

Techno-economic and environmental assessment of floating solar power with innovative charging systems for decarbonizing maritime operations in the UK

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ABSTRACT

Maritime transportation contributes around 3 % of global emissions. As global trade and manufacturing expand, the decarbonization of maritime operations becomes an urgent challenge. Ferry ports in the UK face significant barriers to energy transition, including limited grid capacity, lack of charging infrastructure, and constrained land availability. This study proposes the development of a Floating Photovoltaic (FPV) plant on the sea near the port to independently generate renewable electricity for charging electric vessels operating between UK and France. Four scenarios are analyzed, varying in energy generation targets and ground coverage ratios (GCRs). Energy performance is evaluated using the System Advisor Model (SAM), estimating electricity generation and battery energy storage system (BESS) requirements under limited solar irradiance. A comprehensive economic analysis examines capital expenditure (CAPEX), operational expenditure (OPEX), levelized cost of energy (LCOE), revenue, and payback periods. The study also assesses environmental benefits by quantifying CO₂ emissions for FPV lifespan and compares them to diesel-based energy. Moreover, charging technologies are reviewed in relation to current technologies, and a logistics plan for integrating FPV systems and electric vessels is proposed. Results demonstrate that the FPV plant can minimize BESS requirements, and reduce payback periods to as little as 3.62 years, facilitating the pathway of ferry ports to achieve net-zero emissions by 2045, with an estimated reduction of 17million tonnes of CO₂ annually. This study is among the first to assess the feasibility of using FPV systems to charge electric vessels at a UK marine port, integrating real-world spatial constraints, phased deployment planning, and life-cycle environmental analysis. It also introduces the conceptual integration of floating wireless charging infrastructure, offering a forward-looking approach to maritime electrification.

1. Introduction

Maritime transportation plays a critical role in global commerce, serving as the primary mode of transportation for goods exchanged across borders. Currently, maritime transport accounts for over 70 % of the total value of international trade and more than 80 % of its physical volume [1,2]. Furthermore, nearly 90 % of external freight trade in Europe is conducted via seaborne routes, underscoring the pivotal role of shipping in facilitating global and regional commerce [3]. Maritime transportation has increased due to the globalization of manufacturing processes and the increase of global-scale trade [4]. It contributes to more than 3 % of the global carbon dioxide emissions and has become a

huge and growing source of greenhouse gas emissions (GHGs). Such emissions have a significant impact on the environment and include atmospheric concentrations of several pollutants [4–6] mainly emitting carbon dioxide (CO₂), nitrogen oxides (NO_x), sulphur dioxide (SO₂), carbon monoxide (CO), hydrocarbons and primary particulates, as well as secondary particulate precursors [7].

Maritime transport noticeably contributes to the degradation of air quality in coastal areas [8–10], especially concentrated near the coast and within ports [10]. Seaports play important roles in international trade, serving as nodes connecting seagoing vessels with inland logistics. There has been growing demands for increasing capacities of ports to accommodate larger volumes of cargo and support increasing global

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trade [11]. Consequently, decarbonizing ports and vessels has become a significant and urgent challenge for the maritime sector as they strive to meet the growing demands of the maritime transportation industry, while aligning with global sustainability goals. Furthermore, shipping companies have started decarbonizing their vessels, by replacing diesel-powered vessels with hybrid or full electric vessels, adopting green methanol-powered vessels, or retrofitting vessels with low carbon propulsion systems. The infrastructures of electric vessels, such as charging stations, are crucial to enable the transition to electric vessel deployment and operation. Wärtsilä Ltd. launched onshore plug-in charging stations for full and hybrid electric vessels with a maximum of 15 MWAC and 7 MWDC charging power [12]. They have also developed pilot wireless charging stations with power up to 2 MW [13]. It has been noticed that the power generation for charging the vessel needs to be renewable to reduce emissions.

Applying renewable energy such as wind, marine and solar energy to ports and ferries is a feasible approach to decreasing the local environment. Wind plants might not be suitable in the busy port area due to space requirement and environmental impacts. Furthermore, tidal energy has geographical limitations and may harm the oceanic ecosystem, as marine mammals could collide with turbines. As an alternative, solar energy is cheap, clean and easy to access. One of the common methods to harvest solar energy is to use solar photovoltaic (PV) panels. The traditional PV panel is installed on land that can have a negative impact, such as an increase in the local temperature in dense urban environments that cause 'local urban warming effects' [14]. However, solar coverage onshore of the port is also limited due to exhausted space.

Floating photovoltaics (FPV) implies making solar panels floating on a water/sea surface [15]. FPV can be very appealing for ports as the sea space outside is abundant. Although the complexity of installation and assembly associated with water-based systems presents challenges, they remain attractive due to their land-saving benefits, sustainability advantages, avoiding local temperature rise and reducing water evaporation [16,17]. The worldwide installed capacity of FPV power plants has experienced remarkable growth, reaching over 3 GW in 2021 from 100 MW in 2016 and is expected to have a growth rate of 22.5 % by the year 2030 [15,18]. Most economic analysis studies are conducted by analyzing the Levelized Cost of Electricity (LCOE), an index that expresses the cost of producing each kWh of electricity over a system's lifetime [19]. The LCOE for FPV is very dependent on the location, system design and labor cost. A lifecycle assessment analysis has found a LCOE of 20.3 ¢cents/kWh for a FPV on a reservoir in Thailand [20] [], and a study conducted in Brazil, Spain, and the UK reservoirs has reported LCOEs ranging from 0.050 ¢cents/kWh/kWh to 0.096 ¢cents/kWh [21]. There is not much research assessing the economic and energy generation of FPVs globally. Furthermore, almost all of these studies are focused on high solar irradiance areas such as India, Ghana and Abu Dhabi with a small energy output scale. A systematic analysis that combines energy, economic and environment assessments for oceanic FPV in low solar irradiance areas, while considering their interaction with commercial ports and live vessel schedules, is not yet available in the literature.

This study presents a novel integrated techno-economic-environmental assessment of deploying FPV systems to charge electric vessels. By incorporating phased deployment strategies, real-world tidal and navigational constraints, and exploring the potential of floating wireless charging infrastructure, the paper provides a realistic and forward-looking framework for maritime decarbonization. This work represents one of the first comprehensive evaluations of FPV-supported vessel electrification in a UK marine port context. Section 2 highlights the specific background of the ferry port, including the natural resources and governmental policies, and the FPV system design with components selection. In Section 3, four scenarios with different energy generation requirements and Ground Coverage Ratio (GCR) are studied and compared; the FPV energy assessment is investigated with the battery storage system by the System Adviser Model (SAM) due to its superior

reliability and detailed customizable simulation capability among all similar software. Section 4 reports a systematic economic analysis, including CAPEX, OPEX, LCOE, NPV revenue and payback year, is considered. Moreover, a sensitivity analysis is conducted to analyze the tax, battery and electricity price effects on economic behaviors with confidence interval applied. Section 5 presents an environmental impact analysis for using FPV farm compared against fossil fuel emissions, and ecological impact for FPV farm. Furthermore, the logistic plan for the vessel and FPV plant that indicates the timeline for the progress of the ferry port electrification transition is developed in Section 6. Section 7 reports the charging technology for the electric ferry and the logistics plan for the electrification of vessels in the ferry port are presented considering commercially available technologies. This study provides a framework for ports in low solar irradiance regions to decarbonize using FPV systems, demonstrating that optimized design and strategic planning can enable reliable energy generation, cost efficiency, and significant emissions reductions. It offers actionable insights to support the global transition to sustainable maritime operations.

2. FPV power plant design

2.1. Problem definition

The ferry port under this study is located in the southeast of England, seeking a decarbonization solution for passenger vessels operating between southeast England and northern France. Currently, there are three companies operating vessels between the ferry port in southeast England and northern France: DFDS, P&O Ferries and Irish Ferries, with 13 vessels operating in total [22,23]. With the help of these commercial companies promoting energy transition plans, P&O launched two hybrid vessels, and other companies are making plans to replace diesel vessels with hybrid/full electric vessels. However, the current hybrid vessels are still running and charging their batteries with diesel engines due to a lack of charging infrastructure in the port, which delays the transient progress.

It is thus essential to design a charging system with a renewable energy plant to supply the electricity for charging vessels. The ferry port considered here is a trust-owned port that restricts the use of hydrogen plants nearby. Wave activities are violent and not commercially ready or structurally sustainable wave energy converters have been identified yet. Wind or tidal turbines would cause large environmental impacts, including noise and negative impacts on sea life in busy areas. Furthermore, there is no more land space for building large-scale energy plants. Moreover, CAPEX for FPV is generally lower than that of offshore wind and tidal energy technologies. In the UK context, the CAPEX for offshore wind ranges from approximately 1.94 \$Million/MW – 4.54 \$Million/MW, while tidal energy systems can range from 2.92 \$Million/MW – 5.19 \$Million/MW [24]. In contrast, FPV installations typically fall within a range of 0.9 \$Million/MW – 2 \$Million/MW [25]. Thus, a FPV energy plant appears a good solution for generating vessel electricity for the charging system. However, the energy generation, plant size, and economics of the FPV plant need to be assessed due to the low solar irradiance in the southeast of England.

