-time energy management scheme to serve FCS at an offshore site in the Arabian Sea near Gujarat, India.

Methodology of the work: An analysis of the operational viability of the FCS system in an Indian scenario is considered in this work. The offshore location selected for the analysis was in the Arabian Sea, near Gujarat, India. An energy management system (EMS) with an energy management (EM) scheme in real-time was integrated into the FCS system, including real-world data on renewable energy sources at the selected offshore location. The data procured from the National Renewable Energy Laboratory (NREL) & Solcast database and the National Institute of Wind Energy (NIWE) & Brighthub database was used for analysing the practical operation of FCS [10-13]. This study is an extension of the previous work on FCS feasibility analysis at an offshore site in the North Sea, Europe [6]. The EM scheme proposed in [6] was used in this work as well, and a comparative study on the two offshore locations is also included in this paper. The targets entitled to the EM scheme for the FCS include balance of energy flow throughout the functioning of the FCS, consistent recharging of the energy storage system (ESS) of the FCS, maximized usage of RES to fulfil the E-vessel demands, and recharging of ESS and initiating backup energy source (BES) support when required.

The outline of the paper is structured in following order: Section 2 includes a literature study and a discussion of charging station possibilities in India and globally. Section 3 covers the possibilities of FCS implementation in the Indian scenario, the renewable energy availability in India, and vessel density in the selected offshore location. Section 4 covers the evaluation of the EM scheme to support the FCS at the offshore site in India, and a detailed result analysis and discussion of the operational feasibility are considered. A comparison of FCS operations in the Arabian Sea, India, and the North Sea, Europe, is also included. Section 5 covers the conclusion and future scope of the study.

2. Literature Review

The section outlines the review of marine electric transportation developments, offshore renewable energy production and development and implementation possibilities of charging facilities in India and globally. The global trend toward electrification of marine transportation can be supported by the novel solution of offshore FCS [5]. The implementation of FCS in offshore areas can significantly deal with E-vessel's travel range concerns and onboard battery capacity, as reported in [5, 6]. Considering the vast coastline in India, by tapping renewable energy, the implementation and operation of FCS can facilitate more greener, cleaner, and sustainable marine transportation, similar to an electric vehicle charging station [14]. For FCS to work, it needs reliable offshore platforms, RES, hybrid energy storage devices, reliable power converters, the right charge controllers that manage energy well, and a charging coordination system [5-7, 15, 16]. Enabling proper communication, effective charging coordination, and effective real-time monitoring and control make the operation and management of FCS more effective, as reported in [7].

Considering offshore renewable energy as a promising avenue for sustainable power production, various pilot ventures and feasibility reports are ongoing to assess the deployment of offshore renewable energy in India and globally [17]. Various global agencies like the International Renewable Energy Agency (IRENA), the Global Wind Energy Council (GWEC) and the International Energy Agency (IEA), outlined the details of offshore production ventures that are ongoing globally and are in the planning, operational, and extension phases in the UK, Europe, the U.S., Japan, Korea, and China. The inclusion of the National Offshore Wind Energy Policy in India facilitated the NIWE to conduct various surveys and feasibility research on the potential sites of India, mainly in Gujarat and Tamil Nadu. Along with the backing of various wind power producers, the initiatives on 5GW offshore wind power production in India are anticipated by 2032 [17]. As India is in its growing stage of exploring offshore renewable energy, by utilizing global expertise and practices, the country can accelerate its developments in energy sectors, as reported in [17, 18]. The same can be extended for the global deployment of offshore charging facility systems. Government support with proper regulations and policies plays a vital role in the advancement of E-vessels as reported in [9]. Proper policy support and technological incorporation are integral parts of the development of offshore energy productions, including FCS [19, 20]. Therefore, proper policy support can accelerate the implementation and development of innovative solutions, like FCS, for sustainable transportation globally.

Sustainable transportation is promoted nowadays on a large scale, with a focus on reducing environmental impact and incorporating sustainable development goals (SDGs) worldwide [21-23]. There are many challenges to incorporating the advancements of electric vehicles and vessels worldwide, including range anxieties, charging facilities, and battery deployment [24-26]. The inclusion of autonomous and grid-integrated electric vehicle charging stations is widely focused on as a solution for sustainable transportation. Experimentations and implementations of charging facility setups at shoreside ports and stations to facilitate E-vessel charging have been reported in recent years. Many maritime companies are involved in shoreside charging to promote E-vessel deployment [2-4, 27, 28]. Energy storage devices and smart grid incorporation can augment efficacy and reliability, ensuring uninterrupted charging services for electric vessels [29]. But the literature focusing on offshore E-vessel charging facilities is still limited. Operational aspects of charging stations need to address challenges like maintenance, safety, and automated functionalities [4, 7].

The novel idea of FCS was reported in [5, 30]. The autonomous system focusing on reducing carbon emissions by promoting the usage of E-vessels, especially for long-distance voyages, is the highlight of the FCS system. This innovative concept can therefore promote sustainable marine transportation. During the voyage, E-vessels can depend on the facilities of the floating charging stations. Considering the technical and economic viewpoints, a brief study was conducted on charging stations operating in marine environments and discussed the sizing analysis of conventional and electric ships for the station [31,32]. Shore-based charging infrastructures analysis for vessels are reported in [33, 34]. The functioning of FCS, considering a site-specific analysis at the North Sea, was detailed in [6]. Real-time analysis was considered in the work showing the functional viability of FCS at the North Sea, Europe. These studies outline the necessary requirements and options for integrating FCS systems to support sustainable transportation in the marine sector. The majority of these studies focused on the feasibility analysis of charging infrastructures for vessels, indicating that the research is primarily focused on the planning phase of the FCS developments. Site-specific analysis is a requirement for considering the practical viability of FCS operations. However, there are very few studies specifically focused on site-specific analysis of FCS. [6] focused on a detailed site-specific analysis in the North Sea area, Europe, including real-time scenarios. Reviewing the literature revealed a lack of reported studies on FCS implementation and functional analysis in India. This paper analyses the operational feasibility of real-time EMS at an offshore site in the Arabian Sea, near Gujrat, India.

Figure 1 represents an illustration of a typical FCS system. With the support of offshore RES and ESS, the E-vessels can approach the FCS and get it recharged. Power electronic converters and controllers regulate the operation and power flow in the FCS system, the charging of E-vessels, and the recharging of the FCS's ESS system. The overall energy management system of FCS manages the FCS operation by incorporating regular identification and management of energy source availability and load demand variations [5]. A backup source will be utilized and managed for the FCS system for more reliable operation. Backup power options can be utilized for FCS operations when RES and ESS are unable to fulfil the E-vessel's charging demands.

Floating nuclear power plants (F-NPPs), ocean thermal energy conversion (OTEC), and the major power grid has the capacity to deliver consistent backup power support for the FCS. The major electrical power grid's backup energy can be employed only if the FCS location is near the shore. For offshore FCS, F-NPP and OTEC can be relied on as backup sources.The availability of OTEC is limited to specific tropical ocean sites [35, 36]. At locations where OTEC is unavailable, FCS can rely on F-NPPs for power. Reports are available regarding the operation and utilisation of F-NPPs, which provide high capacity and reduced ecological impact in electric energy production and hydrogen energy production, by taking care of safe radioactive material disposal technologies [37, 38, 39]. Benefits like reductions in emissions and environmental impacts, fuel cost savings, and maintenance cost reductions are achievable through the electrification of marine transportation, as reported in [40]. Marine vessel companies are focusing on vessel design technologies, onboard RES incorporation, and battery-based hybrid power propulsions, considering sustainable development aspects [41, 42]. Thus, the possibility of FCS implementation with economic and environmental sustainability can be highlighted to support marine transportation.

As India is targeting more renewable energy integration, especially from offshore wind, as reported in [17], this can promote the transportation industry by mitigating greenhouse gas emissions and supplementing utility grid power [43]. Even though no work has been reported about FCS implementation in India, the above information points towards the possibility of FCS implementation plans being taken forward in India, taking into account the global perspective. These actions align with the country's promising renewable energy integration targets and steps to promote clean, green, and sustainable transportation [44].

3. FCS operation and implementation in India

FCS operation and implementation in India paves a new way of fostering possibilities like E-vessel promotions and zero-emission transportation in the maritime sector of India and globally. The subsequent sections focus on the FCS's operational feasibility in the Indian context, considering the RES availability for the FCS.

