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A preliminary evaluation of marinized offshore charging stations for future electric ships

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ADB Working Paper Series

**A PRELIMINARY EVALUATION
OF MARINIZED OFFSHORE
CHARGING STATIONS FOR
FUTURE ELECTRIC SHIPS**

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Abstract

The electrification of international shipping has gained attention from the global maritime industry in an effort to reduce pollution and greenhouse gas emissions. Despite rapidly falling battery prices and improvements in battery technologies, electric vehicles (both marine- and land-based vehicles) remain constrained due to their access to fast and convenient charging stations because of the limited mileage possible with a full charge. In the context of international shipping, the long freight distance makes access to charging infrastructure en route a necessity for full electrification. Before countries pour trillions of dollars of investment into future electrification, this study attempted to answer a critical question on the economic feasibility of offshore maritized charging stations for enabling long-distance freight for fully electric vessels. It made several key assumptions on the technical performance related to charging, which it based on practical considerations in shipping operations, as no reference test-bedding projects were available at the point of commissioning this study. The study selected three offshore power technologies, namely wind, solar, and floating nuclear power plants, as there are existing projects available for reference. In a comparison with a comparable vessel using bunker fuel, it found that electric vessels are economically feasible even under the assumed first-of-a-kind costs, especially when floating nuclear power plants supply the power for recharging. While noting the challenge in validating the assumptions via engineering means, it is possible to view the assumptions as reference or desirable performance indicators for future technologies to attain through innovation and policy intervention to facilitate the full electrification of international shipping.

Key words: maritized offshore charging station, cost–benefit analysis, offshore renewable energy, floating nuclear power plant, international shipping, electric vehicle

JEL Classification: R42

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1. INTRODUCTION

Research has recognized renewable and nuclear energy as important options to achieve global climate objectives (IPCC 2014). Due to the decarbonization requirement of the global energy sector and the cost reduction, renewable energy technologies have undergone wide development and achieved a renewable capacity of a total of 161 gigawatts (GW) in 2016 (REN21 2017). Ellabban, Abu-Rub, and Blaabjerg (2014) suggested that offshore clean energy resources could also make an important contribution to the global decarbonization effort. As of 30 June 2020, the largest reported offshore renewable installations are 588 MWe of offshore wind at 2.65 billion British pounds, currently in operation off the coast of Wick in Scotland in the UK (BBC 2019), and a 100 MWe floating solar PV farm in the planning stage off the Dutch coast in the North Sea, the current operation phase of which provides 8.5 kW (Bellini 2019). The only floating nuclear power plant (FNPP) project in the Russian Federation (Nian 2018) has recently entered into commercial operation.

The traditional thinking about offshore energy is about bringing electricity produced from those energy resources for the onshore grid to achieve the decarbonization targets and self-sufficiency, as is observable in all the existing projects. Since offshore renewable technologies are similar to onshore ones in terms of intermittency, recent propositions have included the introduction of electric vehicles (EVs) (Esteban and Leary 2012) and/or a centralized battery energy storage system (BESS) to achieve better utilization of those intermittent renewable energy resources (Chen et al. 2009) and more efficient operation of conventional power plants (Nian, Jindal, and Li 2019).

Also in the traditional thinking, there have been concerns about offshore wind or solar farms becoming potential obstacles to shipping lanes in selected areas of the world, among other ecological concerns (Perveen, Kishor, and Mohanty 2014). While the ecological impact is beyond the scope of this study, it is possible to transform the potential “obstacle” of offshore renewable energy farms into a useful “pit stop.” At the moment, there is a growing interest in electrifying maritime transport to achieve “cleaner oceans” and decarbonization (Horvath, Fasihi, and Breyer 2018). However, the present state of battery technology significantly limits the mileage of fully electric marine vessels, especially when the design considerations factor in the cost. It is conceivable that charging will somehow be necessary if long-distance freight can materialize with today’s battery technology.