2.2. FPV system

This work intends to design a FPV system that can supply the electric vessels charging at a ferry port. Each electric vessel (E-vessel) requires a charge of 5.5 MWh to complete a single crossing of the English Channel between the ferry port and northern France. According to the operational schedule, the vessels are in service 24 h a day, docking at the ferry port three to four times daily. Consequently, the total daily energy demand for each E-vessel amounts to approximately 22 MWh of alternating current (AC) electricity.

Fig. 1 illustrates the schematic diagram of the FPV plant system at the ferry port with consideration to use onshore and floating wireless

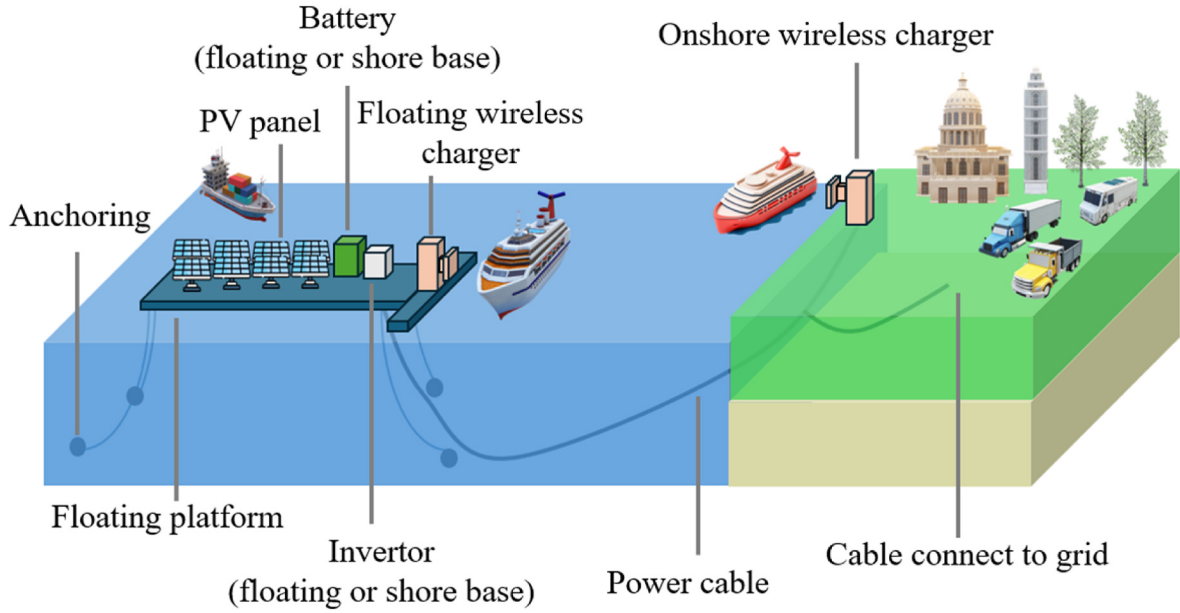


Fig. 1. The schematic diagram for the framework of FPV plant, onshore and floating wireless charging station in ferry port.

charger. A commercial solar panel is selected based on the peak solar irradiance conditions at the ferry port, which are below $300\text{W}/\text{m}^2$. Therefore, the SunPower SPR-E19-310-COM PV panel, with a peak power output of 310W and an efficiency of 19.02% , was selected for this purpose. The panel dimensions are 1.559 m in length and 1.046 m in width. A lithium-ion (Li-ion) battery is connected via a DC-to-DC link at the base of the PV panel to store surplus electricity, which can be utilized during nighttime and periods of low irradiance. Both the PV panels and Li-ion batteries are positioned on a floating structure to minimize land usage.

Additionally, the Sungrow SG250HX-US inverter was selected for converting DC to AC, featuring an 800-V AC (VAC) output and a maximum power point tracking (MPPT) capability of 1300V . The AC is then supplied to the vessel charging station, and any excess energy is sold to the grid. Assumptions are made to simplify the framework: 1) the DC converter between the PV panel and the Li-ion battery, and 2) the AC converter for supplying the vessel charging station and the grid.

Unlike reservoir-based FPV systems, ocean deployment introduces significant engineering challenges due to wave dynamics, salt corrosion, and storm exposure. Appropriate mooring systems, weather-resilient materials, and structural reinforcements are required. Future work should incorporate dynamic simulation and pilot testing to address these open-sea risks. Implementation of FPV systems in maritime ports must also comply with applicable UK and EU regulations, including maritime safety standards, grid interconnection protocols, and environmental permitting requirements. These regulatory considerations will play a critical role in deployment planning and are identified as areas for further work. For instance, the implementation of FPV needs to follow the UK Marine and Coastal Access Act (2009) for the marine planning and get marine licensing from the Marine Management Organisation (MMO). The environmental impact of FPV needs to be assessed by the UK and EU Environmental Impact Assessment (EIA) and Habitats Regulations Assessments (HRAs). Moreover, the maritime safety guidelines need to follow the UK Maritime and Coastguard Agency (MCA). Finally, the energy grid from FPV that connects to the main grid needs to follow the grid connection codes under the UK National Grid Electricity System Operator (ESO), including G99 standards for distributed generation. The detailed study for the legislation is out of the scope. However, it is crucial for the future construction feasibility evaluation.

3. Energy assessment

3.1. Energy assessment approach

The energy assessment quantifies energy output, system efficiency, and space, providing a detailed understanding of trade-offs between spatial requirements and energy performance. This study compares a case with minimized battery requirements ($Case_{REF}$) to a case where energy generation matches the annual energy demand ($Case_{AED}$). Ground coverage ratio (GCR) describes the ratio of the area covered by PV modules to the total ground area occupied by the array. The detailed formula can be found in SAM manual [26]. For locations between 17°N and 75°N latitude, fixed-tilt systems achieve their highest energy density when the ground coverage ratio (GCR) is between 0.5 and 0.7 [27]. The selected port in this study, located at approximately 51.73°N latitude, falls within this range and is characterized by relatively low solar irradiance. Thus, to evaluate the impact of space constraints under such conditions, GCR values of 0.5 and 0.7 are applied in simulation cases. The case name is written in ' $Case_{scenario\ GCR}$ ' format. For instance, case $Case_{REF}$ with GCR 0.7 is $Case_{REF0.7}$.

The energy assessment and the land usage of the FPV plant are investigated by the System Advisor Model (SAM, Version: SAM 2023.12.17) with solar irradiance and temperature historical data in southeast of UK from 2003 to 2023 based on typical metrological year (TMY) collected by PVGIS-SARAH3 [28]. The tilt angle of the PV panel is the same as the altitude with no tracking ability. The shading effect is enabled with the standard nonlinear self-shading model with a PV panel placed in the Portrait direction. Moreover, the DC/AC ratio of the inverter is set to an ideal value of 1.25 to minimize the power loss.

The annual energy-demanding $E_{d,y}$ from the ferry per month can be identified by the docking times per day (N_d), energy demand per docking ($E_{d,n}$), and the day numbers of the month (N_{day}):

$$E_{d,y} = \sum_{n=1}^{12} N_d \times E_{d,n} \times N_{day} \quad (1)$$

The energy difference (δE) between the energy generation (E) and energy demand per month:

$$\delta E = \begin{cases} E - E_d < 0, \text{Deficit} \\ E - E_d \approx 0, \text{Satisfy} \\ E - E_d > 0, \text{Exced} \end{cases} \quad (2)$$

Battery storage capacity for $Case_{REF}$ is designed to accommodate energy needs for nighttime operations, ensuring sufficient storage for vessels docking at the ferry port up to two times after sunset. Additionally, a 20 % capacity margin is included to prevent complete discharge, which could result in permanent battery damage. Thus, the battery capacity at night ($E_{B,night}$) for $Case_{REF}$ can be identified:

$$E_{B,night} = 2 \times E_{d,n} \times 120\% \quad (3)$$

Battery storage capacity for $Case_{AED}$ (E_B) requires the battery to store the energy for nighttime use and to store the excessive energy to use during a deficit period.

$$E_B = E_{B,night} + \delta E \times 120\% \quad (4)$$

3.2. Results and discussion

The energy generation and ocean occupation assessments for multiple scenarios provide essential insights into determining the most appropriate configurations for the ferry port. These evaluations are based on the energy requirements for charging a single vessel and can be extrapolated to estimate the necessary Floating Photovoltaic (FPV) plant size to satisfy varying operational demands. This approach facilitates a systematic and scalable framework for optimizing energy generation and spatial utilization to support the port's decarbonization objectives.

