A Bilevel Hybrid Economic Approach for Optimal Deployment of Onshore Power Supply in Maritime Ports

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Abstract

Onshore power supply (OPS) is an effective measure to curb at-berth emissions by allowing berthed ships to switch off their auxiliary engines and plug into the shore-side electric grid for their power demand. Despite OPS's proven benefits in reducing emissions, port entities are often reluctant to adopt OPS technology due to the expensive electrical infrastructure retrofitting process. Hence, regulatory subsidies often play a key role in the promotion of OPS. This paper proposes a novel bilevel hybrid economic approach to jointly aid both the regulatory agency and the port entity to holistically increase OPS uptake. In the proposed model, the regulatory authority on the upper level acts first and develops the optimal hybrid incentive policy to minimize the negative environmental impacts caused by ships at berth. The port entity on the lower level then decides the most financially favorable and economically viable investment decisions regarding the selection and installation of OPS. The problem is formulated as a mixed-integer bilevel programming model and solved using a column and constraint generation method. The simulation-based case study shows the environmental and economic strength of the proposed hybrid economic approach compared to the conventional regulatory and market-based approaches.

Keywords: Maritime transportation, Transportation Electrification, Onshore power supply, Port energy system, Bilevel programming

1. Introduction

Maritime shipping is considered the most fuel-efficient transportation mode and moves 90% of cross-border world trade as measured by volume [1], [2]. Despite its critical role in advancing global productivity and prosperity, maritime transportation is also faced with constant critiques of its negative environmental impacts. Studies conducted by the International Maritime Organization indicate that maritime shipping accounts for roughly 2.2%, 15%, and 5-8% of the global carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x) emissions, respectively [3], [4]. In view of the expected growth of the maritime sector, emissions from shipping industry are anticipated to increase by 50% to 250% by 2050 [5]. It has become a consensus in the maritime industry that systematic measures must be taken to reduce the environmental impacts of the ships. The reduction of emissions in harbor cities and other densely populated areas with ports located nearby is of particular importance due to the proximity to human habitation [6], [7].

When a ship is at berth, it no longer requires energy from the main propulsion engines. However, its auxiliary engine(s) remains on to supply the vessel's energy demand for in-port activities such as the cargo handling system, lighting, heating/cooling system, and the control system. These operations consume a large amount of diesel fuel and heavy oil, generating a series of harmful environmental impacts, including exhaust fumes, noise, vibrations, and air emissions to the port workers, onboard personnel, and the port area communities and residents [8], [9]. Ship emissions could often be one of the most significant sources of urban pollution. Specifically, air emissions can cause health problems such as lung diseases and birth defects. The particulate matter (PM) emissions from ships near the coastlines and ports are also reportedly linked to increased cardiovascular hospitalization and cancer rates in and surrounding the port area [7].

An effective and emission-free solution to address the aforementioned issues is to connect vessels at berth to the shore electrical supply [4], [10]-[12]. This practice is also known as cold ironing. It is evident that with OPS enabled, the ship can completely shut down its auxiliary diesel-burning engine (i.e., cold ironed) and utilize electricity to support its energy demand during berth. While the potential benefits of OPS are dependent on regional characteristics, grid conditions, and traffic patterns at ports, a previous study has shown that in the UK, implementing OPS would result in a promising 25%, 46%, 76%, and 92% reduction in emissions of CO_2, SO_2, CO, and NO_x, respectively, when compared with using auxiliary engines [7]. Another study [14] confirmed that for container terminals in the US/UK, adopting OPS would lead to a decrease in the emissions of CO_2, SO_2, and NO_x by 48–70%, 3–60%, and 40–60%, respectively, compared to using heavy fuel oil and marine diesel oil. The use of OPS can also eliminate the noise and small particle pollution in

Nomenclature

Indices		**Parameters**	
j	Index for vessel type, $j=1,2,\ldots,h$	m	Total number of berths
i	Index for vessel, $i=1,2,\ldots,l_j$	t_{ji}	Processing time for vessel i with vessel type j, hour
s	Index for the type of OPS installation, $s=1,2,\ldots,k$	p_{ji}	Power demand for vessel i with vessel type j, kWh
Variables		A_s	Capacity of the OPS installation s, kw
e_c	Emission cap assigned to the port, kg	γ	Average utilization ratio of each berth
y	Auxiliary variable	f_{aux}	Emission factor of a vessels' auxiliary machinery, kg/kWh
N_{js}	The number of OPS installation of type s to serve vessel type j	e	Initial emission level of the port, kg
F_j^{aux}	Time duration of using the auxiliary machinery for vessel type j, hour	ε_1	Fixed cost for an OPS installation, $
EM_{ji}	Emission from vessel i of type j, kg	ε_2	Linear capacity-dependent cost for an OPS installation, $/kW
PO_{ji}	Power consumption for vessel i of type j, kW	ω_1	Rate for the usage-based operation and maintenance subsidy per unit of energy, $/kWh
PS	Port's annual electricity consumption, MWh	ω_2	Rate for the OPS operation and maintenance cost per unit of energy, $/kWh
PA_{jis}	Power consumption of vessel i of type j supplied by capacity s OPS , kW	Y	Lifetime of an OPS installation, year
e_t	Achieved port emission following OPS deployment, kg	ρ	Emission reduction target for the port
λ_τ	Binary variable for determining the port's decision about receiving subsidy	α	Weight coefficients
λ_μ	Binary variable for determining the port's decision about paying emission tax	σ	Installation subsidy ratio
c_1	Cost of OPS installations for the port, $	τ	Subsidy rate, $/kg
c_2	Installation subsidy received by the port from the regulator, $	μ	Tax rate for emission, $/kg
c_3	Emission tax paid by the port to the regulator, $	B	Regulator budget, $
c_4	Emission subsidy received by the port from the regulator, $	β	Emission cap upper bound for the port, kg
c_5	Usage-based operation and maintenance subsidy received by the port from the regulator, $	Q	Total hours in one year, hour
c_6	Usage-based OPS operation and maintenance cost incurred by the port, $	M	A very large number

the port vicinity.