The interests and challenges in offshore power technology (OPT) deployment and in electrifying maritime transport suggest an opportunity for synergistic co-development of the two ideas. For the first time, this study proposes the concept of an offshore marinized charging station (MCS) to evaluate the economics of electrifying maritime transport and to compare them with those of conventional vessels using intermediate fuel oil (IFO) bunker fuels. The idea is to identify the opportunities and challenges associated with electrifying maritime transport with today’s proposed technologies and potential improvements in the economics of shipping when it is possible to improve both costs and technologies in the future.

The study proposes three OPT options, namely offshore wind, offshore solar PV, and FNPP. It is conceivable that a marinized BESS (MBESS) would also be necessary to accommodate the uncertainties and intermittency of the electricity output from offshore renewables. However, there is a lack of reference studies and test-bedding projects on the MCS concept. As such, this study had to make a number of key assumptions on the technical specifications related to charging, which it based on practical considerations in shipping operation. Although it will only be possible to validate the

assumptions several years from now, it is conceivable that they could act as reference or desirable performance indicators for future technologies to meet to achieve full electrification of international shipping.

To accomplish the proposed analyses, Section 2 presents a techno-economic assessment of the assumed MCS concept and the various OPT options. Section 3 provides a cost assessment with the assumed costs and carbon tax. Section 4 presents further discussions on the results from the assessments and potential future success factors for electrifying international shipping. Section 5 summarizes the paper and recommends possible future studies.

2. TECHNO-ECONOMIC ASSESSMENT

Research has commonly used cost-benefit analysis (CBA) to evaluate the cost-effectiveness of a given technology or solution in infrastructure projects. One advantage of CBA is its ability to quantify the results of various scenarios to provide more implications and enable better decision making (Arrow et al. 1996). Studies have also referred to CBA as the net present value (NPV) approach because it discounts future benefits and costs (Arrow et al. 2013).

The NPV approach involves some known issues. For instance, it is not able to consider the irreversibility and uncertainties of investment (Abel et al. 1996), ignored sunk costs (Pindyck 1988, 1991, 2002), and variations in the assumed discount rate (Cochrane 2011). Despite the criticisms, the NPV, such as the levelized cost of electricity (LCOE), very often acts as a benchmark for the cost-effectiveness of alternative power generation technologies, as the IEA's studies have shown (IEA 2010, 2015).

2.1 Electric Vessels

At the moment, there are no long-haul marine vessels in operation. The People's Republic of China (PRC) reportedly launched the world's first fully electric cargo ship in 2017 with a maximum range of 80 km on a single charge (Qiu 2017). Japan established a consortium comprising seven companies to design and develop a fully electric tanker, which it named "e5" (Asahi Tanker 2020). According to the specification that the consortium's e5ship.com website published, the battery capacity of the e5 is 3500 kWh or 3.5 MWh and the vessel houses two 300 kW propulsion engines and two 68 kW bow thrusters with a design speed of 11 knots or 20 km/h (E5 Lab Co.). Theoretically, the e5 could cover 150 km on a single full charge. This is the distance from Nagasaki to Fukuoka in Japan, which is relatively a short distance. If a marinized charging station (MCS) was available between the two ports, it would be possible to travel from Nagasaki (Japan) to Busan (Republic of Korea) with one recharge.

Based on a survey of field data, the capital cost of building an electric vessel is \$700,000, excluding the batteries. The annual operating and maintenance (O&M) cost excluding the fuel cost is an estimated \$18,900 per year. The assumptions are that the lifetime of the e5 will be 30 years, the decommissioning cost will be 7% of the capital cost, with a scrap value of \$105,000, and the on-board MBESS will be the most dominant lithium-iron-phosphate (LFP) technology at \$250/kWh according to expert consultation on MBESSs. The MBESS will require no maintenance, but the study assumed that it will be necessary to replace the batteries completely every 15 years.

2.2 The Marinized Charging Station Proposition

The mileage on a full charge and charging are among the most prominent issues concerning land-based EVs. These issues can amplify when they extend to maritime transport. Achieving long-haul operation for electric vessels requires minimum disruptions on a trip needing one or more charging arrangements en route. Battery swapping and battery charging, the land-based EV charging methods, are so far the only feasible options for consideration (Zheng et al. 2014). Due to the large battery size of vessels, it could take days to charge a vessel fully, even when using the current design approach of state-of-the-art land-based fast chargers.