Table 1 and Fig. 2 indicate the specifications and energy generation of the FPV plant for different cases. The energy generation trends in Fig. 2 are directly influenced by solar irradiance levels, weather conditions and the temperature. For instance, energy generation is highest from late spring to early autumn months (March–September), when solar irradiance is at its peak, and significantly lower in winter months (October–February), consistent with the reduced solar availability. The energy demand, as illustrated in Fig. 2, fluctuates slightly between each month due to the natural data for each month being different, with a minimum day of 28 days in February.

Fig. 2 (a) indicates the FPV plant with a GCR value of 0.5 for both cases. $Case_{REF0.5}$ achieves an annual energy generation of 23 GWh, approximately 2.91 times the annual energy demand, with a sea area occupation of 25.44 ha. Monthly energy generation exceeds energy demand throughout the year, with the smallest excess (δE) of 0.006 GWh in December and maximum energy exceed (δE) of 2.96 GWh in April. Additionally, $Case_{REF0.5}$ requires a battery storage capacity of 1.32 MWh to accommodate nighttime energy needs.

$Case_{AED0.5}$ achieves an annual energy generation of 8.063 GWh, closely matching the annual energy demand, with a variance of less than 1 %. The sea area occupation is 9.07 ha, approximately 2.8 times smaller than $Case_{REF0.5}$. During the period from March to September, energy generation surpasses demand, with the minimum energy surplus quantified as 0.3 GWh in May and the maximum reaching 0.57 GWh in April. However, from January to February and October to December, energy generation falls short, with deficits ranging from 0.18 GWh in October to 0.44 GWh in January. This extended deficit period necessitates 2.00×10^3 MWh battery capacity to meet energy demands during these months—1515 times more than the battery requirement for $Case_{REF0.7}$.

Table 1
FPV plant specifications for different cases.

Name	$Case_{REF0.5}$	$Case_{AED0.5}$	$Case_{REF0.7}$	$Case_{AED0.7}$
Area (hector)	25.44	9.07	24.47	6.99
Energy size (MW)	24.2	8.6	32.6	9.3
PV module numbers	78000	27800	105000	30000
Inverter numbers	85	31	115	33
Battery storage (MWh)	1.32	2.00×10^3	1.32	2.23×10^3

Fig. 2 (b) presents the energy generation for the FPV plant with GCR 0.7 for $Case_{REF}$ and $Case_{AED}$. The energy generation trends for GCR 0.7 closely align with those observed with GCR 0.5. $Case_{REF0.7}$ achieves an annual energy generation of 29.7 GWh, representing a 29.1 % increase compared to $Case_{REF0.5}$. The plant occupies an area of 24.47 ha, only 0.97 ha smaller than the corresponding $Case_{REF0.5}$. Monthly energy generation consistently exceeds demand, with the smallest surplus of 0.006 GWh in December and the largest surplus of 4.13 GWh in April. Similar to $Case_{REF0.5}$, $Case_{REF0.7}$ requires a battery storage capacity of 1.32 MWh to facilitate energy discharge during nighttime operations.

$Case_{AED0.7}$ with an annual energy generation of 8.033 GWh is near identical to $Case_{AED0.5}$. The sea area occupied by the plant is 6.99 ha, which is approximately 3.5 times smaller than $Case_{REF0.7}$ and 0.7 ha larger than $Case_{AED0.5}$. The months where energy generation exceeds demand are identical to those in $Case_{AED0.5}$, with a minimum surplus of 0.05 GWh in May and a maximum surplus of 0.63 GWh in April. However, energy generation falls short in January, February, and October to December, with a minimum deficit of 0.21 GWh in October and a maximum deficit of 0.49 GWh in January. This prolonged deficit period indicates that the FPV plant requires 2.23×10^3 MWh battery capacity to meet the energy demand during these months, which is 1813 times and 1.11 times larger than the battery capacity in $Case_{REF0.7}$ and $Case_{AED0.5}$, respectively.

The area of the FPV plant and the GCR have trade-off relations. Lower GCR values require fewer components in the FPV plant to achieve similar annual energy generation. For example, the annual energy generation difference between $Case_{AED0.5}$ and $Case_{AED0.7}$ is only 0.36 %, yet the quantities of PV modules, inverters, and battery cells in $Case_{AED0.5}$ are reduced by 7.9 %, 6.4 %, and 10.3 %, respectively, compared to $Case_{AED0.7}$. Moreover, $Case_{AED}$ has energy generation tends to be higher with a lower GCR in months of low solar irradiance, as the larger gaps between panels minimize the shading effect. Conversely, in high solar irradiance months, a higher GCR performs better, as the increased number of PV panels leads to higher output. This performance variation is attributed to the changing solar angle and daylight hours throughout the year.

GCR has a significant effect in $Case_{REF}$. The difference in energy generation between $Case_{REF0.5}$ and $Case_{REF0.7}$ in the month with the lowest solar irradiance only 0.2 %. However, the annual energy generation for $Case_{REF0.7}$ is 27.1 % higher than $Case_{REF0.5}$, with monthly energy generation consistently 14 %–32 % higher, except in December. This is due to $Case_{REF0.7}$ which has 25.7 % and 26.1 % higher numbers of PV panels and inverters. In low solar irradiance months, despite the increased number of PV panels, the shading effect results in significant energy loss, limiting the performance gains from the additional components. Moreover, the energy assessment indicates FPV plant has the scalability to meet the energy demands of the vessel. However, its large size is a concern. Dividing the plant into different sites can prevent obstruction of navigation routes. Additionally, combining the FPV with other green energy sources could significantly reduce the space occupied by the FPV at sea while ensuring stable energy generation, even in the face of unexpected weather conditions.

4. Economic analysis

The economic assessment demonstrates the feasibility of the proposed energy cases by evaluating their financial performance and viability through comprehensive metrics. The initial one-time investment Capital Expenditure (CAPEX), Operational Expenditure, LCOE, Revenue, Payback period and Net Present Value (NPV) are assessed in this work. Furthermore, the Levelized Cost of Storage (LCOS) for the battery is excluded from the analysis, as the battery infrastructure costs are integrated with the FPV panel calculations.

CAPEX is determined using a scaling method that takes into account nine parameters: PV module and mounting, inverter, battery, electrical

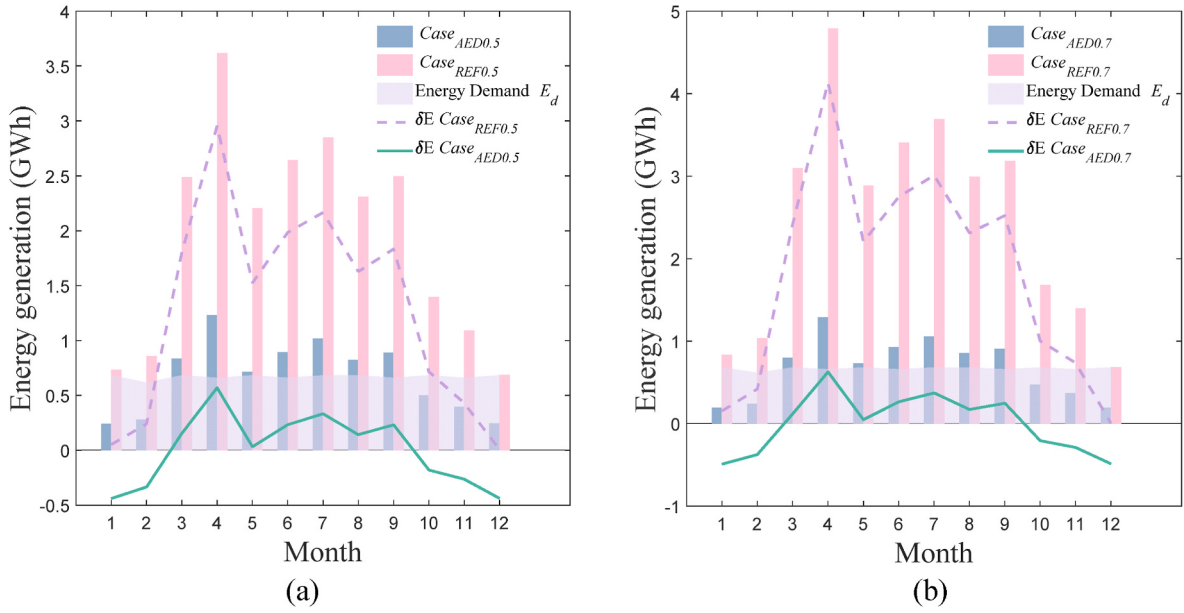


Fig. 2. Energy generation and demand for FPV plant with different GCR values, (a) GCR 0.5, (b) GCR 0.7.