Despite the apparent benefits, investment in infrastructure is required on both the ship and the port/terminal to enable cold ironing [15]. While the ship can be retrofitted at a lower cost, according to the newly developed technical standards, such as IEC/ISO/IEEE 80005-1 for High Voltage Shore Connections (HVSC) [16] and IEC/IEEE 80005-3 for Low Voltage Shore Connections (LVSC) [17], a significant retrofitting investment is required on the port side to provide the appropriate electric infrastructure and an associated energy management system for shore-side connections and to meet the requirement of onboard activities. Commonly the shore-side infrastructure includes a substation to receive power from the local distribution grid at a higher voltage level, e.g., 34.5 kilovolts (kV), one or more transformers and frequency converters to convert the magnitude and frequency of the voltage to be compatible with the vessel's electrical specification, e.g., 6.6/11 kV and 50/60Hz, as well as the cables management system. The detailed list of equipment to provide OPS services to vessels includes switchgear, circuit breakers, shore-to-ship cables, plugs, receptacles, converters, safety interlocks, and other power and communication equipment. It is reported in [18] and [19] that the average cost of building one OPS can lead up to approximately two to five million dollars in the US. The maintenance of OPS can also be financially unfavorable for the port. For instance, the Environ study [18] pointed out that the recurring cost of operations and maintenance (O&M) for shore-side infrastructure can be as high as 12% of the total capital investment annually. Despite the significant cost, the proper selection of the OPS is another major technical challenge for the port operators. As the OPS facility needs to be compatible with the power demands of different sizes/types of berthed ships, the complex arriving patterns of ships have to be carefully predicted and taken into account to optimize the locations and capacities of OPS installations. Due to the aforementioned economical and technical barriers, ports are reluctant to initiate the wide deployment of OPS. In fact, according to [14], there are only 35 ports in the world with OPS installed at a small number of berths.

In light of the aforementioned technical and cost-related issues, government involvement becomes necessary to promote the deployment of OPS. According to [20] and [21], policymakers have three board types of instruments available to promote emission reductions in the ports' energy activities: i) regulatory approach (i.e., command-and-control), ii) economic incentive (i.e., market-based policies), and iii) hybrid approaches (a combination of regulatory and economic incentive). The regulatory approach refers to the traditional design standards and requirements that mandate specific products, technologies, or processes that polluters must adopt to reduce their emission. The economic incentive provides inducements to create an incentive for emission reduction. Market-based approaches include emission taxes, fees, and subsidies to make emission reduction financially attractive for pollution entities. Hybrid approaches combine the certainty in mitigating the emission associated with emission standards with the flexibility of allowing polluters to pursue the most financially favorable emission control strategy. Hybrid approaches, as a "safety-valve," are becoming more appealing to policymakers. However, the design of such policies is not straightforward. Various key factors, such as the specific nature of the environmental impact, regulation attractiveness, and cost-benefit aspects, have to be collectively taken into consideration to form a coherent and mutually beneficial solution.

In practice, numerous previous and on-going efforts have been made by governments and regulators/policymakers to interact with ports under their administration and promote the adoption of OPS in order to reduce port emissions [21]. For instance, the government of China has been demanding local governments to support the construction of port OPS through subsidies, discounted electricity rates, and special investment funds since 2016 [22], [23]. It mandates a 50% baseline coverage of OPS on existing berths at the major ports by the end of 2020 [22]. In the European Union, a directive [25] mandates that ~~from~~ by the end of 2025, OPS facilities should be installed in EU ports, unless there is no demand and the costs overweigh the benefits, including environmental benefits. To meet this stringent requirement, countries such as Germany, Sweden, and Norway are adopting policies, such as financial subsidies, tax exemptions, and tax cuts, to help ports carry out necessary infrastructure expansion for OPS [26]. In the United States, California's at-berth regulation policy [27] requires that the coverage of shore power in California ports be increased from 50% to more than 80% from 2014 to 2020. Financial subsidies, such as grants, have been awarded to port entities such as Port of Los Angeles ($23.73 million from the state of California to develop OPS at 10 berths) , Port of Seattle ($1.4 million EPA grant to install OPS at the Tote terminal), Port of San Diego ($2.4 million for OPS at the cruise ship terminal), Port of Long Beach ($30 million from the state of California to develop OPS at 12 berths) to promote OPS deployment [28]. It is evident that most of the existing regulations and financial policies regarding OPS are highly *ad-hoc*. A systematic framework is yet to be developed to enable cross-sector analysis, adoption of standardized design factors, and co-operation of regulators and port entities as separate stakeholders involved in the design, operation, and management of the OPS system [29].

To address some of the issues highlighted above, we propose a novel hybrid economic approach to jointly aid the regulatory agencies and port entities to holistically increase the uptake of OPS in this paper. More specifically, the proposed approach helps the regulatory authority develop a hybrid incentive policy to minimize the negative environmental impacts caused by ships at berth through emission taxes and subsidies. It also helps the port entity decide the most financially favorable and economically viable investment decisions regarding the selection and installation of OPS based on information of the upcoming berthed vessels in the planning horizon. We formulate this problem as a multi-objective bilevel programming model to capture the hierarchical interactions between the regulatory agencies and port entities in the OPS deployment.