3.1 RES availability in Indian scenario for the FCS

According to the Ministry of New and Renewable Energy (MNRE) Government of India 2023 year-end article, renewable energy developments in India have

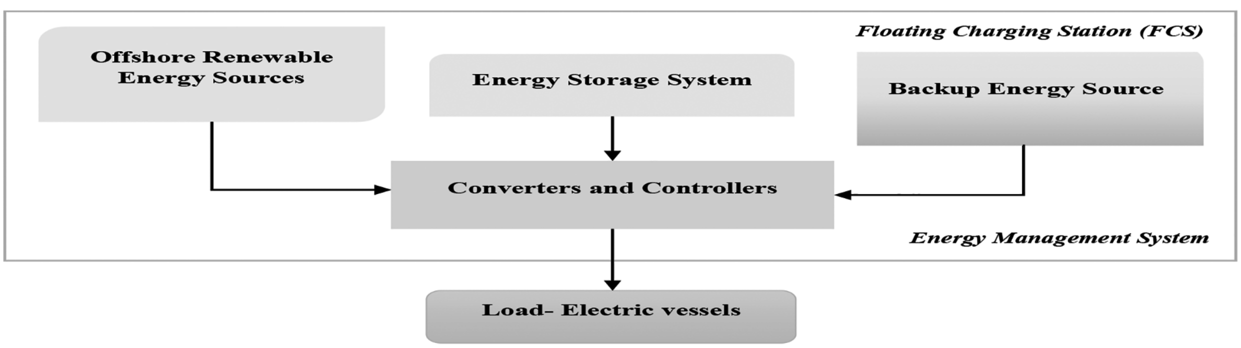

Figure 1: Illustration of FCS system.

shown noteworthy growth of 13.5 GW of renewable energy capacity addition in 2023, along with a collective capacity of 136.57 GW in February 2024 [45]. Based on the 2023 global Figure from the IRENA, India ranks 4th in the installed capacity for renewable energy, 4^{th} in wind energy capacity, and 5th in solar energy capacity worldwide [46]. India's onshore wind energy has grasped 42.6 GW capacity, and offshore wind energy in the country is yet to experience significant growth. The capacity of solar power installed in India had reached almost 70.1 GW in 2023, through favourable policies and incentives by the government. Initiatives such as the National Solar Mission initiated in 2010 address issues such as energy security and changing climate while also contributing to the promotion of clean energy production, demonstrating India's growth as a leading stakeholder in the solar power industry [47].

The nation has a vast coastline spanning over 7,500 km, showing the significant possibilities for offshore renewable energy utilisation. Also, the Exclusive Economic Zone (EEZ) of around 2.3 million km^2, as well as the possibility of utilizing and controlling marine resources, navigation, marine trade, and vessel transport, make India even more suitable for RES production and utilisation [48]. In particular, offshore wind energy can be considered a viable option due to the strong and consistent winds in various of India's offshore geographical regions. The statistics on offshore renewable energy demonstrate the significant potential for producing clean energy, which is crucial for environmental sustainability and energy security. Although the offshore renewable energy division in India is in its budding stages, several initiatives and trial projects have been started, which shows that offshore renewable energy is getting rising recognition in India's energy development strategies [45]. In 2015, the Indian government issued the National Offshore Wind Energy Policy, which focuses on offshore wind energy development and marine space utilisation within India's EEZ. The NIWE was facilitated to lead surveys, resource assessments, and studies for the same [49]. Currently, as per the assessments, pilot studies are being conducted in GW power wind energy potential sites in the Gujrat and Tamil Nadu areas of India [50].

In addition to offshore wind, research and developments in wave and tidal power technologies are ongoing, as India also holds substantial potential for wind and tidal energy. Similar to offshore wind, tidal and wave energy production in the country is also in its nascent stages. Simultaneously, global statistics also indicate that tidal and wave energy production is still in its early stages [51]. India has already reported on trial projects and studies to check the possibility and scalability of ocean wave and tidal energy production [52]. There are reports related to the investigations on the wave climate, wave power variations, and production possibilities in Indian locations [53, 54, 55]. Also, there is sufficient ocean thermal energy potential in Arabian sea areas to harvest energy using ocean thermal energy converters [56]. OTEC energy is abundant in tropical oceans, which cover Arabian Sea locations [56]. All these reports show that even though offshore renewable energy production is in its early stages of development in the country, its offshore energy potential offers immense possibilities for opening the pathways towards a sustainable energy future in India.

India is also a prominent player in the deployment of floating solar PV systems across the country [57]. To harvest offshore solar energy, some offshore solar PV pilot studies have been documented for promoting offshore energy harvesting. The North Sea Energy Outlook 2020 published a plan for 100–500 MW offshore floating solar PV deployment in the North Sea area by 2030–2035 [58, 59]. A successful test of an offshore PV installation in the North Sea was already available in 2021 in Netherlands [60]. Despite the absence of reports on offshore solar PV studies in India, the country's vast solar energy potential presents significant opportunities for the exploration of offshore solar PV energy as well. In summary, we cannot neglect the need for research and development studies to explore India's offshore solar potential as a clean energy production opportunity in the coming years.

3.2 FCS implementation at Arabian Sea, Gujrat, India

As per the Offshore Wind Energy Policy 2015 by the Indian government, GW power wind energy potential sites were identified in the Gujrat and Tamil Nadu areas of India [49]. On the western coast of India, in the EEZ areas near Gujrat, wave energy potential assessment and wave energy production analysis reports show the wave energy production possibilities in those areas [48]. Detailed feasibility research on offshore wind farms in the state of Gujrat was conducted in 2018 by the Facilitating

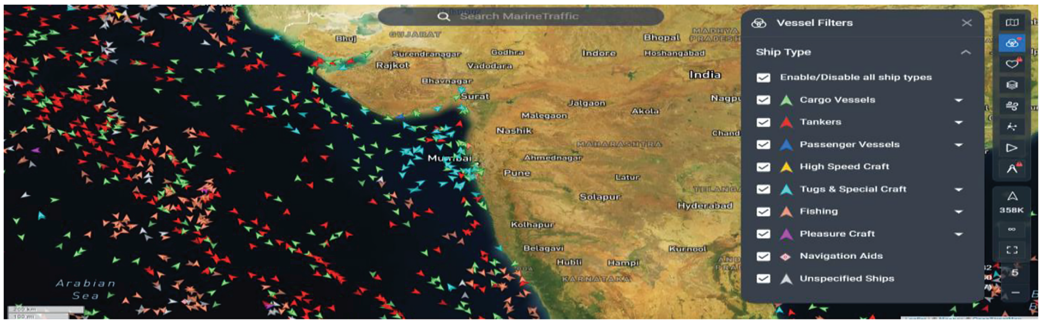

Figure 2: AIS density map at the Arabian Sea, India [63].

Offshore Wind in India (FOWIND), the GWEC, and the study was funded by the European Union [50, 61]. With the support of the NIWE, the MNRE, India, the study encompasses a demonstration offshore wind development project design of nearly 500 MW in Gujarat. The offshore wind sensing system installed off the coast of Gujrat supports the efforts of comprehensive exploration of offshore wind energy possibility in India [61].

The vessel traffic is generally high in these areas, and the major seaports in Gujrat involve Kandla, Mundra, Pipavav, Dahej, and Hazira Ports. There is a high concentration of fishing vessels in Arabian sea locations in the northern region of the Indian Ocean, particularly in EEZ areas [62]. These findings indicate that the high vessel activity in these locations makes them suitable for the implementation of FCS. The implementation of FCS can partially address the emission concerns arising from increased vessel traffic. Figure 2 shows the automatic identification system (AIS) density map in the Arabian Sea [63]. The various colours show the different types of vessels in that area. This shows the need for FCS in Arabian Sea locations that integrate RES utilisation. FCS not only helps to address concerns about emission issues, but it also contributes to significant fuel savings and reduced onboard bunkers for vessels.

4. Analysis of EM scheme for the FCS at the offshore location in India

The feasibility analysis of FCS, including an EM scheme, is elaborated and discussed in this section. A detailed location-specific analysis of an offshore location in India was considered for the study with two assessment periods. Also, the section highlighted a comparison of FCS operations in the Arabian Sea, India, and the North Sea, Europe.

This work is a prolongation of previous work on FCS feasibility analysis at an offshore site in the North Sea, Europe [6], as mentioned earlier. The FCS system power capacity was taken as 10 MW with an 8 MW wind power source and a 2 MW solar PV source. This study also considered BES F-NPP at 35 MW and ESS at 6 MWh capacity. The analysis assumes 2500 kWh as the average battery capacity for the E-vessel [6]. Due to the unavailability of OTEC real-time data at the offshore location, F-NPP is used as the backup source in this study.

4.1 EM scheme for the FCS operation:

The EM scheme's goals were to meet the charging demand of E-vessels with maximized usage of RES, regular recharging of ESS, and maintaining balanced energy transfer in the FCS. Figure 3 illustrates the procedure of the FCS EM scheme.

The EM scheme regularly checks the RES energy availability, ESS energy status, State of Charge (SoC) amounts, and BES energy. The EM scheme controls and manages the operation of FCS on the basis of the presence of RES, responding to the E-vessel energy request it detects. When the RES power fluctuates, the EM scheme adjusts the ESS and BES allocations to meet the E-vessel demand request. During FCS operations, the EM scheme monitors the ESS SoC levels. When the ESS SoC level drops to a minimum, it ceases ESS discharging, and when it reaches its maximum, it stops ESS charging. Therefore, the EM scheme will regularly charge and discharge the ESS, and initiate BES support when the availability of RES and ESS is insufficient to assist FCS charging operations.