balance of system (BOS), structural BOS, permits, inspections and interconnections, equipment and labor, contingency, and shipping and handling. The assessment uses benchmark examples of 5 MW, 10 MW, and 50 MW FPV plants without battery storage in America [29], then scaled based on the plant energy size. For example, for a plant with an energy size of 24.2 MW, the CAPEX without battery can be determined accordingly.

$$CAPEX_{Withoutbattery} = (50MW - 24.2MW) \times \frac{CAPEX_{50MW} - CAPEX_{10MW}}{50MW - 10MW} \quad (5)$$

In 2023, the price of battery packs is approximately \$130 per kWh worldwide [30]. Additionally, several assumptions are made when calculating CAPEX: taxes and financing are not taken into account, there is no additional infrastructure needed for the battery, such as a cabinet, and costs associated with occupying the seabed are excluded. Therefore, the total CAPEX, which includes the battery costs, is:

$$CAPEX = CAPEX_{Withoutbattery} + P_{battery} \times E_{storage} \quad (6)$$

The operational expenditure (OPEX) for the floating photovoltaic (FPV) plant is calculated on an annual basis. The investor plans to replace the entire system every 10 years, while the photovoltaic (PV) panels need to be replaced every 30 years. The OPEX for the plant encompasses both the FPV system and the battery energy storage system (BESS). For both the FPV system and the BESS, the OPEX can be considered as a fixed operation and maintenance (O&M) cost, estimated at 2.5 % of their capital expenditure (CAPEX) [31,32]. Thus:

$$OPEX = CAPEX \times 2.5\% \quad (7)$$

LCOE analysis calculates the total cost of generating 1 kW-hour (kWh) of energy from a FPV plant. It includes CAPEX, OPEX, discount rate r of 6.4 % [33,34], and an annual FPV degradation rate (rd) of 1.18 % [35]. Additionally, it assumes that the FPV plant, as well as the photovoltaic panels and batteries, have a lifespan (t) of 30 years.

$$LCOE = \frac{CAPEX + \sum_{t=0}^n \left(\frac{OPEX}{(1+r)^t} \right)}{\sum_{t=0}^n \left(\frac{E \times (1-rd)^t}{(1+r)^t} \right)} \quad (8)$$

The revenue of the FPV plant indicates the annual cash inflow. The

generated energy sells to the vessel operators with a UK average industrial electricity price $E_{sale} = 0.259$ \$/kWh (USD) [36]. The excess energy can be sold to other locations outside the port at the same price.

$$Revenue = E_{sale} \times E \quad (9)$$

The payback period in years defines the period to recoup the initial cost of an investment:

$$Payback \text{ (years)} = \frac{CAPEX}{Revenue - OPEX} \quad (10)$$

The NPV is a way of measuring the value of an asset that has cash flow by adding up the present value of all the future cash flows that the asset will generate.

$$NPV = \sum_{t=1}^n \frac{Revenue - OPEX}{(1+r)^t} \quad (11)$$

4.1. Economic performance

Economic performance indicates the feasibility of various cases, particularly in terms of CAPEX for FPV systems with battery energy storage systems (BESS) indicated in Fig. 3 with the percentage of each component identified. The CAPEX for $Case_{AED}$ is significantly higher than $Case_{REF}$, as the high quantity of batteries needed drives up costs. For $Case_{AED0.5}$, the CAPEX is \$269.47 million, with 96.6 % allocated to the battery system and only 1.2 % to the PV panels.

In contrast, $Case_{AED0.7}$ has a CAPEX of \$302.55 million, primarily due to the requirement for additional batteries, which account for 96.0 % of the CAPEX, leaving just 1.3 % for the PV panels. On the other hand, $Case_{REF}$ features significantly lower CAPEX, with an identical allocation of 6.71 % for the battery system and 36.2 % for the PV Panel. CAPEX for $Case_{REF0.5}$ is 10.54 times less than $Case_{AED0.5}$, and CAPEX for $Case_{REF0.7}$ is 11.84 times less than $Case_{AED0.7}$. Additionally, $Case_{REF0.7}$ is \$0.21 million cheaper than $Case_{REF0.5}$, attributed to larger quantities of equipment that lead to a lower price per unit. Overall, the findings emphasize that the number of batteries has a greater impact on CAPEX compared to the number of PV panels, and the distribution of the nine CAPEX parameters, excluding battery costs, varies between cases due to the employed scaling methodology.

Understanding the financial feasibility of the plant involves analyzing financial behaviors, including OPEX, LCOE, revenue, gross

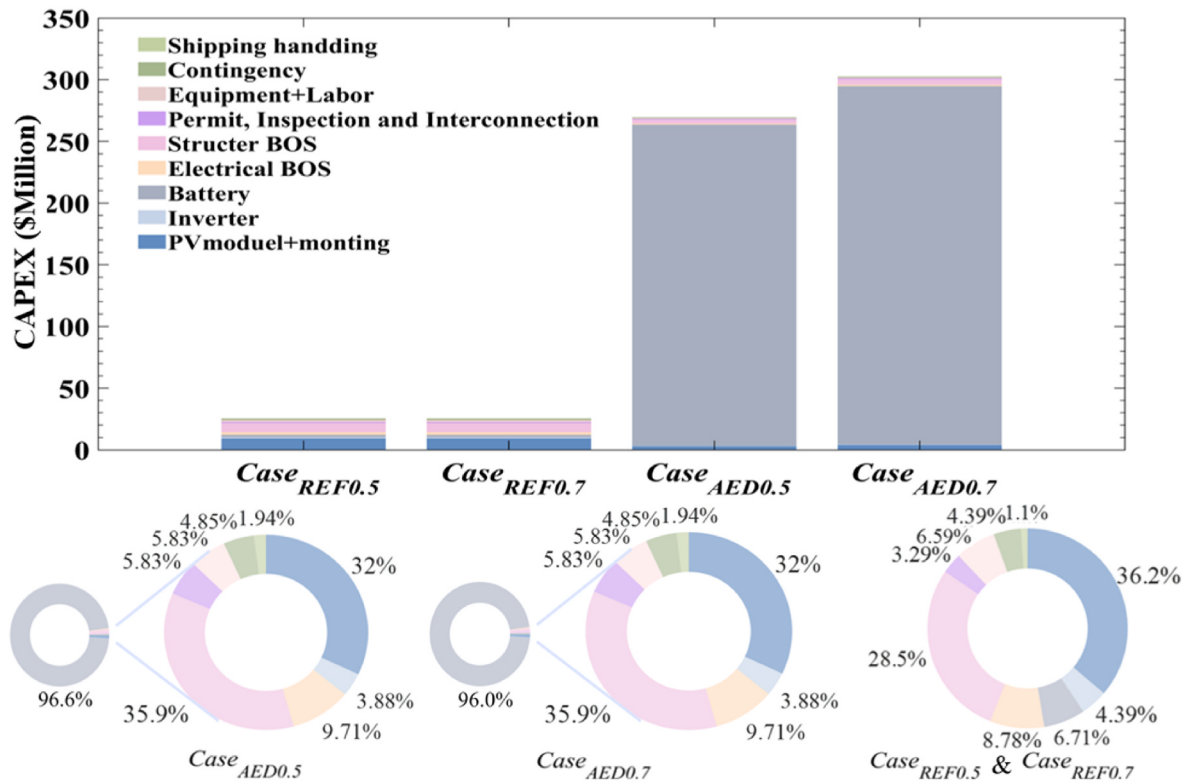


Fig. 3. Capital Expenditure (CAPEX) of different cases with percentage distribution for each parameter.

profit, NPV, and payback indicated in Table 2. $Case_{AED}$ has OPEX almost 10 times larger than $Case_{REF}$ due to higher CAPEX. The LCOE for $Case_{AED}$ with GCR 0.5 and 0.7 is 29.46 and 43.53 times larger compared to $Case_{REF}$, due to higher CAPEX, OPEX and lower energy generation. Moreover, the revenue for $Case_{AED}$ with GCR 0.5 and 0.7 are 2.81 and 3.69 times smaller than $Case_{REF}$. Conversely, another option has high CAPEX and OPEX combined with limited energy generation, resulting in low revenue alongside negative gross profit and NPV, indicating that the investment is not feasible for payback.

$Case_{REF}$ has low LCOE with values of 0.13 \$/kWh and 0.099 \$/kWh for $Case_{REF0.5}$ and $Case_{REF0.7}$, which fall within the range of FPV for reservoir LCOE costs in the [21]. Furthermore, $Case_{REF0.7}$ has the largest revenue of \$7.69million, that is \$1.82 million larger than $Case_{REF0.5}$ primarily due to high energy generation in summer. Moreover, $Case_{REF}$ has OPEX and CAPEX and high energy generation yields high revenue, gross profit, and NPV. The results indicate that $Case_{REF0.5}$ and $Case_{REF0.7}$ can achieve payback in 4.89 and 3.62 years, respectively.