The contributions of this paper can be summarized as follows:

- This paper proposes a hybrid economic approach to seek the synergies between the regulatory agency and port entity in the adoption and deployment of OPS to collectively reduce the at-berth emissions. To the best of our knowledge, this paper is the first of its kind.
- This paper develops a novel bilevel programming model to capture the decision-making hierarchy of different stakeholders involved in the decision-making process of OPS deployment. The proposed model empowers each stakeholder to maximize its own point of interest while taking into account their hierarchical interactions.
- This paper conducts a comprehensive and quantitative analysis of both parties' behaviors under the proposed framework. For the first time, our results reveal the environmental and economic advantages of the hybrid economic approach in simulating the electrification and decarbonation of the maritime transportation system compared to other conventional policies.

The remainder of this paper is organized as follows. Section II presents the outlines, key structures, and optimization model involved in the proposed problem. Section III discusses the solution methodology to solve the formulated mixed-integer bilevel programming model. Simulation-based case studies are carried out in Section IV with the conclusions drawn in Section V.

2. Modeling methodology

2.1 Problem Description and Assumptions

The proposed problem involves two types of players acting sequentially on two levels: the regulator and the port entity. On the regulator's level: The goal of the regulatory agency is to reduce at-berth emission via a hybrid incentive strategy where an emission cap is set for the port. In this paper, we consider that three categories of subsidies are granted by the regulatory agency: 1) a fixed subsidy which is a one-time equipment investment subsidy, 2) a variable subsidy which is based on OPS usage, and 3) an emission subsidy if the port can reduce its emission level below the emission cap set by the regulator. The fixed subsidy can be used towards upgrading the infrastructure and the construction of OPS to ease the required large capital investment. The variable subsidy is in the form of a rebate to help the port entity mitigate the operation and maintenance cost incurred by the usage of OPS. For the emission subsidy, the regulator adopts a combination of the emission tax and subsidy instruments. More specifically, if the

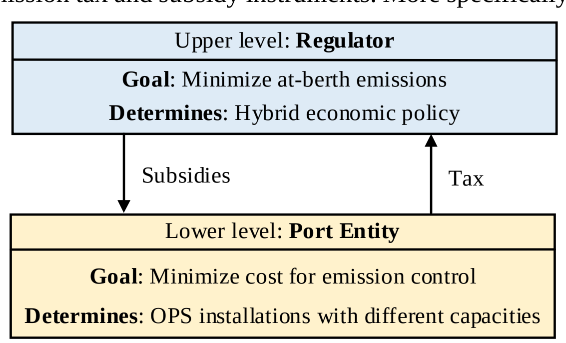

Fig. 1. Structure of the proposed bilevel hybrid economic approach

port deploys a sufficient number of OPS installations to bring its emission down below the emission cap, it receives an emission subsidy from the regulator. Otherwise, the port has to pay an emission tax. The goal of the regulator is then to decide the overall economic policy to minimize the emission, subject to a pre-specified budget constraint. While different organizations can play the managing role described previously in practice, this paper considers the role of an aggregated regulatory agency that oversees the port operations and makes uniform management decisions.

On the port entity level: As a profit-driven organization, a port entity needs to justify the pursuit of emission-reduction efforts, such as OPS installation decisions and the associated investment costs in terms of economic means, such as payback and return on investment to their stakeholders. We assume that the port reacts to the hybrid incentive policy made by the regulator and determines the quantity and capacity of OPS to be installed based on the emission caps. The goal of the port is to minimize the cost of emission control, including the annualized cost of the installation and operation of OPS as well as the amount of taxes and subsidies paid or received from the regulator, based on the representative load profile that provides the anticipated frequency of vessel visits, the vessel types and their power demand. Meanwhile, the port entity also aims to minimize its operation cost once the OPS facility is installed.

This hierarchical nature of the interactions can be naturally modeled by a bilevel programming approach, as shown in Fig. 1. In the decision-making process, the regulator acts first. The port, as the follower, reacts to the regulator's decision based on its best interest. Note that we consider information transparency in the paper, which suggests both players have knowledge about each other's decision-making process.

Several key assumptions are adopted in this paper. We assume that a berthed vessel can use OPS and its auxiliary engine simultaneously. Specifically, if the OPS capacity installed at the berth can meet the power demand of the vessel, only OPS is used. Meanwhile, if the installed OPS capacity is less than the vessel's power demand, it would use its onboard auxiliary engine to make up the difference. We also assume that each OPS facility comes with a different capacity, and the pricing of OPS with each capacity is different. Similarly, vessels served at the port can be classified into different types as well, based on their deadweight tonnage (DWT). For instance, oil/LNG tankers are classified as large vessels, while container ships and bulk carriers are classified as medium/small vessels.

2.2 Mathematical Formulation

First, we introduce the modeling strategy for the port entity. In the absence of OPS stations, vessels need to keep auxiliary engines running at berth and use marine diesel fuel to generate electricity to meet their energy demand. Hence, the total emission generated by a vessel can be calculated based on its processing time (i.e., at-berth time, t_{ji}), its power demand during berth (i.e., p_{ji}), and an emission factor (i.e., f_{aux}) for the diesel fuel consumed by the auxiliary engine. The total annual emission of a port is then the summation of the emission from all vessels anticipated to be served within a year:

$$e = \sum_{j=1}^{h} \sum_{i}^{l_j} p_{ji} t_{ji} f_{aux} \tag{1}$$

Following the deployment of OPS, the power demand of vessels at berth is satisfied through the OPS installations and the vessels' auxiliary engines (if the OPS capacity is insufficient). Suppose we have *k* types of OPS installation options based on the capacity, and the port invests in deploying N_{js} OPS installations of type *s* to serve vessel type *j*. Then, the total annual service hours to provide for vessel type *j* by OPS while at berth is:

$$\sum_{s=1}^{k} N_{js} \gamma Q \tag{2}$$

where γ is the average berth utilization rate. Note that with the consideration that within one year, the berth/OPS may not remain operable all the time, we use the berth utilization rate to define the service hours each OPS could yield annually. In this way, the total hours that vessels type *j* use their auxiliary engines while at berth during a year is:

$$F_j^{aux} = \sum_{i=1}^{l_j} t_{ji} - \sum_{s=1}^{k} N_{js} \gamma Q, \ j = 1, 2, ..., h \tag{3}$$