Land-based slow or fast chargers are of much lower concern than MCSs as land-based EVs can afford to charge overnight, noting the challenge of refueling midway through a long-distance journey. It is inconceivable for commercial tankers to wait at an MCS overnight or even for a few hours to charge. Every hour is critical for cargo deliveries due to the long distance and the running cost. It would be reasonable to assume that the time to recharge the e5 would be no more than an hour. This study selected several charging time options for investigation, namely 60 minutes, 30 minutes, and 10 minutes. As such, the respective charging power requirements are 3.5 MW, 7 MW, and 21 MW.

The reasoning for the e5 potentially being able to accommodate the high charging power demand is as follows. The e5 is much larger than a land-based EV. As such, it has the possibility to accommodate multiple charging points. Also in consideration of size, the distribution of the battery cells in the e5 could cover a much larger area than in a typical land-based EV, which could help to dissipate heat quickly during fast charging, especially with the possible help from the hull of the vessel at the bottom to channel heat from the battery cell into the water. Assuming the possibility of distributing the total charging power over 100 contact points with the battery cells, each contact point would have 35, 70, and 210 kW charging power, respectively, under the assumed charging time options. Compared with the typical fast charging power of a land-based charging station and the size of a land-based EV, the highest assumed charging power of 210 kW would appear to be feasible for a marinized charging station.

2.3 Power Sources

There are three potential technology options for providing the power source for an MCS, namely offshore wind, offshore solar PV, and a floating nuclear power plant (FNPP). These options have the collective name of offshore power technologies (OPTs). It is very likely that the charging station will integrate stationary battery energy storage systems (BESSs) to improve the utilization rate of renewables and/or provide additional power for charging the vessels. Depending on the future design standardization and industry development, the marinized BESS could also adopt a standardized design for battery swapping. It is highly likely that the charging station will use lithium-ion technology, being the preferred BESS technology for both mobile and stationary applications, especially considering the rapidly falling cost of batteries (IRENA 2017).

There is no practical approach for sizing the batteries for such MCSs, but the following major factors will guide the principle of sizing the BESS: the charging power requirement, the frequency of vessel visits, the variability of renewable power sources, and the fixed maintenance schedules of FNPPs.

2.4 Offshore Renewables

According to (Nian, Liu, and Zhong 2019), the economics of offshore wind depend primarily on the wind conditions of offshore locations and the distance to the shore. Depending on the location of the MCS, it is conceivable that the MCS could function as both a charging station, as this study proposes, and as a typical offshore wind or solar farm providing electricity for onshore facilities. Within the scope of this study, the only assumption was that the annual and/or total energy demand for charging the electric vessels primarily determines the size of the wind or solar farm. If there is excess electricity, the study assumed that the facility will sell it to the onshore grid; taking into consideration the frequency of vessel visits and the size of the marinized BESS, the assumption was that no excess electricity would supply onshore facilities.

As of 30 June 2020, the largest reported offshore renewable installations are 588 MWe of offshore wind at 2.65 billion British pounds currently in operation off the coast of Wick in Scotland in the UK (BBC 2019) and a 100 MWe floating solar PV farm at the planning stage off the Dutch coast in the North Sea with a current operating phase providing 8.5 kW (Bellini 2019).

2.5 Offshore Floating Nuclear Power Plant

As of 31 July 2020, Akademik Lomonosov is the only operational floating nuclear power plant (FNPP) in the world. The FNPP has two 35 MWe KLT-40S nuclear reactors with a total of 70 MWe of electricity-generating capacity and an estimated capital cost of 3,314 \$/kWe (Nian and Zhong 2020). The PRC is reportedly building the ACP-50S (Nian 2017) with 50 MWe electricity-generating capacity, but there is no confirmed date for its official launch of the FNPP.