Notably, $Case_{REF0.7}$ achieves the shortest payback period, which may appear optimistic. This result stems from several favorable assumptions that were applied consistently across all cases. First, $Case_{REF0.7}$ has relatively low CAPEX, as it avoids extensive battery use, battery costs being a major driver of total capital investment. Second, the higher GCR of 0.7 enables increased installed PV capacity, leading to higher annual energy production. Third, the revenue is based on the average UK industrial electricity price, which remains high relative to historical levels

and is assumed for both on-site charging and excess energy sales. Finally, OPEX is estimated at 2.5 % of CAPEX annually, and a 6.4 % discount rate is used with a 30-year project lifespan. These factors, when combined, yield a favorable financial return in $Case_{REF0.7}$.

The results indicate that the number of batteries significantly affects the financial behavior of the FPV plant due to the currently high prices for batteries. To maximize profitability, FPV panels should minimize the number of batteries used. However, as battery prices decrease each year, the impact of battery pricing on financial behavior will diminish. Additionally, $Case_{REF}$ is profitable while $Case_{AED}$ may struggle to achieve a sufficient payback. $Case_{REF}$ with different GCR does not significantly affect the financial behavior, especially for OPEX and CAPEX. Nevertheless, FPV plants with a higher number of PV panels can enhance energy generation in the summer, thereby reducing the LCOE and increasing revenue.

4.2. Sensitivity analysis

A sensitivity analysis is conducted to assess how variations in key economic parameters, particularly battery cost, electricity price, and tax rate, affect the financial performance of the proposed FPV-based vessel charging system. These parameters are selected due to their significant influence on CAPEX, LCOE, and payback period.

4.2.1. Battery cost variability

Since the commercial introduction of lithium-ion batteries in 1991, their cost has decreased by approximately 97 %, with an average annual decline of about 18.5 % [37]. Given this historical trend and future market uncertainty, battery cost is modeled within a variation range of -20% to $+20\%$.

4.2.2. Electricity price volatility

Electricity prices for non-domestic users in the UK have experienced considerable volatility in recent years, particularly after 2020. The most notable changes include a 46 % increase between 2022 and 2023,

Table 2
Economic behavior of FPV plant.

	$Case_{AED0.5}$	$Case_{AED0.7}$	$Case_{REF0.5}$	$Case_{REF0.7}$
OPEX (\$Million)	6.74	7.56	0.64	0.64
LCOE (\$/kWh)	3.83	4.31	0.13	0.099
Revenue (\$Million)	2.09	2.08	5.87	7.69
Gross Profit (\$Million)	-4.65	-5.48	5.23	7.05
NPV (\$Million)	-61.35	-71.24	69.07	93.07
Payback (year)	N/A	N/A	4.89	3.62

followed by an 18 % decrease from 2023 to 2024 [38,39]. To capture this volatility and reflect plausible future market conditions, electricity prices were varied between −50 % and +50 % in the sensitivity analysis.

4.2.3. Tax rate assumptions

The tax rate also plays a crucial role in the system's economic feasibility. According to UK VAT policies, the tax rate for residential PV and battery storage systems was reduced from 20 % to 0 % in 2022, with plans to return to 5 % after 2027. However, other components related to the construction and infrastructure of the FPV plant remain subject to a 20 % VAT. To represent these regulatory dynamics, the sensitivity analysis applied tax rates of 0 %, 5 %, and 20 % to the PV and battery components, while holding the tax rate for other components constant at 20 %.

Fig. 4 illustrates the impact of varying battery costs, electricity prices, and tax rates on CAPEX, LCOE, and payback period for both $Case_{AED}$ and $Case_{REF}$. Due to the extensive battery usage in $Case_{AED}$, both its CAPEX and LCOE are more sensitive to battery price fluctuations, exhibiting a variation of approximately ± 19.3 %. In contrast, $Case_{REF}$ shows only a minor variation of about 1.3 %, reflecting its limited reliance on battery systems.

The tax variation influences the CAPEX $Case_{AED}$ with 19.5 % and $Case_{REF}$ with 8.6 % fluctuation. The corresponding impacts on LCOE are 18.9 % and 6.5 %, respectively. Overall, $Case_{REF0.5}$ exhibits a greater financial sensitivity to all three economic parameters due to its higher dependence on battery storage and solar energy availability.

Regarding payback period, $Case_{AED}$ does not reach a break-even point across the range of electricity price scenarios, indicating limited economic viability under current assumptions. In contrast, $Case_{REF}$ is more sensitive to electricity price changes than to battery cost. The shortest payback period is 2.3 years, observed in $Case_{REF0.7}$ occurs under a favorable scenario: a 20 % decrease in battery price, a 50 % increase in electricity price, and a 0 % tax rate. Conversely, the longest payback (12.5 years) results from a 20 % battery price increase, a 50 % decrease in electricity price, and a 20 % tax rate.

The mean payback period for $Case_{REF0.7}$ is estimated at 4.21 years, with a 95 % confidence interval of [3.81, 4.60] years. For $Case_{REF0.5}$, the mean is 5.73 years with a confidence interval of [5.18, 6.29] years. These intervals reflect uncertainty due to fluctuations in economic inputs and reinforce the reliability of the model's central estimates under realistic future conditions.

5. Environmental impact

5.1. Emission impact

The fuel consumption for vessels operating between the ferry port and northern France is unclear. Therefore, the CO_2 emissions from FPV and diesel combustion engines are compared to determine the amount of energy required annually.

The marine diesel engine generates 3.17 t of CO_2 for every tone of fuel consumed [40]. The energy density (U_d) of diesel used in marine engines is 42,190 kJ/kg [41]. Assuming no engine efficiency loss and shaft loss. The amount of diesel required to generate the same quantity of energy needed for each charging session ($W_{d,charging}$):

$$W_{d,charging} = \frac{E_{d,n}}{U_d} \quad (12)$$

The annually CO_2 production ($W_{CO_2,diesel}$) by using diesel can be funded:

$$W_{CO_2,diesel} = \frac{W_{d,charging} \times 3.17 \times 10^3 \times N_d \times 365}{1000} \quad (13)$$

While PV panels do not emit CO_2 during electricity generation, the manufacturing phase is a major contributor to the overall carbon footprint—accounting for approximately 60 %–70 % [42] of the total life-cycle CO_2 emissions of an FPV system. The Yin et al. [43] indicated the 1 MW monocrystalline silicon PV produce a total of 717.36t CO_2 . It should be noted that CO_2 emissions associated with the transportation of FPV components are not included in this assessment. While transport

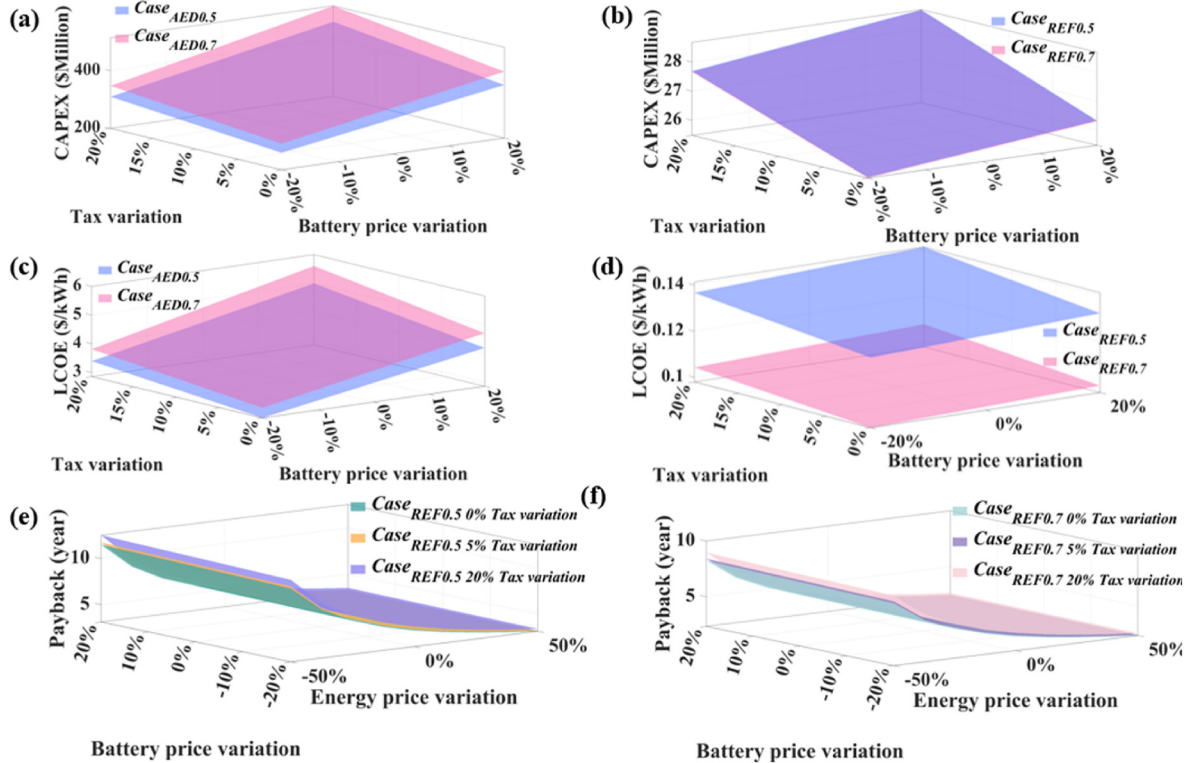


Fig. 4. Economic behavior for the sensitivity analysis of electric and battery price.