After calculating the average of terms provided in (2) and (3) for every vessel type *j*, the annual OPS usage, measured by hours, for vessel *i* can be calculated as $t_{ji} \sum_{s=1}^{k} N_{js} \gamma Q / \sum_{i=1}^{l_j} t_{ji}$, and the annual hours for a vessel to use its auxiliary engine can be calculated as $t_{ji} F_j^{aux} / \sum_{i=1}^{l_j} t_{ji}$. Therefore, the annual amount of emission for the vessel *i* of type *j* is determined by (4):

$$EM_{ji} = \frac{\left(\sum_{s=1}^{k} N_{js} \gamma Q t_{ji} (p_{ji} - A_s)^+ + F_j^{aux} p_{ji} t_{ji} \right) f_{aux}}{\sum_{i=1}^{l_j} t_{ji}} \tag{4}$$

Then, the total annual amount of emission for the port as the summation of emission from all vessels can be derived as:

$$e_t = \sum_{j=1}^{h} \sum_{i=1}^{l_j} EM_{ji} \tag{5}$$

Note that in (4), $(p_{ji} - A_s)^+$ equals 0 if $A_S \geq p_{ji}$. This ensures that the vessel only uses OPS if the OPS capacity, i.e., A_s, is sufficient for providing the vessel's power demand, i.e., p_{ji}. Hence, the vessel produces no emission. Otherwise, $(p_{ji} - A_s)^+$ equals $p_{ji} - A_s$ as the vessel needs to turn on its auxiliary engine.

Suppose the installation cost of a type *s* OPS with capacity A_s includes a baseline set-up cost of ε_1 and a capacity-dependent cost of $A_s \varepsilon_2$; thus, the overall installation cost of OPS for the port entity can be calculated as:

$$A_s \varepsilon_2 + \varepsilon_1 \tag{6}$$

Assuming that the service life of an OPS installation is *Y*, equation (7) determines the total annualized cost of OPS installation for the port:

$$c_1 = \sum_{j=1}^{h} \sum_{s=1}^{k} N_{js} (A_s \varepsilon_2 + \varepsilon_1) / Y \tag{7}$$

Note that in (7), the effect of depreciation is not considered for the sake of simplicity. Assuming a subsidy rate of σ, the fixed installation subsidy the port would receive from the regulator for the purchase and build-up of OPS can be represented as c_2 and is described by (8):

$$c_2 = c_1 \sigma \tag{8}$$

If the achieved port emission level, i.e., e_t, is higher than the regulator-assigned emission cap, i.e., e_c, an emission tax will be applied to the port. We denote such emission tax as c_3 and calculate it as a linear function of the gap between the achieved port emission level and its assigned emission cap:

$$c_3 = \lambda_\mu \mu(e_t - e_c) \tag{9}$$

Meanwhile, if the achieved port emission level is lower than the emission cap, an emission subsidy will be rewarded to the port, which is shown by c_4. Similar to the emission tax, the value of the emission subsidy is determined by a linear function of the gap between the port's emission level and its emission cap:

$$c_4 = \lambda_\tau \tau(e_c - e_t) \tag{10}$$

Note that (9) and (10) contain the products of binary variables λ_τ, λ_μ and continuous variables e_t, e_c, which can be linearized by introducing a set of new continuous variables and auxiliary constraints as described in [30].

The power demand for vessel i of type j can be determined based on the different power demands of the vessels (i.e., p_{ji}) as well as the capacity of each OPS installation A_s in the form of:

$$PA_{jis} = p_{ji}, if\ A_S \geq p_{ji} \tag{11a}$$

$$PA_{jis} = A_s, if\ A_S < p_{ji} \tag{11b}$$

Therefore, the annual electricity consumption for vessel i of type j can be derived by (12):

$$PO_{ji} = t_{ji} \frac{\sum_{s=1}^{k} N_{js} \gamma Q PA_{jis}}{\sum_{i=1}^{l_j} t_{ji}} \tag{12}$$

The annual electricity consumption of the port through the use of OPS, denoted by PS, can be calculated as the summation of electricity consumption of all vessels by using OPS:

$$PS = \sum_{j=1}^{h} \sum_{i=1}^{l_j} PO_{ji} 1e^{-3} \tag{13}$$

Knowing the annual amount of electricity consumption of the port, the OPS usage-based variable subsidy the port would receive from the regulator to compensate the operation and maintenance of the OPS facility can be determined as:

$$c_5 = \omega_1 PS \tag{14}$$

where ω_1 denotes the rate for the usage-based OPS subsidy per unit of energy consumption. Meanwhile, the annual usage-based OPS operation and maintenance cost for the port can be determined in a similar way as shown in (15):

$$c_6 = \omega_2 PS \tag{15}$$

where ω_2 denotes the rate for the usage-based OPS cost incurred by the port per unit of energy consumption.