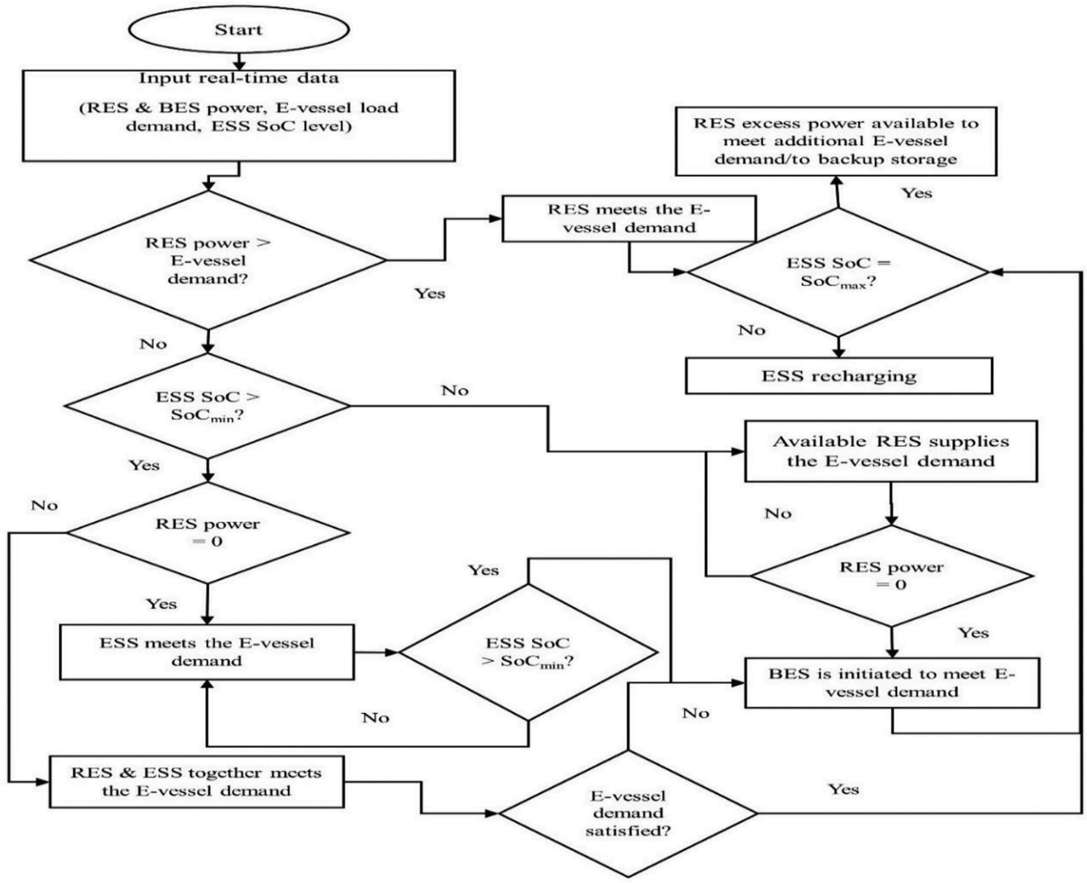

Figure 3: Energy management approach for the FCS.

4.2 Location-specific study of FCS- Arabian Sea, Gujrat, India

The offshore location in India for the evaluation of the EM scheme for the FCS implementation was located at 20° 45’ 19.1” N and 71° 41’ 10.9” E, in the Arabian Sea zone, India. In India, the summer time is generally from March to May, whereas the monsoon season spans from June to September, and the winter from November to February. Actual wind speed and solar irradiance information for the period 2021-2024 for the Arabian Sea location were retrieved from the NIWE & Brighthub database and the NREL & Solcast database for the periods of April (high irradiation) and June (low irradiation) [10-13].

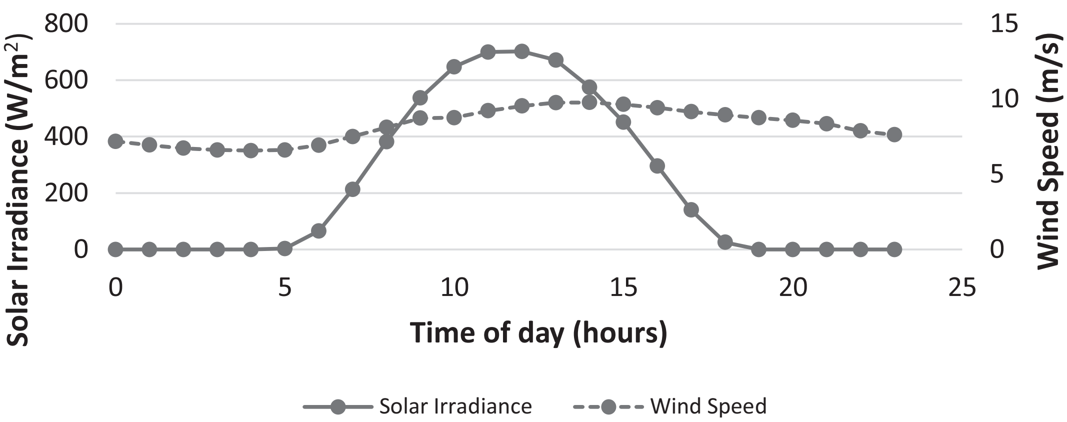

Figure 4: Solar irradiance and wind speed values at the Arabian Sea FCS (June).

A.FCS operation analysis for the period June at the Arabian Sea, India

Figures 4 to 13 show the inputs and results obtained to validate the EM scheme for the FCS during the month of June at the Arabian Sea, India location.

Figure 4 shows the monthly average hourly data for solar irradiance and wind speed in June to evaluate the effectiveness of the real-time EM scheme for the FCS in India [10-13].

For the viability evaluation, the E-vessel energy request illustrated in Figure 5 was utilised to examine the EM scheme in the Arabian Sea FCS site. Figure 6 displays the EMS evaluations of the solar PV source, wind source, and overall RES power for June, taking into account the variable solar irradiance and wind speed information.

As shown in Figure 7, the power existing in ESS can support FCS in E-vessel charging. EMS ensures that E-vessel charging will not utilize ESS support beneath the pre-established minimum level ESS SoC of 20–30%. Figure 8 shows that the energy provided by the FCS and the E-vessel energy request on the FCS are identical. It illustrates that the energy flow to and from the FCS is consistent, confirming that the EM scheme has successfully met the FCS's primary goal of fulfilling the E-vessel energy request. Figures 9, to 13 show the FCS energy flows in and out based on the Arabian Sea data for June.

Figure 9 shows that the energy transfer from FCS to E-vessel are maintained by RES/ESS/F-NPP/all. Figure 10 indicates the recharging of ESS by FCS with the assistance of RES/F-NPP/both. Figures 9 and 10 exhibit balanced energy flows. The graphs in Figures 9 and 10 show that majority of the energy support was sourced from RES in the FCS.

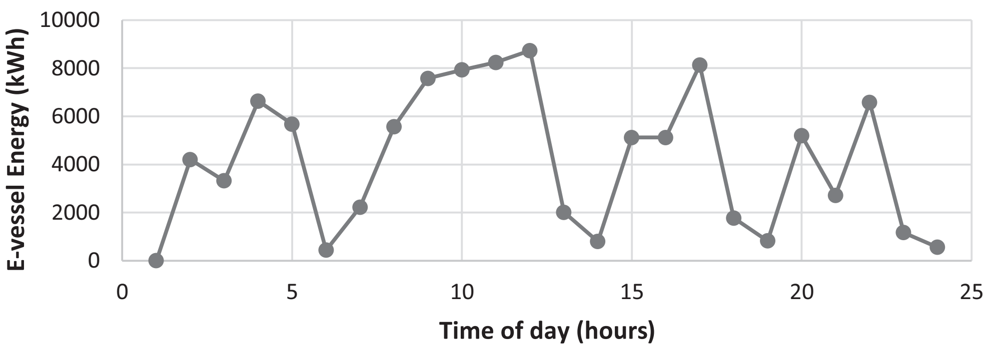

Figure 5: E-vessel energy request for FCS [6].