can contribute to life-cycle emissions, especially when components are shipped internationally, prior studies have shown that it typically accounts for a minor share compared to manufacturing processes. Due to limited availability of location-specific transport data, this factor was excluded from the current analysis but may be considered in future detailed LCA studies. Thus, the lifetime CO_2 emission from manufacturing PV panels ($W_{CO_2, lifetime}$) for $Case_{AED0.5}$, $Case_{AED0.7}$, $Case_{REF0.5}$ and $Case_{REF0.7}$ is 6169.30 t, 6670.89 t, 17360.11 t and 23385.94 t, respectively. The annual emission rate $W_{CO_2, PV}$ of FPV is typically calculated based on the life cycle emission:

$$W_{CO_2, PV} = \frac{W_{CO_2, lifetime} \times 1.4}{30} \quad (t) \quad (14)$$

The primary processes contributing to CO_2 emissions from Li-ion batteries are manufacturing and raw material processing. The carbon footprint of Li-ion batteries varies based on the manufacturing location. On average, batteries produced in Europe or North America have a lower carbon footprint compared to those manufactured in China [44,45]. For instance, the average CO_2 emissions ($W_{CO_2, battery}$) for Li-ion batteries made in Europe is 69.4 kg/kWh [46]. Therefore, the annual total annual CO_2 emissions from battery storage can be calculated based:

$$W_{CO_2, battery} = \frac{W_{CO_2, battery} \cdot E_{storage}}{30} \quad (t) \quad (15)$$

Thus, the annual total CO_2 emission from the FPV plant can be identified by:

$$W_{CO_2, FPV} = W_{CO_2, PV} + W_{CO_2, battery} \quad (t) \quad (16)$$

Using Floating Photovoltaic (FPV) plants significantly positively impacts the environment compared to using diesel. Fig. 5 indicates the comparison of CO_2 emissions between FPV plants and diesel usage reveal that the primary source of emissions from FPV plants comes from batteries. The annual emissions for $Case_{REF0.5}$ and $Case_{REF0.7}$ are 812.98 t and 1094.19 t, respectively, with 99.7 % of these emissions attributed to the FPV used. $Case_{AED0.5}$ and $Case_{AED0.7}$ have annual emission 4.91×10^3 t and 5.47×10^3 t, with emissions 94.1% and 94.3% contributes to battery, respectively. The emission from battery are negligible for $Case_{REF}$ due to less number of battery and large number of FPV involved, with these emissions being approximately 10.87 times

smaller than those from $Case_{REF}$.

Diesel has the highest emissions, with an annual of 2.17×10^6 t value that surpasses the emissions from FPV plants for $Case_{REF}$. Around 2.17×10^6 t of CO_2 can be saved using $Case_{REF}$ each year, which is equal to the annual CO_2 emissions of 122,807 UK households, based on an average household emission of 17.67 t in the UK [47,48]. This amount of CO_2 savings is 2.4 times greater than the total household emissions in the local district, which had 50,552 households in 2011 [49].

The CO_2 emission intensity can be used to assess and compare the GHG emissions with other renewable energy sources:

$$I_{CO_2} = \frac{W_{CO_2, FPV}}{E} \quad (17)$$

The CO_2 emission intensity for $Case_{REF}$ and $Case_{AED}$ are 36.10 g/kWh and 645.23 g/kWh, respectively. For context, offshore wind energy typically exhibits life-cycle CO_2 emissions in the range of 11–25.7 g/kWh [50,51], while tidal energy ranges between 10 and 35 g/kWh [52]. In this study, $Case_{REF}$ demonstrates a moderately higher emission intensity relative to offshore wind and tidal systems, but still represents a substantial reduction compared to fossil-based alternatives. The significantly higher emission intensity observed in $Case_{AED}$ is attributed to the extensive use of battery storage systems. Battery manufacturing is known to be highly carbon-intensive, especially for lithium-based chemistries, which substantially increases the overall life-cycle emissions of the system.

The environmental impact of FPV is far beyond CO_2 emissions. For instance, FPV systems can reduce water evaporation and offer shading benefits in some freshwater applications, but in marine environments, corrosion and potential disturbance to benthic habitats must be considered. Additionally, long-term exposure to saltwater may accelerate material degradation, raising concerns about microplastic release and maintenance frequency. A comprehensive environmental impact can be assessed by a full life cycle assessment (LCA) and incorporating with multiple impact categories—including effects on aquatic ecosystems, water resource use, and material degradation. However, it is out of the scope of this paper.

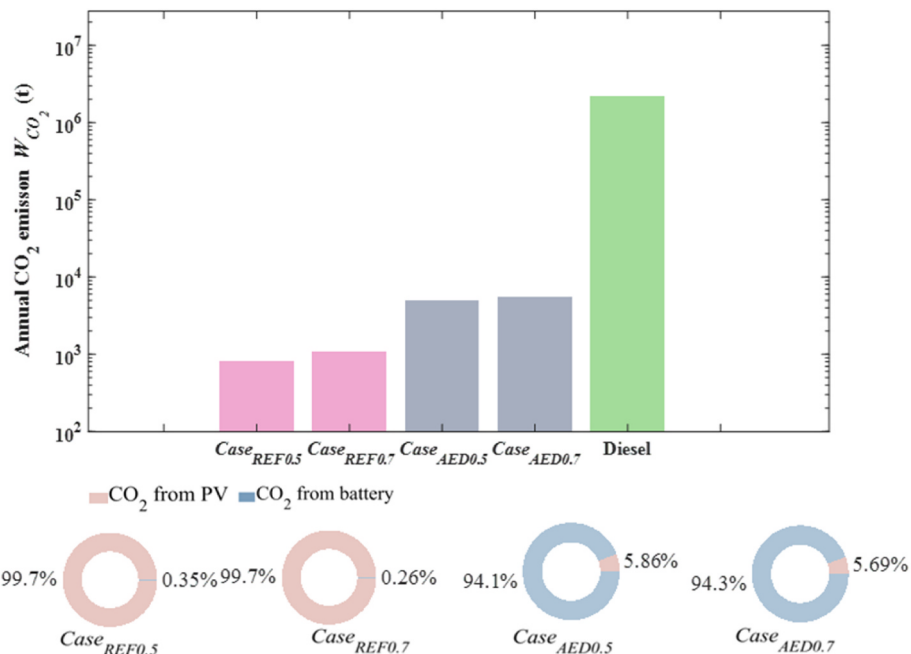


Fig. 5. Annual CO_2 emission for FPV and Diesel with CO_2 distribution battery and PV panel for FPV plant.

5.2. Ecological impact

The deployment of FPV systems in marine environments, such as the ferry port, presents unique environmental challenges compared to inland or freshwater installations. Given ferry port coastal location, a dynamic tidal zone with sensitive marine habitats. It is essential to consider the potential long-term ecological impacts associated with FPV integration.

The marine ecology survey, including flora and fauna near the ferry port, is regularly tracked and updated following the Water Framework Directive (WFD), Sites of Special Scientific Interest (SSSIs) and National Nature Reserves (NNRs) since 1992 [53]. This survey indicated that the ferry port has a very rich ecological system. In 2023, for marine ecology, 46 types of trawling species such as crabs, fin fish; 27 species of benthic fauna; 23 sightings were documented for marine mammals and most of them are seals. For terrestrial ecology, a total of 13,537 individual birds were observed, and 98 species of ground flora were identified. Although the data looks good but comparing to past years, the numbers of marine flora and fauna have dramatically reduced.

The long-term ecological impact for using FPV has both positive and negative effect. The shading effect for the FPV is benefic for fishes, as the shade makes them difficult to spot [54] and increase the visual advantage to fish with increasing water clarity [55]. However, the large shading can reduce the underwater solar irradiance, that may affects the photosynthesis for symbiotic algae (zooxanthellae) inside of the reef-building corals [56]. Although the tidal nature and high turbidity of the ocean wave may mitigate some of these effects, careful assessment is still required, particularly in areas close to intertidal zones or biologically sensitive seabeds.