Based on the above formulations, the bilevel model of the proposed hierarchy can be formulated as follows:

$$\min \ \alpha_1 \frac{e_t}{e} + \alpha_2 \frac{|e_c - e(1-\rho)|}{e} \tag{16}$$

$$s.t.\ c_2 + c_4 + c_5 \leq B \tag{17}$$

$$0 \leq e_c \leq \beta \tag{18}$$

$$\min \ c_1 + c_3 + c_6 - c_2 - c_4 - c_5 \tag{19}$$

$$s.t.\ -M\lambda_\mu \leq e_c - e_t \leq M\lambda_\tau \tag{20}$$

$$\lambda_\mu + \lambda_\tau = 1 \tag{21}$$

$$\sum_{j=1}^{h} \sum_{s=1}^{k} N_{js} \leq m \tag{22}$$

$$\sum_{s=1}^{k} N_{js} \gamma Q \leq \sum_{i=1}^{l_j} t_{ji},\ j = 1, 2, ..., h \tag{23}$$

$$N_{js} \in Z^+, \lambda_\mu, \lambda_\tau \in \{0,1\} \tag{24}$$

Equations (16) – (18) define the model for the regulator on the upper-level. Equation (16) represents the goal of the regulator, which contains two terms: 1) the emission level of the port e_t and 2) the gap between the assigned emission cap e_c and the emission reduction target $e(1-\rho)$. While minimizing the emission level in the port region reflects the direct social welfare benefits of deploying OPS, the second term of equation (16) embodies the flexibility of the proposed hybrid economic approach: while the regulator is encouraging the port to meet the emission reduction target, it is considered in the decision-making process as a preference so that other factors can be taken into account. In other words, the regulator can choose to set up a more economically efficient emission cap which may be different than the emission reduction target. In addition, equation (17) ensures that the total subsidy given out by the regulator does not exceed its budget. Meanwhile, the emission cap should always be positive and subject to an upper bound, as shown in (18).

In the port entity model on the lower-level (equations (19) – (24)), the goal is to minimize the annualized cost for the port from OPS installation and operation (19). This goal contains six terms: 1) the annualized installation cost of c_1, 2) the emission tax of c_3, 3) the operation and maintenance cost of c_6, 4) the installation subsidy of c_2, 5) the emission subsidy of c_4, and 6) the usage-based operation and maintenance subsidy of c_5. Equation (20) decides whether the port pays emission tax or receives subsidies according to its emission level and the emission cap. Equation (21) ensures that the port either pays taxes or receives subsidies. Equation (22) states that the total number of installed OPS stations should be less than the number of berths. Equation (23) indicates that the total service capacity of OPS installed for each type of vessel does not exceed the total berth time for economic considerations. Finally, Equation (24) denotes the constraints for decision variables N_{js}, λ_μ, and λ_τ.

To deal with the absolute term $|e_c - e(1-\rho)|$ in (16), we introduce a variable y ($y \geq 0$), such that (16) can be replaced by (25) with two new sets of constraints as shown in (26) and (27):

$$\min \ \alpha_1 \frac{e_t}{e} + \alpha_2 \frac{y}{e} \tag{25}$$

$$e_c - e(1-\rho) \leq y \tag{26}$$

$$e_c - e(1-\rho) \geq -y \tag{27}$$

It is evident that the proposed problem is formulated as a bilevel mixed integer programming (BiMIP) model with a mixed-integer programming (MIP) model in the lower-level.

3. Solution Methodology

Bilevel programming models are in general computationally very difficult to solve (i.e., a class of non-deterministic polynomial-time (NP)-hard problem). When the lower-level model is convex, the most common solution approach is to transform the bilevel model into a single-level optimization model based on the Karush-Kuhn-Tucker (KKT) conditions [30][31].

However, as the proposed BiMIP model has a mixed integer lower-level problem, we adopt and modify a computationally efficient column and constraint generation algorithm (CCG) [32] to reformulate and solve the BiMIP model. The CCG algorithm is shown to converge in finite iterations by a decomposition scheme as described in [32].

For notation brevity, we recast the BiMIP into the following abstract model formulation:

$$\text{BiMIP: } \Delta^* = \min_{e_c \in \Theta} \alpha_1 \frac{e_t}{e} + \alpha_2 \frac{y}{e} \tag{28}$$

$$s.t. \quad \begin{aligned} e_t \in F(e_c) \equiv \arg\min\{c_1 + c_3 + c_6 - c_2 - c_4 - c_5 : \\ \boldsymbol{K}e_t + \boldsymbol{P}N_{js} + \boldsymbol{A}c + \boldsymbol{V}x \le \boldsymbol{R}\} \end{aligned} \tag{29}$$

where $\Theta = \{e_c \mid e_c \le \beta, -y \le e_c - e(1-\rho) \le y\}$.

The inequality $\boldsymbol{K}e_t + \boldsymbol{P}N_{js} + \boldsymbol{A}c + \boldsymbol{V}x \le \boldsymbol{R}$ represents the constraints of the lower-level model (equations (20)-(24)) in which $\boldsymbol{K}$, $\boldsymbol{P}$, $\boldsymbol{A}$, and $\boldsymbol{V}$ are the coefficient matrices, and $\boldsymbol{R}$ refers to the right-hand side vector. Variable x represents the rest of the lower-level model decision variables, and c_1-c_6 are denoted together as c.

To solve the proposed BiMIP, the model is transformed into a single-level model. The first step is to reformulate the BiMIP shown in equations (28) - (29) into an equivalent, yet easier to solve, model BiMIP$_d$. The BiMIP$_d$ comprises the upper-level problem, the decision variables and constraints of the lower-level problem, and an additional constraint to embrace the optimal decision of the lower-level model (equation (32)).

$$\text{BiMIP}_d\text{: } \Delta^* = \min_{e_c \in \Theta} \alpha_1 \frac{e_t^0}{e} + \alpha_2 \frac{y}{e} \tag{30}$$

$$s.t. \quad \boldsymbol{K}e_t^0 + \boldsymbol{P}N_{js}^0 + \boldsymbol{A}c^0 + \boldsymbol{V}x^0 \le \boldsymbol{R} \tag{31}$$

$$\begin{aligned} c_1^0 + c_3^0 + c_6^0 - c_2^0 - c_4^0 - c_5^0 \le \min\{c_1 + c_3 + c_6 - c_2 - c_4 - c_5 : \\ \boldsymbol{K}e_t + \boldsymbol{P}N_{js} + \boldsymbol{A}c + \boldsymbol{V}x \le \boldsymbol{R}\} \end{aligned} \tag{32}$$

Equations (31) and (32) ensure that $(e_t^0, N_{js}^0, c^0, x^0)$ is the optimal solution of the lower-level model for any e_c. Hence, the equivalence between BiMIP$_d$ and BiMIP is straightforward.