3. COST OF SHIPPING

Based on the review of the present projects, Table 1 shows the peak power of selected OPTs. The study based the availability factor of offshore wind and offshore solar on the data that it obtained from the (IEA 2018). On a theoretical basis, the peak power output of the OPTs is sufficient to meet the assumed maximum power demand for charging an e5 even under the shortest assumed charging time of 10 minutes. However, the only OPT with the possibility of guaranteeing a continuous stable supply of electricity is the FNPP under normal conditions. It is very likely that offshore wind and solar power will have close to zero output when the weather conditions are not favorable. Thus, a BESS would be necessary for offshore wind and solar power but not for an FNPP.

Table 1: Peak Power and Annual Energy Output of Selected Offshore Power Technologies

Options	Offshore Wind	Offshore Solar	FNPP
Peak Power (MWe)	588	100	70
Assumed Availability Factor (%)	35%	20%	90%
Annual Output (GWh)	1,802.81	175.20	551.88

The study assumed the annual operating and maintenance (O&M) cost of 15% for offshore wind, 10% for offshore PV (IEA 2010, 2015), and 15% for an FNPP (Nian and Zhong 2020). It assumed that the uranium cost will be \$130 per tonne of uranium (t/U). Using the same assumptions as the on-board MBESS, the LFP technology for the charging station's MBESS is \$250/kWh with no maintenance cost but with a replacement cycle of 15 years. The study assumed that the decommissioning costs for all the OPTs are 15% of the total capital costs.

By definition, it is possible to express the NPV as

$$TDC = \sum_t (INV_t + O\&M_t + FUEL_t + CO2_TAX_t + DECOM_t) \times (1 + r)^{-t} \quad (1)$$

where INV_t represents investment costs (including both OPT and BESS where applicable), $O\&M_t$ represents the O&M costs, $FUEL_t$ represents the fuel costs, $CO2_TAX_t$ represents the carbon tax, $DECOM_t$ represents the decommissioning costs, all in year t , and r represents the discount rate. In the case of OPT with an MBESS, the study broke down the INV_t component further into INV_OPT_t and INV_MBESS_t to represent the investment costs for the OPT and the MBESS, respectively.

We can express the LCOE as

$$LCOE = \frac{TDC}{\sum_t ELC_t \times (1 + r)^{-t}} \quad (2)$$

where ELC_t represents electricity production in year t .

Similarly, the levelized cost of shipping is

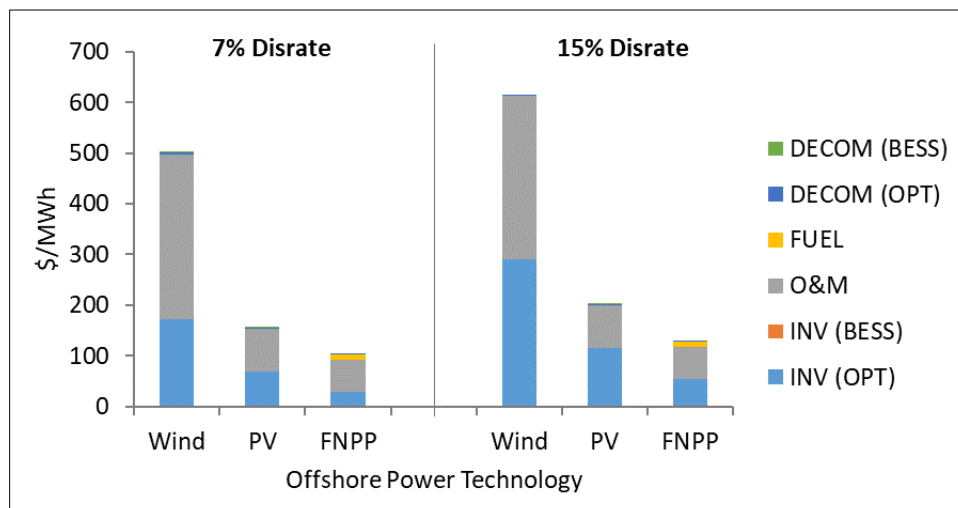
$$LCOS = \frac{TDC}{\sum_t GOODS_t \times (1 + r)^{-t}} \quad (3)$$

where $LCOS$ represents the levelized cost of shipping goods and $GOODS_t$ represents the amount of goods shipped or delivered in year t . The per unit fuel cost is the $LCOE$ for the e5 and the IFO price for a conventional tanker.