The floating structure could provide novel opportunities for pinniped species such as seal to remain at sea for longer and/or exploit previously inaccessible areas, as has already been observed anecdotally in at least one marine FPV test site in the southern North Sea (Prof. K. Camphuysen, Netherlands Institute for Sea Research, Pers. Comm., 2022) [57]. However, anchoring or mooring systems used to stabilize the FPV array may disturb the benthic habitats. Improper anchoring can lead to seabed scouring, loss of seagrass, and disruption of benthic invertebrate communities [58]. In addition, floating platforms may act as substrates for biofouling or artificial reef effects, potentially altering local species compositions.

The large reflection of the light from FPV could disturb the terrestrial settings. The waterbird may perceive the PV array as water bodies, which then collided with the structures as they attempt to land [57]. Such collisions may cause injury whilst uninjured birds may face significant difficulties taking off again. Moreover, The reflected sunlight can become partially linearly polarized could cause ecological traps for many animal groups, including insects, birds, amphibians, and others, are polarotactic, or sensitive to polarized light, which they use as an environmental cue to locate open water [59].

Mitigation steps can be taken to minimise the negative impact from the FPV panels. The deployment of the FPV farm can be separate into multiple areas to minimize the large area of shading effect and reduce the level of light reflections. Design of modular FPV layouts with strategic spacing between arrays to maintain adequate light penetration and allow for water movement. Moreover, Use of eco-sensitive anchoring techniques, such as helical screw anchors or tension-leg systems, which minimize seabed disturbance [60,61]. Most importantly, implementation of a long-term environmental monitoring plan, including baseline studies and regular assessments of water quality, biodiversity, and sediment conditions. Furthermore, siting FPV in ecologically sensitive zones, such as protected marine habitats or designated conservation areas should be avoided.

Although the environmental footprint of FPV systems is generally lower than land-based solar in terms of land use, the marine deployment context requires site-specific assessment to ensure that energy gains do not come at the expense of coastal or marine ecology. These

considerations are especially relevant in the UK, where coastal zones are subject to strict environmental regulations under agencies such as the Environment Agency and Natural England.

Further research and pilot-scale monitoring at sites like the ferry port area can provide valuable insights into the ecological interactions of marine FPV, supporting the development of sustainable deployment frameworks for similar ports in the UK and globally.

6. Logistics plan for electric vessels

The ferry port aims to complete its energy transition by 2050. The logistics plan for the electric vessel and FPV plant outlines the planned transactions, steps, and milestones. *Case_{REF0.7}* is chosen for logistics planning due to its excellent economic feasibility, energy generation performance and low carbon emission.

Several factors may influence the logistical progress of the FPV and wireless charging system installation, including weather-related delays, supply chain disruptions, conflicts with ongoing port operations, and delays in regulatory approvals. Given the variability of marine weather in the UK, particularly during winter, it is recommended that construction activities be scheduled during spring and summer months, when weather conditions are more stable. Additionally, contingency periods should be incorporated into the project timeline to accommodate potential delays. To mitigate supply chain risks, a diversified procurement strategy involving multiple suppliers and early ordering of long-lead components is advised. In active port environments, construction may interfere with regular ferry services or cargo handling operations. To address this, close coordination with port authorities is essential. A phased construction schedule should be developed to carry out installation during off-peak periods or planned operational downtimes. For charger installation, a staggered approach will be adopted, whereby only one wharf is temporarily closed at a time to minimize disruption to port traffic. Furthermore, recognizing the possibility of delays in securing marine construction and grid connection permits, early engagement with regulatory bodies is recommended. Incorporating legal and regulatory advisors into the planning team can also help anticipate and address compliance challenges proactively.

Approximately 423.8 MW of FPV capacity will be needed to fully transition all vessels to electric power. Fig. 6 (a) illustrates the timeline for the logistic plan aimed at achieving net-zero emissions between 2025 and 2045. To mitigate potential navigational conflicts and optimize the use of available water surfaces within the ferry port. This plan is divided into four phases, each spanning five years and situated in a separate location. This modular deployment strategy not only enhances the technical feasibility by allowing for better integration with port operations, but also supports environmental monitoring and the transition strategies of the vessel operation companies. From a financial planning perspective, phasing the installation enables staggered capital investment, which can ease funding requirements and improve risk management. Although deploying multiple smaller systems may introduce additional logistical and interconnection costs [62], such as increased cabling, site preparation, and mooring adjustments. These are partially balanced by benefits such as early revenue generation from initial phases, reduced upfront financial burden, and the opportunity to incorporate newer technologies in later phases. Furthermore, this approach provides greater flexibility in aligning with evolving regulatory, spatial, and operational constraints within an active marine port environment.

Phase I (2025–2030) exhibits the slowest construction progress compared to the subsequent phases, primarily due to the time required for investigations and preparations, such as finding suppliers and exploring legislative requirements. The goal of Phase I is to construct a 33 MW FPV plant. The Phase I FPV site, shown in Fig. 6 (b) covers an area of 24.77 ha and is situated next to the eastern dock to minimize transfer losses and avoid interference with the adjacent park and residential area near the western dock. Two charging stations are located on

Dock 2 and Dock 3, which share the same wharf, as indicated by the orange box in Fig. 6 (c). During this phase, five hybrid vessels are operating, with two from P&O and three from Irish Ferries. However, the power generation in Phase I will meet only 7.78 % of the demand, meaning that most hybrid vessels will still depend on their diesel engines.

Phase II (2030–2035) plans to construct a 167 MW FPV plant adjacent to the Phase I site, bringing the total FPV capacity to 200 MW. This will occupy a total area of 151.96 ha. Additionally, three charging points will be established at Docks 5, 6, and 7, as highlighted in a blue box in Fig. 6 (c). During Phase II, DFDS will introduce five new fully electric vessels. The FPV plant is expected to meet 61.34 % of electricity demand, with priority supply given to the fully electric vessels, while the hybrid electric vessels will continue to rely primarily on diesel engines.

Phase III (2035–2040) is expected to establish a 200 MW site, as shown in Fig. 6 (b), on the east side of the Phase I and Phase II sites, approximately 1.1 km from the shore. This location is chosen to minimize any negative impact on the nearby residential area. Additionally, two charging points, highlighted in green in Fig. 6 (c), will be added at Docks 8 and 9. Each dock at the ferry port will have its own charging point for vessels. All vessels are expected to transition to either hybrid or fully electric models, with a plan for three hybrid and ten fully electric vessels. The energy generated by the FPV plant is anticipated to meet 94.38 % of the energy demand.

Phase IV (2040–2045) aims to achieve net zero emissions for vessels operating between southeast England and northern France. A 200 MW site will be established 3.6 km from the western side of the port and 2.27 km from the shore, creating a FPV plant with a total capacity of 600 MW and covering an area of 455.89 ha, as shown in Fig. 6 (b). The considerable distance from the port and the shore increases transmission losses. Therefore, it is essential to minimize the impact on nearby residential areas, coastal parks and avoid interfering with the Channel tunnel near the port. It is assumed that the technology for floating charging facilities will be commercialized between 2040 and 2045; thus, a floating charging station will be added to the east side of the Phase III site to ensure that the route for other vessels remains clear. Furthermore, it is expected that all vessels will transition to fully electric models, and the energy generated by the FPV plant is projected to meet 141.58 % of the energy demand for these vessels.

The energy generation from FPV is crucial for meeting increased energy demands, especially since older sites may need to suspend operations to maintain or replace components, such as PV panels and batteries, every 25–30 years. Additionally, the surplus energy can be transferred to ports to supply power for cruise ships, thereby accelerating progress toward net-zero emissions and increasing revenue. Furthermore, as technology develops rapidly, we can expect more advanced and mature technologies for vessel charging, batteries, and PV panels to be developed and commercialized, enhancing logistics planning.

7. Vessel charging technology

The key requirements for charging electric ferries are centered around operational safety and charging speed. Vessels dock at the ferry port under study for a total of 45 min, which includes approximately 15 min for maneuvering and 30 min for loading passengers and vehicles. The charging process can only occur while the vessel is docked at the wharf. Therefore, the charging rate for the vessel should be at least 11 MW for an hour depending on the charging infrastructure. Current available commercial charging infrastructures for vessels include both wireless and cable charging options.

A cable charger can transfer more energy than a wireless charger. For instance, the ZPP850 charger from Zinus can deliver a maximum energy output of 3.3 MW per set of cables, and it can accommodate up to two sets of cables per charger [63]. Wärtsilä Ltd. has introduced the world's first commercial wireless charging system for vessels, which operates

with a 50 cm gap between the charging pad and the vessel, transferring approximately 1–2 MW of power per hour [64]. Moreover, depending on the application, a cable charger can have an energy transfer rate of over 90 %, while a wireless charger can have an energy transfer efficiency of around 80 %–93 %.