If we assume that for any given upper-level variables and lower-level integer variables that the remaining lower-level problem has a finite optimal value, this assumption is called a *relatively complete response*. For those combinations of variables in which this property might not hold, we can introduce additional variables r_g ($r_g \ge 0$) with a big-M penalty coefficient for constraint violations. The addition of the big-M penalty coefficient and the new variables leads to an extended formulation of the BiMIP$_d$, which has the relatively complete response property and has the same optimal solution as the optimal solution of the original problem [32].

$$\begin{aligned} c_1^0 + c_3^0 + c_6^0 - c_2^0 - c_4^0 - c_5^0 \le \min\{c_1 + c_3 + c_6 - c_2 - c_4 - c_5 + M\sum_g r_g : \\ \boldsymbol{K}e_t + \boldsymbol{P}N_{js} + \boldsymbol{A}c + \boldsymbol{V}x + \boldsymbol{I}r_g \le \boldsymbol{R}\} \end{aligned} \tag{33}$$

Afterwards, Algorithm 1 is implemented to solve BiMIP$_d$ and obtain the optimal solution. Algorithm 1 involves solving three optimization problems: 1) a master problem that initially contains the upper-level model and the constraints of the lower-level model; 2) the first subproblem which is the lower-level model; and 3) the second subproblem which contains a subset of the upper-level objective function and a set of modified lower-level constraints. As shown in Step 1 of the algorithm, the lower bound (LB) and the upper bound (UB) of the objective function are first initialized to $-\infty$ and $+\infty$, respectively. In Step 2, the LB is updated based on the solution from the master problem, LB= $\underline{\Delta}^*$. In Step 4, we solve the first and second subproblems based on the optimal decision of the regulatory agency about the emission cap (i.e., e_c^*). The outputs of the second subproblem are used to update the UB. In Step 5, new variables and constraints in the form of the KKT conditions of the linear portion of the lower-level model are added to the master problem. More specifically, the primal feasibility, dual feasibility, complementary slackness, and stationarity constraints of KKT conditions are shown in equations (36)-(39), respectively. The master problem is then solved based on the newly added information, and the algorithm converges when the gap between the lower and upper bounds becomes less than a pre-set convergence criterion as shown in Step 3.

$$\min_{e_c \in \Theta} \alpha_1 \frac{e_t^0}{e} + \alpha_2 \frac{y}{e} \tag{34}$$

$$s.t. \quad \begin{aligned} & c_1^0 + c_3^0 + c_6^0 - c_2^0 - c_4^0 - c_5^0 \le \\ & c_1^u + c_3^u + c_6^u - c_2^u - c_4^u - c_5^u + M\sum_g r_g^u, 1 < u < n \end{aligned} \tag{35}$$

$$\boldsymbol{K}e_t^u + \boldsymbol{P}N_{js}^u + \boldsymbol{A}c^u + \boldsymbol{V}x^u + \boldsymbol{I}r_g^u \le \boldsymbol{R}, 1 < u < n \tag{36}$$

$$\boldsymbol{I}^t \pi^u \le M, 1 < u < n \tag{37}$$

$$r_g^u \left(\boldsymbol{I}^t \pi^u - M\right) = 0, 1 < u < n \tag{38}$$

$$\pi^u \left(\boldsymbol{K}e_t^u + \boldsymbol{P}N_{js}^u + \boldsymbol{A}c^u + \boldsymbol{V}x^u + \boldsymbol{I}r_g^u - \boldsymbol{R}\right) = 0, 1 < u < n \tag{39}$$

To address the nonlinearity arises from the complementary slackness conditions of the added KKT conditions (38)-(39), we linearize those nonlinear equations by introducing a set of binary variables and new constraints [30]. With all the constraints linearized, the master problem and the two subproblems can be solved using a MIP solver.

4. Numerical Experiments

In this section, we evaluate the performance of the proposed approach in reducing emission and designing efficient economic policies through a set of simulation-based case studies. We consider a terminal with 7 berths serving 3000 vessels annually. The vessel fleet is categorized into three types according to their tonnage: large (7 and 10 ten thousand tonnage), medium (3 and 5 ten thousand tonnage), and small (0.5, 1, and 2 ten thousand tonnage). The specific vessel information, including their tonnage, visiting frequencies, auxiliary engine specifications, and approximated processing time, is modified from [33] and provided in Table I.

Table I. Anticipated vessel arrival to the port within the upcoming year

Vessel type	Small			Medium		Large	
Tonnage of vessels (DWT)	0.5	1	2	3	5	7	10
Proportion (%)	10	5	15	15	30	10	15
Power of auxiliary engines (KW)	320	430	700	1260	1960	2320	2760
Processing times (hour)	8	10	7	10	10	20	20

Three capacities of OPS are considered: 0.8MW, 2MW and

3MW. We assume that the average service life of all OPS stations is 20 years. The fixed investment cost of each set of OPS is 1 million dollars with a linear capacity-dependent cost of $100/kW. The installation subsidy given by the regulator for each OPS facility is set to 30% of its total cost. According to the berth utilization rate of 57.97%, we can set the service capacity of each set of OPS to 5080 hours/year.