3.1 No Carbon Tax

Based on the assumptions for the various cost components, Figure 1 shows the LCOE values (with a breakdown by major cost components) of the selected OPTs in this study. For easy comparison, the LCOE values are 500.88 (wind), 155.85 (PV), and 102.52 (FNPP) \$/MWh under the 7% discount rate and 614.51 (wind), 200.92 (PV), and 127.83 (FNPP) \$/MWh under the 15% discount rate. The study assumed that these LCOE values are the respective fixed electricity cost at a constant 2020 dollar value for the e5 over its lifetime.

Figure 1: Levelized Cost of Electricity Production from Selected Offshore Power Technologies



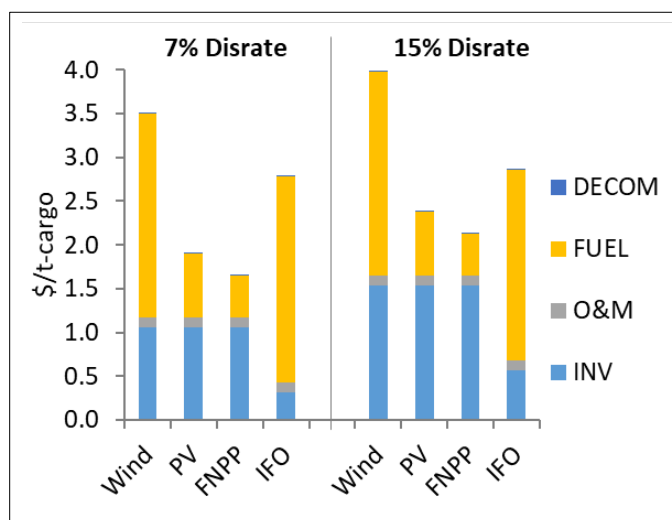
The annual shipment of goods also depends on other factors, such as the waiting time, loading time, maintenance down time, as (Nian and Yuan 2017) described. All such factors are applicable since the assumed e5 is a tanker ship. In effect, the e5 tanker can make a maximum of 106 return trips based on a port-to-port distance of 300 km, taking all those factors into consideration.

The study assumed that the fuel price for the conventional vessel is 250 \$/t in 2020 with an annual rate of increase pegged to that of crude oil (\$60 per barrel in 2020) at \$1.5 per barrel per year until 2050, as the (EIA 2019) showed. The fuel consumption of the conventional vessel when cruising at 10 knots is presumably 5.67 tonnes per trip with the same travel distance as the e5 of 300 km. The study calculated the fuel consumption following the exact formulation that (Nian and Yuan 2017) presented based on the assumed speed. Assuming the same turnaround time as the e5 (without the need for charging in this case), the conventional ship can theoretically make 108 return trips between the two assumed ports with an estimated annual fuel consumption of 1,235.6 tonnes.

Based on all the assumptions, the e5 can deliver a maximum of 159 thousand tonnes of crude oil per year and the conventional vessel can deliver a maximum of 163 thousand tonnes of crude oil per year. The levelized cost of shipping (LCOS) values for the e5 under the different charging options and the conventional vessel running on IFO are 3.51 (wind–e5), 1.90 (PV–e5), 1.65 (FNPP–e5), and 2.79 (IFO ship) under the 7% discount rate and 3.99 (wind–e5), 2.38 (PV–e5), 2.13 (FNPP–e5), and 2.87 (IFO ship) under the 15% discount rate (Figure 2).

With the assumed costs, the shipping cost of e5 appears to be competitive against that of conventional tankers even if a “pit stop” is necessary during a journey. The FNPP has an obvious advantage in providing electricity for the MCS due to its stable availability factor.