Cable chargers can be categorized into two types: manual connection and automatic connection. However, high energy transfer requires thick power cables to ensure efficient energy flow to the vessel, which makes the charging cables quite heavy and difficult to handle manually. Automatic connection reduces the need for human operation, enhancing safety and maximizing available charging time during docking. This system is particularly suited for vessels with short docking times [64]. Nonetheless, electric hazards such as short-circuiting still exist in particular during severe and stormy weather conditions. The maintenance requirements mainly depend on the working mechanism and the chargers in this case. Cable charging systems involve higher maintenance due to frequent physical handling, exposure to harsh maritime conditions, and mechanical degradation of connectors, which necessitate more frequent cleaning, inspection, and part replacement.

The need for safe and high charging rates poses significant challenges for conventional wired charging systems used for vessels. One of the main issues is the electrical hazards that operators face when handling plugs and connectors, especially in the moist environments typical of a port. These hazards are heightened by the high voltage and current levels required for fast charging. In contrast, wireless charging offers a safer alternative by eliminating direct contact with conductive components, which significantly reduces the risk of electrical accidents. Furthermore, wireless charging supports autonomous operations that require no human involvement. Wireless charging systems, while technologically more complex and requiring precise alignment between transmitter and receiver units, benefit from reduced mechanical wear due to their contactless nature. This translates into lower routine maintenance and decreased susceptibility to corrosion-related failures in marine environments. However, high-power wireless charging encounters significant challenges, including magnetic field interference, heat generation, and efficiency concerns. Recent advances in off-grid modular floating wireless charging technology, such as the system proposed by authors [65] offer promising solutions to overcome several limitations of the conventional charging infrastructure. The design features a buoyant, self-aligning wireless charging platform with validated energy transfer efficiency of 82 % in wave-affected conditions, and an automatic docking system. Moreover, this off grid charging facility is powered by FPV only. This technology reduces direct human involvement, mitigates corrosion and contact-related wear, and enhances safety by eliminating the need for physical connectors. It enables modular offshore charging nodes at remote areas, reduces congestion at onshore terminals, and provides emergency charging capacity along ferry routes.

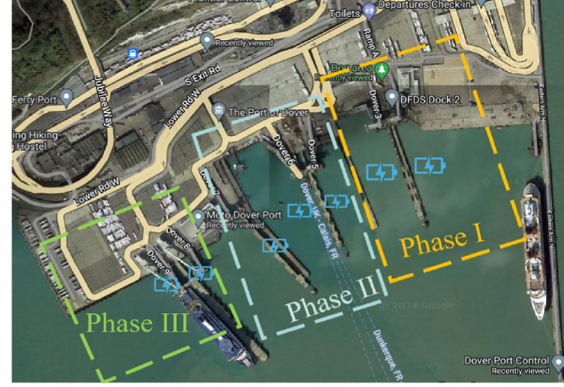
The conceptualize FPV system with floating wireless charger is demonstrated in Fig. 7. Both the wireless charger and the FPV plant are designed to be scalable, allowing them to meet various requirements and demands. To enable high-power wireless fast charging, the vessel's battery can be divided into two or more parallel charging systems. This design allows for the addition of multiple wireless charging pads, facilitating parallel charging to meet fast-charging needs. Compared with an onshore charger, the floating charger helps reduce traffic within the port by allowing vessels to charge offshore. Additionally, it extends the range of electric vessels by placing the charger along their routes or providing a backup option in case of emergencies. However, the structural and system complexity of offshore floating chargers is higher than for onshore chargers. Wireless transfer chargers allow for a distance between the charger and the vessel, reducing the risk of mechanical damage to both during adverse weather conditions. However, an anchor system must be designed to maintain a relatively stationary position between the charger and the vessel.

	2025	Phase I	2030	Phase II	2035	Phase III	2040	Phase IV	2045
Plant size		33 MW plant		200 MW plant		400 MW plant		600 MW plant	
E-vessel numbers		5 hybrid		5 hybrid, 5 electric		3 hybrid, 10 electric		13 electric	
Charging Point		2 on berth		5 on berth		8 on berth		8 on berth, 2 floating	
			7.78% demanding satisfied		61.34% demanding satisfied		94.38% demanding satisfied		141.58% demanding satisfied

(a)



(b)



(c)

Fig. 6. Logistic plan for electric vessels and FPV plants (a) FPV plant locations and locations of the in-port charger and out-port floating charger, (b) FPV plant locations, (c) charging points in port.

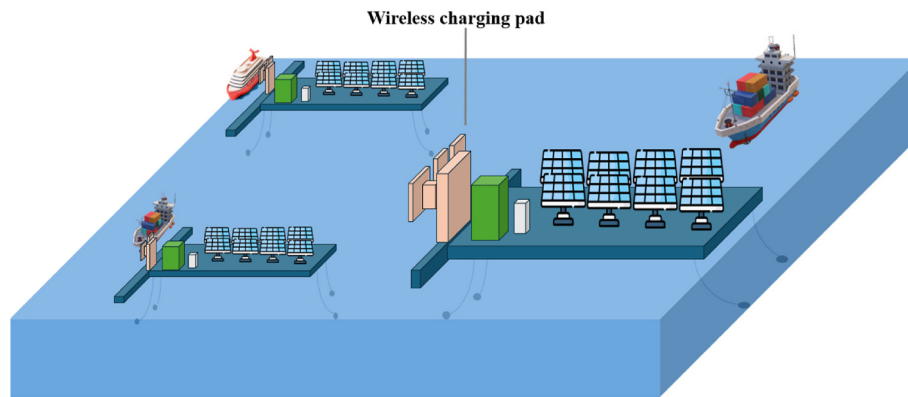


Fig. 7. Conceptualize of the stability and modularity of FPV with floating wireless charger.

8. Conclusions

This study investigated the energy generation and economic feasibility of installing FPV plant at ferry port to generate green electricity for charging the electric vessel operating between southeast of England and northern France. The novelty of this work lies in its integrated techno-economic-environmental assessment of FPV-based vessel charging at a real-world site, under marine and operational constraints. Furthermore, the proposed concept of combining FPV with floating wireless charging infrastructure presents a scalable and future-proof solution for decarbonizing port operations.

Four cases are presented with different energy generation requirements and GCR and calculated based on the demand for one vessel. The results indicate that $Case_{REF0.7}$ has the highest energy generation

amount at 29.7 GWh annually with an area of 24.47 hector and the shortest payback period of 3.62 years. The sensitivity analysis indicates $Case_{AED}$ is unable to recover the cost even with battery price decrease 20 % and electricity price increase of 50 %, while $Case_{REF0.7}$ has an average payback 4.21 years, with a 95 % confidence interval ranging from 3.81 to 4.06 years. The FPV plant can be divided into multiple smaller sites to prevent blocking the route. Additionally, combining the FPV plant with other green energy sources would reduce its size and enhance energy generation stability during unexpected weather conditions. Moreover, the environmental analysis indicates there is no local emission after transient to FPV. However, with considering the emissions from components manufacturing and logistic chain, using $Case_{REF}$ by minimising the battery storage capacity for the FPV plant, CO_2 emissions can be reduced 2275 times compared to diesel engines that produce the same

amount of energy. This amount of CO_2 savings is 2.5 times more than the total household emissions in local District in 2011. The logistic plan indicates ferry port can achieve net-zero transactions for southeast of England to northern France route by 2045. Finally, the current commercially available chargers are hard to meet in terms of the requirements for the electric vessel needs in ferry port. However, modifying the vessel battery into two or more parallel charging systems is capable of reducing the charging power required and time. Developing a high-power wireless charging system is essential for future floating charging station design. Finally, validating the assessment results using data from industry stakeholders is essential. However, the current assessment lacks comparable real-world construction projects, which limits its reliability. Therefore, incorporating actual data provided by a UK ferry port is crucial to enhance the credibility and accuracy of the evaluation.

Although the technical and economic performance is influenced by local factors such as solar irradiance, electricity tariff, and infrastructure, the underlying methodology and modulated system design principles, including FPV-charging system design, remain applicable globally. For instance, ports in regions with higher solar potential—such as Southern Europe, Southeast Asia, or the Middle East—may achieve even greater cost-effectiveness and energy yields.

CRedit authorship contribution statement

Qing Qin: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Lukman Adeboye:** Writing – original draft, Software, Formal analysis, Data curation. **Khalifa Aliyu Ibrahim:** Writing – review & editing, Investigation, Formal analysis. **Patrick Luk:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Ying Xie:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Patrick Verdin:** Writing – review & editing, Investigation, Funding acquisition. **Zhenhua Luo:** Writing – review & editing, Resources, Investigation, Funding acquisition, Conceptualization. **Luofeng Huang:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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