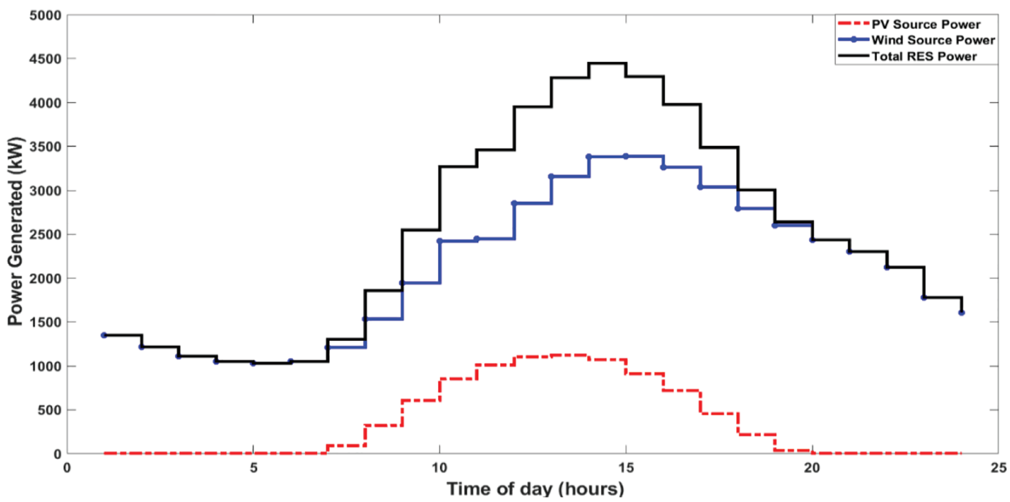

Figure 6: RES power output of Arabian Sea FCS (June).

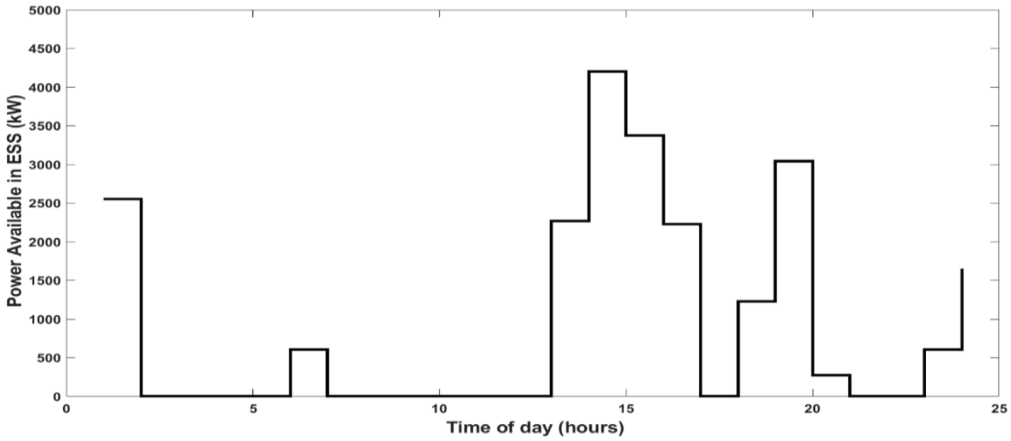

Figure 7: Power available in ESS of Arabian Sea FCS (June).

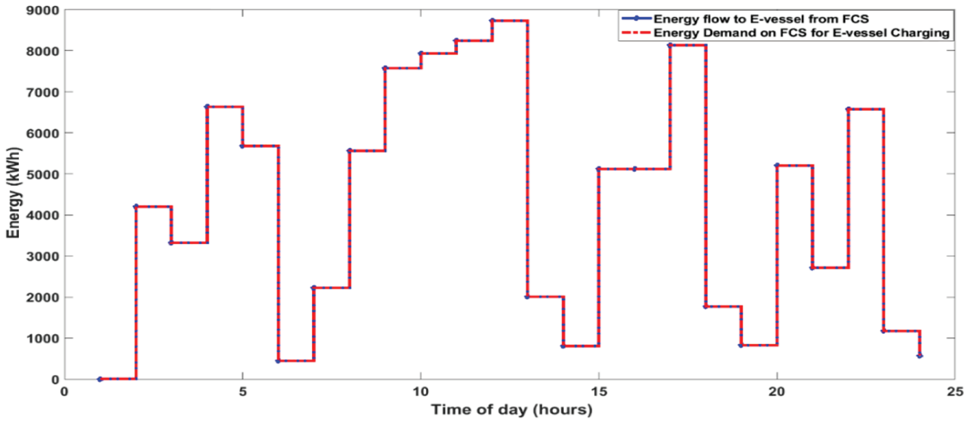

Figure 8: E-vessel energy request fulfilled by Arabian Sea FCS (June).

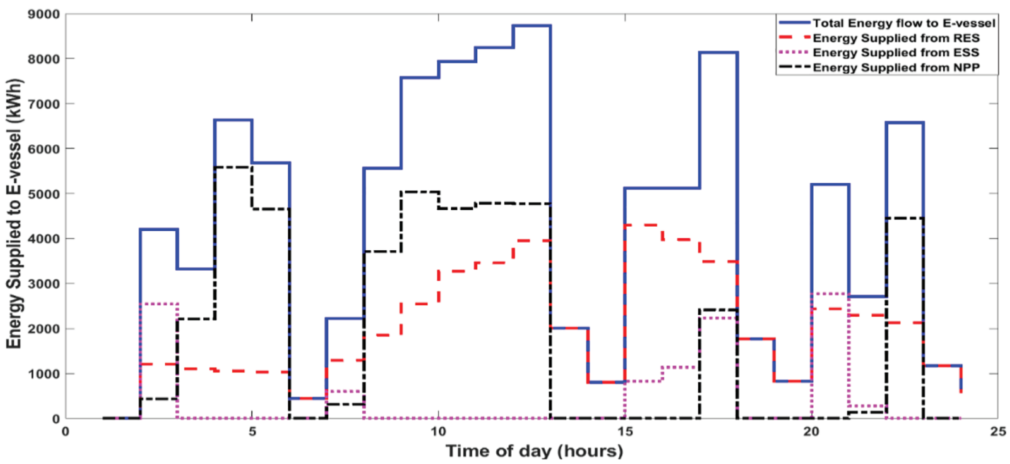

Figure 9: Energy transfer to E-vessel for charging at the Arabian Sea FCS (June).

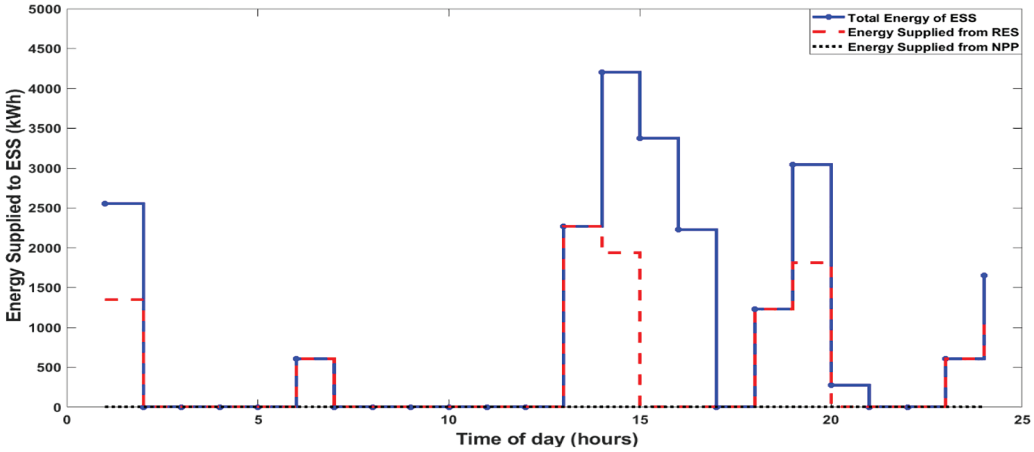

Figure 10: Energy transfer to ESS for charging at the Arabian Sea FCS (June).

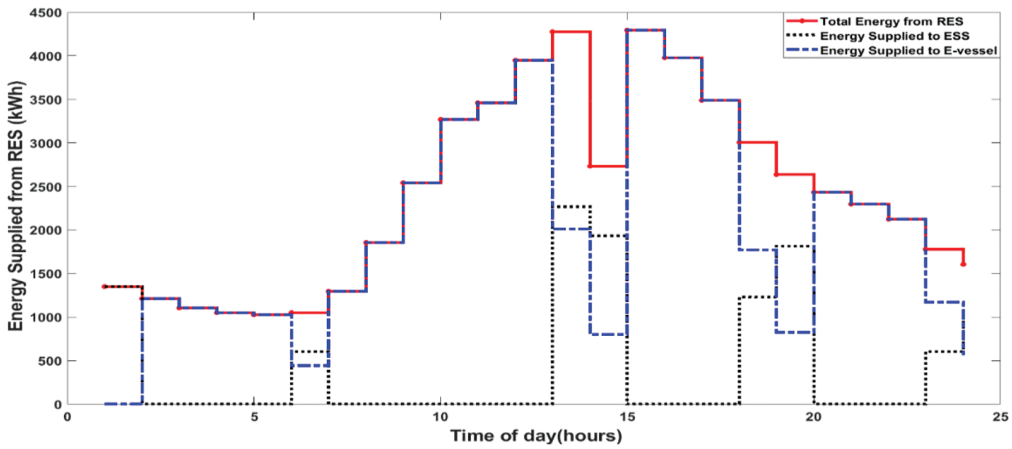

Figure 11: Energy transfer from RES at the Arabian Sea FCS (June).