Figure 2: Levelized Cost of Shipping Based on Different Fuel Options



3.2 With Carbon Tax

This study assumed two CO₂ tax scenarios, namely the business-as-usual (BAU) and high-tax scenarios. The BAU scenario assumes a fixed carbon tax of \$24.39 per tonne of CO₂ equivalent (\$/t-CO₂e) due to the combustion of fossil fuels. The high-tax scenario assumes that the carbon tax will progressively increase linearly from today's 24.39 \$/t-CO₂e in 2020 to 150 \$/t-CO₂e in 2050.

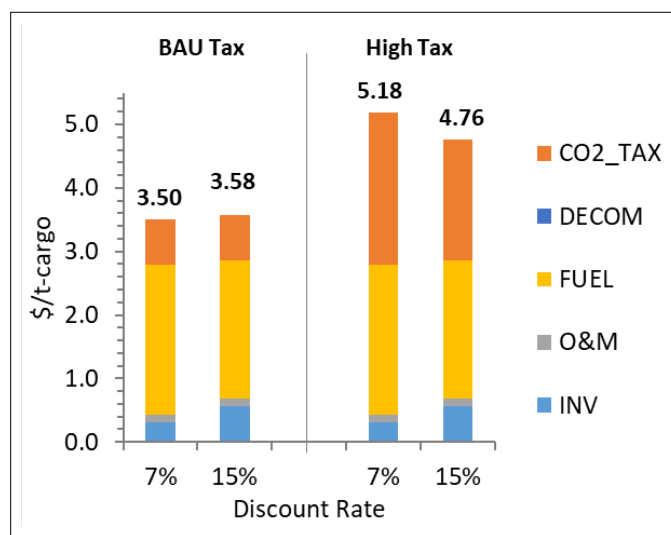
The carbon tax is only applicable to the conventional tanker given the boundary of this study. The greenhouse gas emission factor of the combustion of typical marine IFO is about 3.87 t-CO₂e/t-fuel (IPCC 2014) with the breakdown that Table 2 presents.

Table 2: Greenhouse Gas Emission Factors of Marine Fuel
(Unit: Tonne per Tonne of Fuel)

Greenhouse Gas	Emission Factor	CO ₂ Equivalent
CO ₂	3114	1
CH ₄	0.06	28
N ₂ O	0.15	265
CO	2.77	1.57
NO _x	83	8.5
SO ₂	5	0.44
Total CO ₂ -e		3.87

Based on the annual fuel consumption of 1,235.6 tonnes, as the study estimated earlier, the annual emissions from the conventional tanker amount to 4,778 t-CO₂e/year. Thus, it is possible to compute the carbon tax annually and then the NPV. Figure 3 shows the calculation for the LCOS with carbon tax added to the NPV calculation. With a lower carbon tax, the LCOS increases as the discount rate increases from 7% to 15%. With a higher carbon tax, a higher discount rate would lead to a lower LCOS due to the much higher discounting in later years under the 15% discount rate than under the 7% discount rate.

Figure 3: Levelized Cost of Shipping with Carbon Tax



Although the results are numerically correct, the message from such results could be misleading. Although the carbon tax payment occurs on an annual basis, as the TDC formula assumes, it is incorrect to assume that future years’ carbon tax payments (and the fuel price payment for that matter) can receive a high “discount” since they are many years away. Intuitively, it would not be sensible to assume a lower shipping cost (or price) when the carbon tax is likely to increase drastically due to an assumed higher discount rate. This is precisely the danger of assuming a uniform and fixed discount rate on different price payments in an NPV calculation. Nonetheless, the LCOS values that this calculation obtained are still useful for comparison with the LCOS values without the carbon tax.

Comparing the obtained results in Figure 2 and Figure 3, adding carbon tax would obviously make conventional shipping uncompetitive against marine EVs on an LCOS basis. However, the upfront investment costs of the e5 are many times higher than those of a conventional tanker due to the cost of the MBESS. With potential future reductions in battery costs, it is possible for marine EVs to become commercially competitive against conventional tankers in terms of both upfront costs and long-term running costs.