Furthermore, the pollutant considered in the case study is sulfur dioxide (SO_x), which is one of the most harmful substances that contribute to the environmental issues in port areas. Note that the proposed approach can be applied to any other pollutants or a combination of them through greenhouse gas equivalencies offered by [34] in a similar fashion. As mentioned in the previous discussion, the vessels' electricity demand met by OPS will not produce any pollutants in the port area. The emission factor of SO_x is 0.003 kg/KWh for the auxiliary engines that use marine diesel [35]. In the proposed bilevel mode, the weight coefficients in (16) are set to $\alpha_1 = 0.5$ and $\alpha_2 = 0.5$. We consider a total regulator budget of 2 million dollars. The initial emission level of the port is 197 tons. The emission reduction target ρ is set to 30%.

All computational experiments are done on a PC with Intel i5 CPU and 8 GB of memory. The model was solved using IBM CPLEX.

4.1 Impacts of different tax and subsidy rates

We first evaluate the performance of the proposed approach under different combinations of emission tax and environmental subsidy rates. The case studies in Table II are designed to study the effects of low (Cases 1.1-1.4), moderate (Cases 2.1-2.4), and high tax and subsidy rates (Cases 3.1-3.4), respectively. The results are given in Table III. Note that in Table III and the following discussion, the term "subsidy" refers to the emission subsidy c_4 unless noted otherwise.

Table II. Testing cases

Case #	Subsidy rate ($/kg)	Tax rate ($/kg)
1.1	0	0
1.2	1	1
1.3	0	1
1.4	1	0
2.1	0.8	1.2
2.2	1.2	1.2
2.3	1.2	3
2.4	3	1.2
3.1	3	3
3.2	3	5
3.3	5	3
3.4	5	5

Table III. Case study results

Case #	Emission (ton)	Tax paid ($)	Subsidy received ($)	PS (MWh)	OPS Installation		
					0.8 MW	2 MW	3 MW
1.1	197	0	0	0	0	0	0
1.2	197	59119	0	0	0	0	0
1.3	197	59119	0	0	0	0	0
1.4	197	0	0	0	0	0	0
2.1	118	0	15695	26,246	0	0	2
2.2	118	0	23542	26,246	0	0	2
2.3	118	0	23542	26,246	0	0	×2
2.4	65.7	0	216698	43,784	0	×2	×2
3.1	65.7	0	216698	43,784	0	×2	×2
3.2	65.7	0	216698	43,784	0	×2	×2
3.3	57.9	0	400259	46,390	×1	×2	×2
3.4	57.9	0	400259	46,390	×1	×2	×2

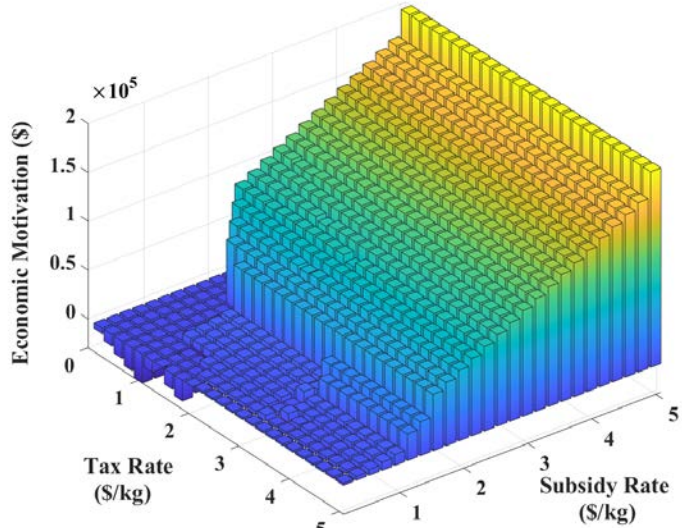

Fig 2. Port emission level under different tax and subsidy rates

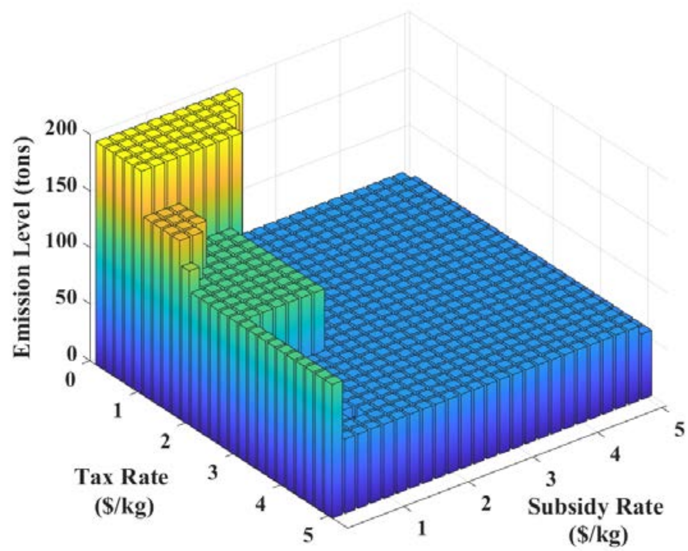

Fig 3. Economic motivation under different tax and subsidy rates

We can observe from Cases 1.1 to 1.4 that, when the tax and subsidy rates are low, the port entity is not willing to make an investment in OPS to reduce its emission level. It prefers to pay emission tax instead as a cheaper alternative. Therefore, the port's emission level stays unchanged with respect to the initial level, and no subsidy is received from the regulator as the port emission exceeds the emission cap in all four cases. When we increase the tax and subsidy rates in Cases 2.1 to 2.4, it can be observed that the port changes its investment strategy and adopts OPS. This effect is clearly shown in Cases 2.1. Compared to Case 1.2 having both the tax and subsidy rates at $1/kg, we can see from Case 2.1 that increasing the tax rate from $1/kg to $1.2/kg would motivate the port to adopt OPS installations in order to avoid the emission tax, even with a slightly reduced subsidy rate ($1/kg in Case 1.2 to $0.8/kg in Case 2.1). Following the OPS installation, the port's emission level is reduced to 118 tons, which is lower than the emission cap set by the regulator (138 tons). As a result, the port receives a subsidy. Furthermore, once the tax rate is sufficiently high (as in Cases 2.2 to 2.4), increasing it further as a penalty will not result in additional emission reduction. Instead, a higher subsidy rate becomes necessary to motivate the port to install more OPS and further reduce its emission. When the subsidy rate is increased from \$0.8/kg in Case 2.1 to \$3/kg in Case 2.4, the port would add two more OPS installations to lower its emission down to 65.7 tons. For all of the test cases, a uniform emission cap of 138 tons was obtained.