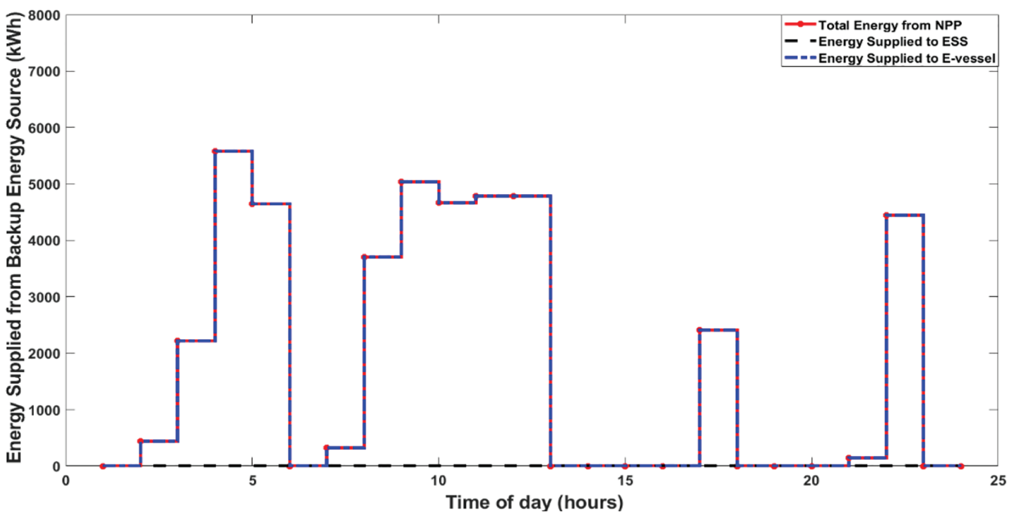

Figure 12: Energy transfer from BES at the Arabian Sea FCS (June).

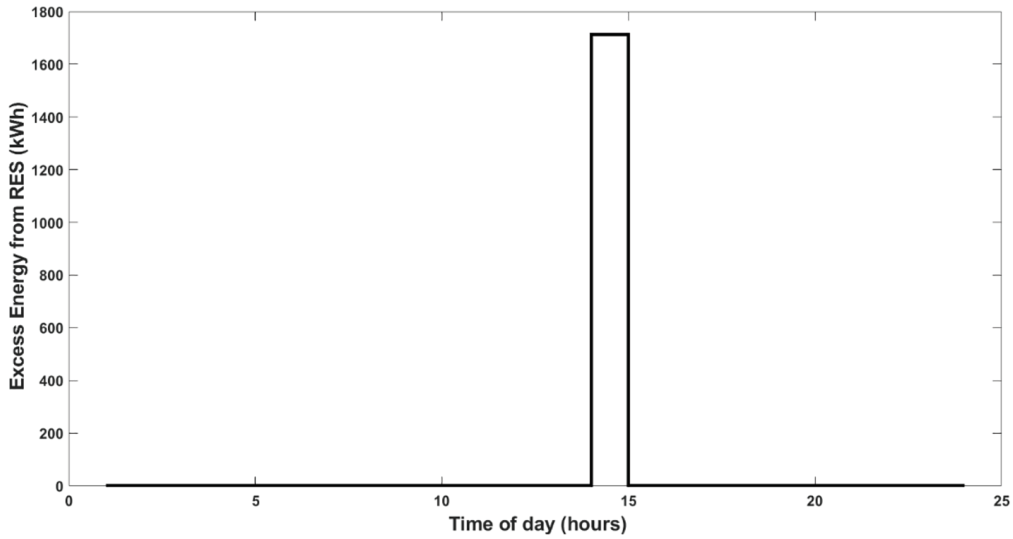

Figure 13: Additional energy offered from RES at the Arabian Sea FCS (June).

Figures 11 and 12 show the flow of energy from RES and BES [F-NPP], correspondingly, to keep E-vessel and ESS recharge requisitions, while the EM scheme maintains balanced energy transfer in the FCS. Figure 12 shows that the FCS needs BES support for an overall duration of 13 hours in a day. The selection of the E-vessel demand assumed a high volume of E-vessel traffic, similar to the bustling North Sea region [6]. During the monsoon period of June in India, the harsh weather can lead to a decrease in E-vessel traffic. As a result, FCS's BES dependency can also decrease, thereby meeting E-vessel demand.

Figure 13 indicates the overall additional RES energy obtainable a day after fulfilling the energy requirements of the E-vessel and ESS charging needs for approximately 1 hour a day at the Arabian Sea site in June. The results show that when the EM scheme was in charge of the FCS, there was enough RES energy to meet the recharging needs of even more E-vessels within the FCS's capacity. Table 1 summarizes the findings of the FCS study in conjunction with EMS at the nominated Arabian Sea site in June.

B.FCS operation analysis for the period April at the Arabian Sea, India

The analysis also includes an additional assessment period to assess the functional feasibility investigation of FCS at the specified Arabian Sea, India, site. Figure 14 shows the monthly average hourly estimates of solar irradiance and wind speed at the same Arabian Sea location, taken in June in the previous analysis, for the period April. The energy demand of E-vessel given in Figure 5 was considered to evaluate the EM scheme of the FCS operation for April as well. For the India location, April is included in the summer season, and June is included in the monsoon/rainy season. Therefore, this analysis assumed June and April to be the low irradiation and high irradiation months, respectively.

Table 1: Summary of results of the investigation of FCS for June.

Evaluation of FCS with EMS at the Arabian Sea, India: Overview of results (June)
• The findings (Figures 8 and 9) exhibited that the FCS in conjunction with EM scheme completely fulfil the E-vessel energy request through the existing energy sources.
• The FCS operation at the Arabian Sea site in June confirmed that balanced energy transfer was achieved using the EM scheme.
• The FCS relied on the BES support for 13 hours, i.e., 54% time of day in June with the selected E-vessel demand.
• Due to the possibility of a harsh sea climate in June, E-vessel traffic can be comparatively less, and the FCS's dependability on BES can be lowered to a limited duration in the period of June in the actual scenario of FCS operation.
• The outcomes that were attained in Figure 13 confirmed the EM scheme's performance in the administration of FCS, including the option of fulfilling any added E-vessel energy requirement within the energy capability of the FCS. In June, we observed the additional energy from RES for nearly an hour.

The variation in solar irradiance is visible in Figures 14 and 4 for April and June, respectively. The intensity of solar radiation at the Arabian Sea in June was small, with a highest irradiance value of 702 W/m^2, compared to the intensity of solar radiation at the Arabian Sea in April, with a maximum irradiance of 1000 W/m^2. Thus, the generation of solar PV power was also lower in June compared to April. RES power generated in FCS and ESS power availability are shown in Figures A1 and A2 in appendix.

The RES power generated from solar PV source, wind source and the collective RES power for April are illustrated in Figure A1 in appendix. Comparing June (Figure 6) with April (Figure A1), we can see that the power generation in April was significantly higher than in June. Similar to the June period, EMS ensured appropriate energy transfer from FCS to E-vessel and ESS. Figure A3 in appendix indicates that the FCS was able to meet the E-vessel energy demand during April as well. As shown in Figure A2 in appendix, the power that is present in ESS can support FCS in E-vessel charging. EMS ensures that E-vessel charging will not utilize ESS support beneath the pre-established minimum ESS SoC of 20–30%. April results again confirm that the FCS with EM scheme could accomplish the major objective of satisfying E-vessel energy requirements.

Figures 15 and 16 show the separate and combined appropriate energy transfers from the FCS to the E-vessel and ESS. Figures 17 and 18 show the separate

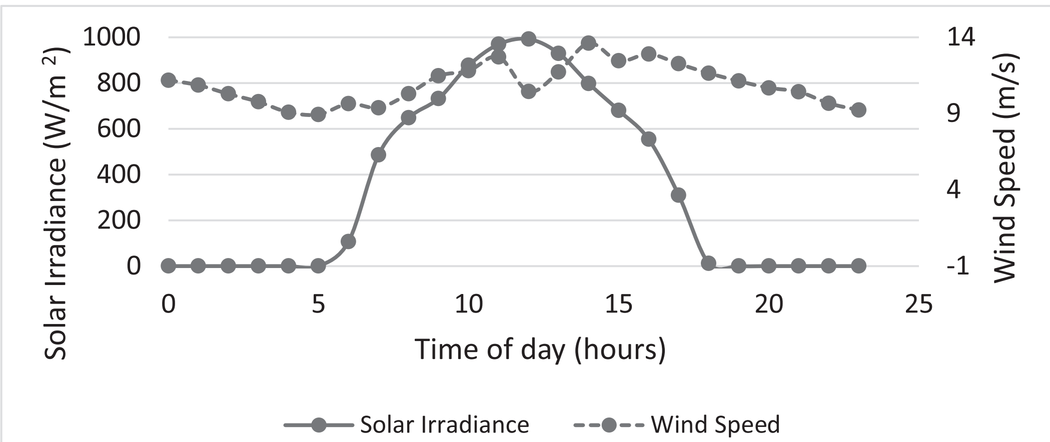

Figure 14: Solar irradiance and wind speed values at the Arabian Sea FCS (April).