4. FUTURE PERSPECTIVES

4.1 Cost Reductions

As the NPV calculations showed, marine EVs are already cost competitive against conventional tankers from the perspective of LCOS, despite the high upfront investment cost. While the battery cost might arguably reduce to 100 \$/kWh, the upfront cost of marine EVs would still be higher than that of conventional tankers (near doubling in this paper’s comparison of the e5 with a comparable sized tanker). However, the significant cost reductions in battery prices would not have a strong influence on the LCOE values of the MCSs. Significant reductions in the LCOE values of the OPT can only derive from a significant reduction in the capital cost of offshore wind and solar and FNPP technologies.

4.2 Economies of Scale

The economies of scale are known for conventional tankers. The same kind of economies of scale could be applicable to marine EVs in terms of the cargo volume. Based on our current analysis, a doubling of the cargo space in the e5 would not lead to a doubling of the battery and/or engine sizes. As such, the LCOS value could reduce further when scaling the e5 up to a larger vessel. However, there would be challenges with the MCSs to charge a larger battery fully within an hour.

4.3 Opportunities and Future Challenges

An MCS, as this study proposes, can be co-located with an offshore wind or solar farm. Direct integration and integration through an additional offshore structure connected with an FNPP are both possible solutions for an FNPP-powered MCS. When no marine EVs are charging, the OPT can sell the electricity that it produces to the onshore grid as an offshore energy resource. In such a way, the MCS concept introduces a new element of consideration when co-optimizing the performance of offshore energy resources and the decarbonization of both the onshore electricity industry and the maritime industry.

Safety and reliability pose major technological challenges to the proposed MCS. Although these challenges are potential barriers even for a test-bedding project, it is conceivable that such challenges also represent opportunities for the development of new technological solutions for a cleaner maritime transport environment. Since the charging power requirement of the proposed MCS is many times higher than that of a land-based charging station, the proposition is to maximize the use of industrial automation and minimize human interference to improve the safety of the charging operation and reduce the possibility of human errors. In turn, the increasing industrial automation would allow the development of advanced technologies, such as artificial intelligence and smart sensing, for the operation of a future autonomous vessel. With a sufficient number of MCSs deployed around the world along major shipping routes, the induced competition could allow further opportunities for potential new business models to emerge to improve the cost-efficiency of international shipping.

4.4 Strategic Considerations

In addition to charging ocean liners, MCSs could charge unmanned autonomous vehicles (UAVs) or underwater electric vessels for scientific and strategic applications. Marinized charging stations can transform into intermediate substations for remote communication with UAVs for underwater surveillance. With the proposed future ability to charge UAVs autonomously, MCSs could significantly extend the servicing hours of UAVs per mission.

5. CONCLUSION

Electrifying maritime transport is a sensible approach that international shipbuilding and shipping companies could and should quickly pursue in partnership with offshore renewable builders. Even with today's battery and floating nuclear power plant technologies and costs and the absence of carbon tax, the average shipping cost of fully electric tankers is already competitive with that of conventional tankers. With future improvements in costs and technologies and economies of scale, the cost of fully

electric shipping could fall significantly in the future. Such a discovery can provide important insights for the maritime industry and the regulator in a timely manner.

Marinized charging stations can radically change the current business thinking for ocean liners and ports as there may no longer be a need for refueling at ports with a sufficiently large number of such charging stations distributed optimally across the shipping routes. With the ability of marinized charging stations to supply electricity to non-commercial vessels, the design considerations could factor in the benefits from both commercial and strategic use to enable greater scope of applications and potential profitability of marinized charging stations. This study recommends in-depth research on an ecosystem of electrifying international shipping, taking into consideration the vessel size, fleet management, locations of charging stations, and relevant other variables, as a future research direction.

Marinized charging stations can potentially induce new waves of technological innovations in smart sensing and artificial intelligence to ensure the safe, reliable, secure, and efficient operation of marinized charging stations autonomously. There will be implications for the regulators to ensure that such applications have justifiable purposes and do not pose undesirable consequences, especially safety threats to commercial international shipping. The study recommends research on future developments in maritime regulations to facilitate the safe and sustainable adoption of the offshore charging concept as a second future research direction.

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