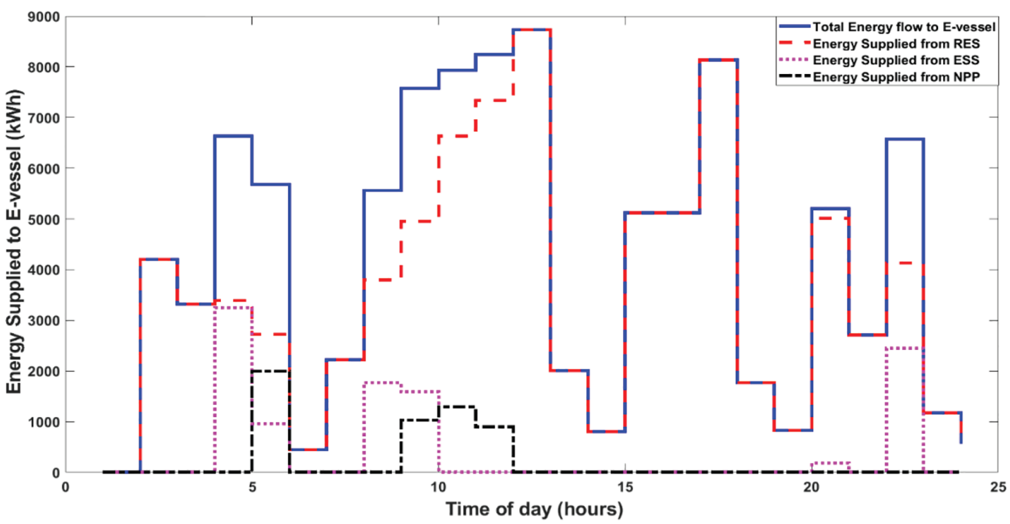

Figure 15: Energy transfer to E-vessel for charging at the Arabian Sea FCS (April).

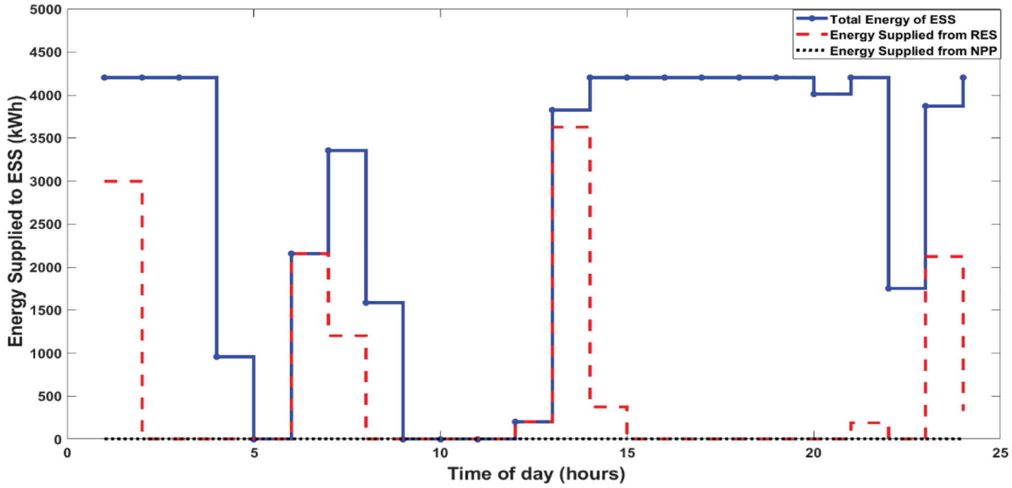

Figure 16: Energy transfer to ESS for recharging at the Arabian Sea FCS (April).

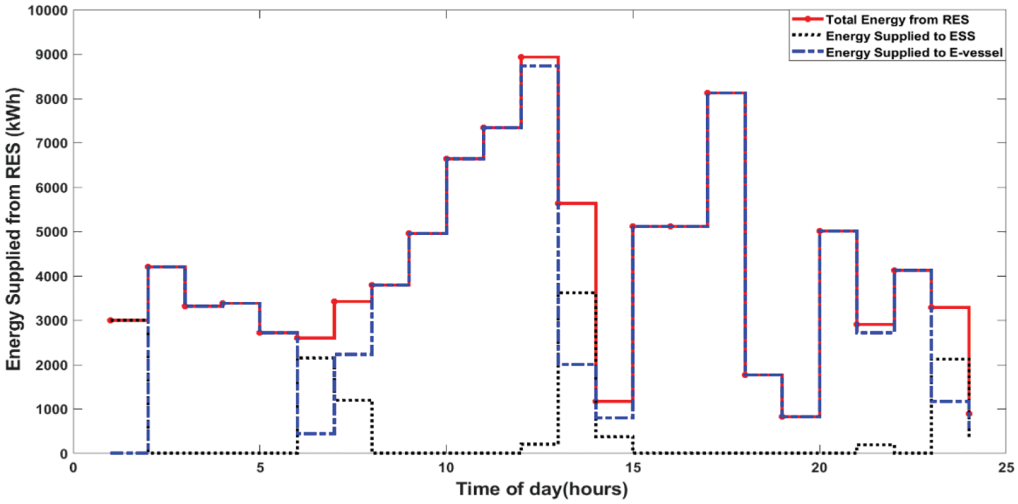

Figure 17: Energy transfer from RES at the Arabian Sea FCS (April).

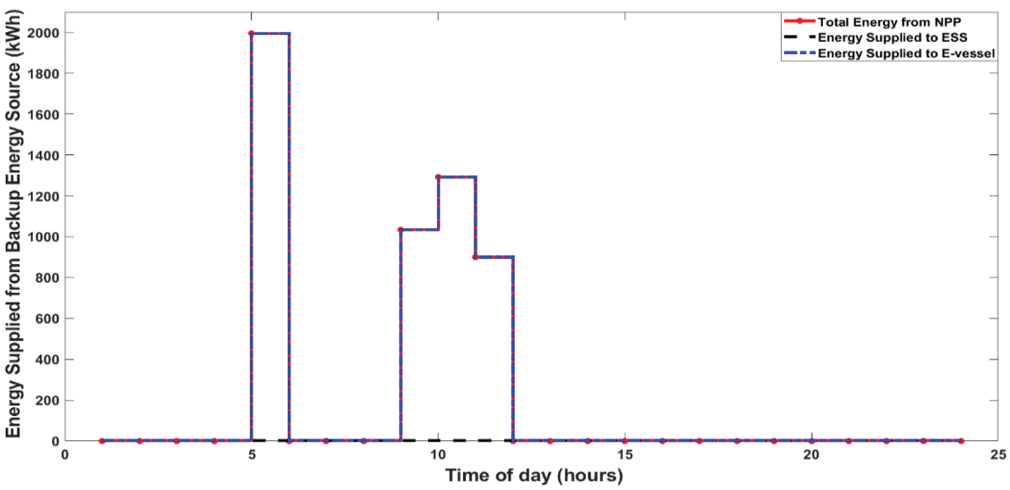

Figure 18: Energy transfer from BES at the Arabian Sea FCS (April).

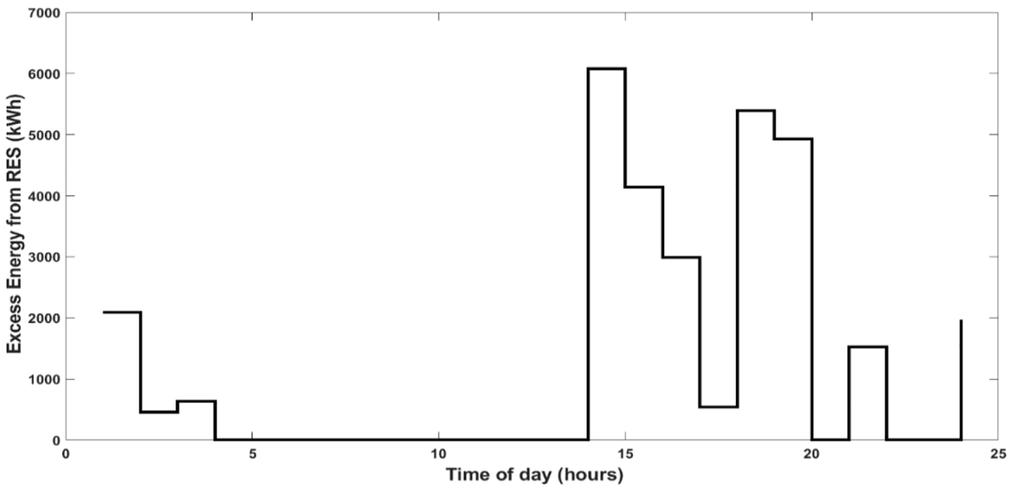

Figure 19: Additional energy offered from RES at the Arabian Sea FCS (April).

and combined appropriate energy transfers from RES and BES (F-NPP) that assist E-vessel and ESS recharging operations.

From the previous findings, the proposed EM scheme for the FCS at the Arabian Sea, India, was capable to provide the balanced energy transfer in June and April as well. In Figure 18, it is visible that the FCS needs BES [F-NPP] support for an overall duration of 4 hours in a day in April.

Figure 19 indicates the overall additional RES energy obtainable a day after satisfying the E-vessel energy requests and ESS charging needs. Additional RES availability of nearly 11 hours a day with a surplus energy of 30,746 kWh at the Arabian Sea location in April can support any additional energy demand from E-vessel within the FCS energy capacity. Table 2 summarizes the findings of the study on FCS with EMS at the designated Arabian Sea site in April.

4.3 Findings and discussions of FCS operational feasibility at Arabian Sea, India.

The analysis of FCS in the Indian scenario demonstrates the EM scheme's ability to satisfy the E-vessel energy request with minimal assistance from the (F-NPP) BES. An ample amount of RES energy was accessible in April rather than June. On a daily basis, RES provided 30,746 kWh for nearly 11 hours in April (Figure 19) and 1,713 kWh for nearly 1 hour in June (Figure 13). The additional energy availability from RES, after meeting the current recharging demands of E-vessel and ESS, indicates the potential to satisfy extra E-vessel charging requirements within the constraints of FCS's energy capacity. The results presented in Figure 18 show a reduction in FCS's reliance on BES (F-NPP) to 4 hours, representing nearly 16% of the day in April. This shows a considerable reduction from 13 hours in June, i.e., a 69.2% reduction in time compared to June. Thus, the BES assistance required for

Table 2: Summary of results of the study of FCS for April.

Evaluation of FCS with EMS at the Arabian Sea, India: Overview of results (April)
• The results (Figures A3 in appendix and 15) showed that in April, the FCS with EM scheme completely fulfilled the E-vessel energy request with the support of the existing energy sources.
• The power generated in the summer period of April at the designated Arabian Sea site was found to be high, with a maximum value of nearly 8930 kWh (Figure 17) compared to June, which indicates the diminished energy dependency on BES (F-NPP) in April.
• The FCS only relied on BES support for 4 hours, i.e., nearly 16% of time of day in April (Figure 18), whereas the FCS relied on BES for 13 hours of the day in June (Figure 12). This demonstrates FCS's reduced dependency on BES, indicating FCS's operational feasibility with less BES support.
• The energy assistance from BES (F-NPP) declined from 43,175 kWh in June (Figure 12) to 5,223 kWh in April (Figure 18), a decrease of 87.9%.
• The results attained in Figure 19 confirmed the EM scheme's performance in the administration of FCS, with the option of fulfilling any added E-vessel energy requirement within the energy capability of the FCS. The additional energy offered by RES daily was 1,713 kWh in June (Figure 13) for nearly 1 hour and 30,746 kWh in April for nearly 11 hours (Figure 19), showing a huge improvement in RES support.

FCS declined by 69.2% in a day in April. The energy support from BES (F-NPP) declined from 43,175 kWh in June to 5,223 kWh in April, showing a drop of 87.9%, as indicated in Figures 12 and 18, respectively. FCS operational feasibility evaluation for June and April at the designated site in the Arabian Sea, India, was executed with the identical high E-vessel traffic data in this investigation for an enhanced assessment, similar to the busy North Sea area [6]. Nevertheless, during the monsoon period of June in India, due to harsh weather, E-vessel traffic can reduce. Thus, the BES dependency of FCS can also be scaled down due to the reduced E-vessel traffic during the month of June.

4.4 Comparison of FCS operation in Arabian Sea, India and North Sea, Europe:

A similar study was conducted in the paper [6], which previously stated the feasibility of FCS operations in the North Sea. This paper included the FCS operational feasibility analysis at the location in the Arabian Sea, India. Although these two locations are geographically distinct, comparing the results can provide insights into the operation of FCS in each area. Table 3 provides a comparison of the results for both the North Sea and Indian locations. The same high E-vessel traffic data was selected for both analyses so that the result assessments can be made clearly. The North Sea is a busy marine area in the Atlantic Ocean, mainly bordering the English Channel and the Baltic Sea. Typically, when comparing the North Sea site with the Arabian Sea site, the North Sea experiences a higher volume of vessel traffic than the Arabian Sea, particularly in the vicinity of India [63]. The duration of the analysis was selected based on the actual data received for renewable power sources in the selected locations. For the North Sea FCS analysis, January and June [6] and for the Arabian Sea, India-located FCS, April and June were the selected periods for the study. The detailed comparison of FCS performance analysis at the North Sea site with the Arabian Sea, India location is given in Tables 3 and 4.

The results from the viability study of FCS at the North Sea [6] and Arabian Sea locations mostly show changes in the amount of renewable energy available, the amount of support needed for FCS from BES, and the amount of extra energy available from RES.

When comparing these two studies, it is not possible to directly conclude that the North Sea FCS is only operationally feasible compared to the Arabian Sea-located FCS due to the higher availability of RES at selected locations.

Both locations have their own geographic energy diversity, and the North Sea exhibited a slight upper hand in RES availability. Despite the lower vessel traffic

Table 3: Comparison of FCS operations in the North Sea and Arabian Sea.

	North Sea		Arabian Sea		Comments
	January	*June*	*June*	*April*	
Season/ weather	Winter	Summer	Rainy/ Monsoon	Summer	• January for the North Sea and June for the Arabian sea were selected as low irradiation periods. • June for the North Sea and April for the Arabian Sea were selected as high irradiation periods.
E-vessel demand	Same	Same	Same	Same	• Generally, E-vessel traffic is probably less in January for the North Sea and in June for the Arabian sea due to bad weather condition. • But, for the analysis, the same E-vessel activity was taken for all cases.
RES energy generated (near maximum value)	5500 kWh	9000 kWh	4300 kWh	8900 kWh	• PV power generation was found to be low during low irradiation periods. • PV power generation is found to be higher in the Arabian Sea location compared to the North Sea location. • Wind power generation was generally found to be high in the North Sea location compared to the Arabian Sea location
PV irradiance (maximum value)	150 W/m^2	520 W/m^2	702 W/m^2	1000 W/m^2	
Wind speed (maximum value)	18 m/s	16 m/s	10 m/s	14 m/s	

(Table 3 continued)

BES dependency in a day	6 hours, i.e., (25% of a day) Energy requirement of 29,138 kWh	1 hour, i.e., (4% of a day) Energy requirement of 1028 kWh	13 hours, i.e., (54% of a day) Energy requirement of 43,175 kWh	4 hours, i.e., (16% of time) Energy requirement of 5,223 kWh	• Obtained a BES energy requirement reduction of 96.5% and a 95.8% reduction in BES support time for the North Sea location between January and June. • Obtained a BES energy requirement reduction of 87.9% compared to June and April and a 69.2% reduction in BES support time for the Arabian Sea location compared to June and April.
Excess Energy from RES	18,690 kWh	43,368 kWh	1,713 kWh	30,746 kWh	• An improvement of 132% in excess energy availability was observed in North Sea FCS in June compared to January. • An excess renewable energy availability of 29,033 kWh, i.e., a 1695% rise, was obtained in April rather than in June for the Arabian Sea.

Table 4: Summary of comparison of FCS operation in the North Sea and Arabian Sea locations.

- The North Sea site demonstrated ample RES energy availability in June 2018 rather than January 2018 [6]. The availability of RES energy at the Arabian Sea FCS was higher in April (Figure A1 in appendix) compared to June. The North Sea-located FCS showed relatively higher renewable energy obtainability than the Arabian Sea-located FCS [6].
- It can be concluded that the objectives of the EM scheme fulfilling E-vessel energy requests, ESS recharging needs by completely exploiting the existing renewable energy sources, and balancing the energy transfer of FCS were achieved in both location feasibility studies.
- FCS depended on BES assistance for E-vessels charging, which experienced a 96% reduction in daily duration, and energy utilized from the BES displayed a 97% decline at the North Sea FCS [6]. The BES's daily assistance time for FCS decreased by 69%, and the BES's energy support (F-NPP) decreased by 88% at the Arabian Sea FCS (Figures 12 and 18).
- Additional RES availability at the North Sea in the summer season exhibited an observable 132% increase [6], whereas at the Arabian Sea it exhibited a huge increase of 29,033 kWh of additional energy, a nearly 1695% increase (Figures 13 and 19).

in the Arabian Sea location compared to the North Sea location, this analysis maintains the same E-vessel demand data for each location, allowing for a more accurate comparison of the results [6, 63]. When vessel traffic is lower at the Arabian Sea-located FCS, the reliance on BES can further decrease, resulting in the FCS operating with minimal reliance on BES.

Another advantage of the Arabian Sea-located FCS is the possibility of integrating OTEC, a renewable-based base load plant, as a backup source. Ocean thermal energy is abundant in tropical oceans, such as the Arabian Sea [56]. However, the North Sea-located FCS must rely on F-NPP as a BES due to the scarcity of ocean thermal energy resources in the North Sea geographic area. So Arabian Sea FCS, with OTEC as BES, can operate reliably with no fuel costs, whereas F-NPP BES-connected FCS operates reliably with additional expenditure on fuel costs and its variations. However, offshore regions with no OTEC power production capability can use F-NPP as a backup energy source for the FCS.

Even though North Sea FCS showed slightly better values in terms of reduction in BES usage and increase in RES excess energy, Arabian Sea FCS operation feasibility is also evident from the results. Typically, actual E-vessel data on traffic, which is currently unavailable, can provide a much better picture of the efficacy of FCS. However, based on the assumed E-vessel demand data for the study, the outcomes of the FCS with the EM scheme at locations in the North Sea and the Arabian Sea demonstrate that FCS can function with the assistance of both RES and ESS, requiring only a minimal amount of BES support.

5. Conclusion and future prospects

This investigation confirmed the operational viability of floating charging stations (FCSs) that can provide environmentally friendly and sustainable maritime transportation in the Indian scenario. The location selected for the study was in the Arabian Sea, near India. A previous study on FCS at a North Sea location in Europe [6] was considered the base paper for this study. A real-time EM scheme was included in this work to assess the practical operational viability of FCS operations in the framework of an Indian scenario. This article also included a thorough comparative study to assess the operational feasibility of FCS at various offshore locations. The Arabian Sea, India-located FCS successfully achieved the main objectives of the EM scheme, which included meeting E-vessel energy demands, ESS recharging needs by fully exploiting accessible RES, and balancing the energy transfer of FCS. For the Arabian Sea FCS, the results showed an 88% reduction in BES energy requirements and a 69% reduction in BES support time. The FCS at Arabian Sea exhibited a huge increase of 29,033 kWh of additional energy, a nearly 1695% increase in additional RES energy availability in the summer months with the selected E-vessel demand. North Sea FCS exhibited a 97% reduction in BES energy support and a 132% increase in additional RES energy availability for the same E-vessel demand. The FCS system's assessment results showed operational feasibility with reduced BES support in both locations.

The analysis was restricted to the Arabian Sea location in this paper and is compared with the North Sea location. The findings in the paper are limited to location-specific analyses. However, the verification and analysis of the FCS operational feasibility of two such locations offshore can offer a stepping stone for the marine transportation industry and shipping companies to channel the large-scale deployment and development of E-vessels and thus afford sustainable marine transportation. Similar to this work, the operational feasibility study plays a crucial role in the implementation of FCS at any offshore location. However, it is primarily recommended to conduct extensive research on the economic analysis necessary for a comprehensive feasibility study of FCS operations in any selected offshore location. Widespread research options can be integrated into this work, which are not limited to E-vessel traffic management and investigations at major offshore locations of FCS implementation, feasible location analysis for FCS, including energy resource assessments, and guidelines and protocols for E-vessel operations.

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Appendix: Additional figure details

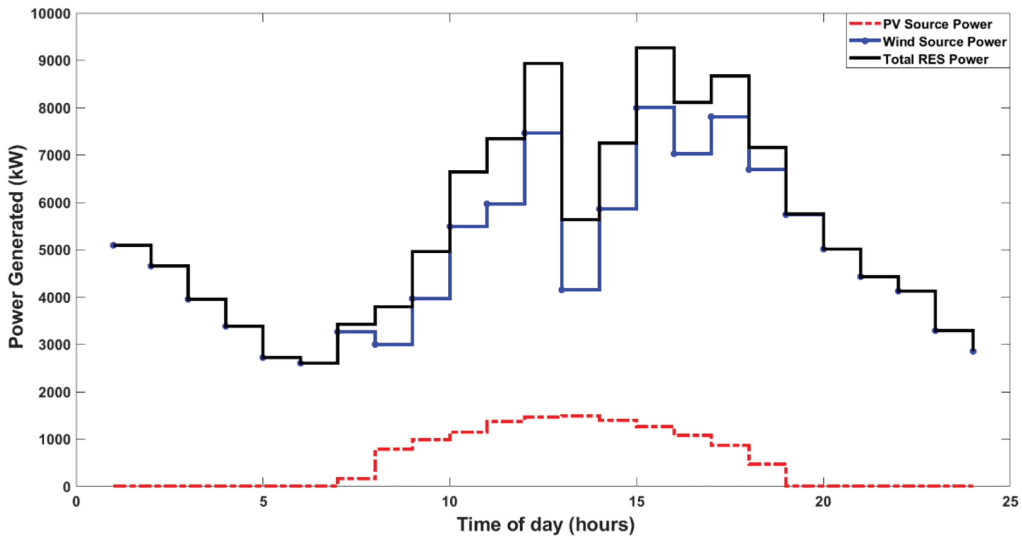

Figure A1: RES power output of Arabian Sea FCS (April)

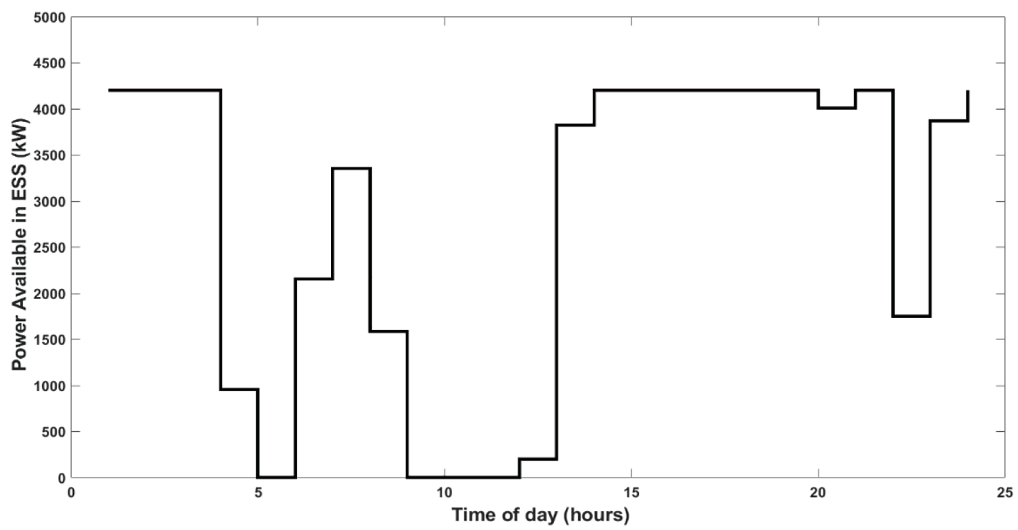

Figure A2: Power available in ESS of Arabian Sea FCS (April)

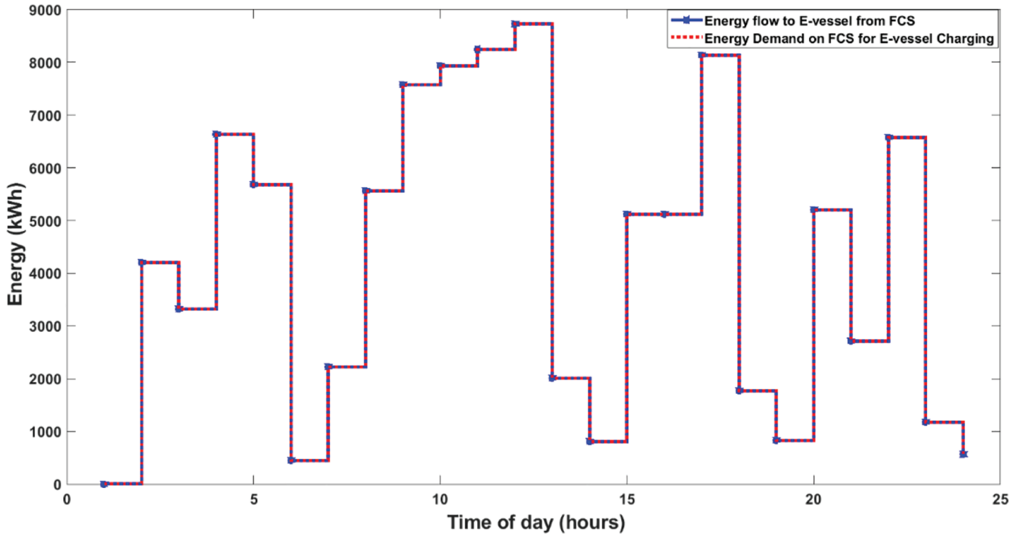

Figure A3: E-vessel energy request fulfilled by Arabian Sea FCS (April)