The same trend can be observed when we further increase the subsidy and tax rates as in Cases 3.1 to 3.4. By comparing Cases 2.4, 3.1, and 3.2, we can observe that the increased tax rates (\$1.2/kg in Case 2.4 to \$3/kg in Case 3.1 to \$5/kg in Case 3.2) do not impact the port's decision-making process and its emission level under the same subsidy rate. As shown in Case 3.1 and 3.3, an increased subsidy rate would be more effective in achieving emission reduction. Another trend can be observed from Table III, in which the port tends to invest in OPS installations with higher capacity so that it can better serve larger vessels that generate significant emissions at berth. This is consistent with the expectation that OPS installations should be prioritized to serve vessels with the highest emission factors and environmental impacts.

Additional results are shown in Figs. 2 and 3 to further analyze the influence of different combinations of tax and subsidy rates with regards to port emission and the economic interactions between the port and the regulator. Fig. 2 shows the terminal port emission obtained under different combinations of tax and subsidy rates. It is noticeable that when the tax rates are low, higher subsidy rates should be considered to motivate the port to deploy OPS for emission reduction. In comparison, the combination of high tax rates and low subsidy rates would also stimulate emission reductions through OPS. However, it is less effective. In fact, in order for the port to achieve the lowest emission level, a high subsidy rate is required. Fig. 3 shows the economic interactions between the port and the regulator. We can observe that when the tax and subsidy rates are both low, the emissions generated by the port are higher than the regulator-defined emission cap and taxes must be paid to the regulator, which results in negative economic flows from the port to the regulator. When the tax rate and the subsidy rate increase, the economic flow is reversed, and the port starts to receive subsidies increasingly. We can also observe that the economic interactions change greatly around the subsidy rate of \$2/kg and the tax rate of \$0.8/kg. The policy maker should pay close attention to such discontinuities (i.e., threshold values) above which sudden large changes in emission levels or costs could occur due to small fluctuations in the subsidy/tax rates.

Note that for all the experiments conducted in the previous case studies, the average calculation time of the program is roughly 10 secs. The program converges in two iterations on average.

We can also evaluate the impact of the OPS installations on the port's emission level as well as the port's electricity consumption, as shown in Fig. 4. We can observe that as the number of OPS installations increases, the electricity consumption of the port continues to rise. Meanwhile, as more OPS are made available for different types of incoming vessels, the emission level in the port area continues to decline. Fig. 4 signifies that while OPS can effectively mitigate the port-area emission, it essentially shifts the emission burden from vessels at berth to the electric power generation units. The ever-increasing power consumption resulted from the OPS would also significantly burden the utility transmission and distribution grid. Therefore, OPS can be coupled with clean and local power production technologies such as microgrid, distributed renewable generation, and energy storage to reduce operation burden on utilities, defer transmission and distribution expansion expenditures, while achieving further emission elimination and higher energy efficiency.

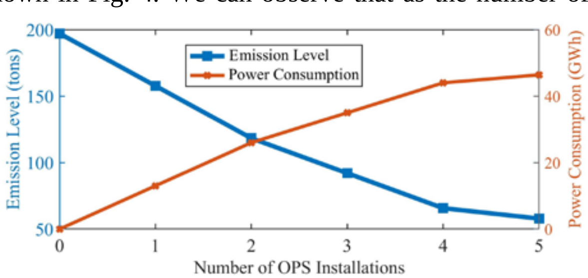

Fig 4. Emission level and power consumption of the port

4.2 Performance evaluation

To highlight the advantages of the proposed approach, we compare the environmental and economic performance of our approach with the conventional regulatory approach (i.e., command-and-control) and market-based approach as performance benchmarks subject to the same budget constraint for the regulator. In the regulatory approach, we assume that the regulator mandates the port entity to lower its emission level to meet the regulator's emission reduction target, denoted by $e(1-\rho)$. The regulator provides the one-time installation subsidy and the usage-based operation and maintenance subsidy to the port in a similar fashion as the proposed approach. In the market-based approach, we consider that the regulator is providing an economic incentive for each ton of emission reduced to promote the deployment of OPS. Note that this incentive rate is determined based on the emission reduction target and the total budget of the regulator. The results of this comparisons for different emission goals (i.e., α=30%, 50%, and 70%) are shown in Tables IV-VI, respectively. Note that in the tables, *RD* refers to the total regulatory spending and *PD* refers to the total port spending.

We can clearly observe that in all three testing scenarios, the regulatory approach, which mandates the emission control for the port leads to the least spending for the regulator and the highest spending for the port. While such an approach could be most financially beneficial for the regulatory agency and provide a high level of certainty, it requires the regulator to dictate the operation permits for the port entity to comply with and thus is highly prescriptive with little flexibility. In addition, due to its restrictive nature, the regulatory approaches can present significant legislative burden on the regulator and enforcement challenges for implementation. We can also notice that specifying a given emission reduction level would cause the port to lose the incentive to further reduce emissions below the limits.

On the other hand, the market-based approach, while flexible and easier to comply, can be significantly more expensive for the regulator to be financially attractive for port entity to take actions and proactively achieve the desired level of emission mitigation. We can observe in Table IV to VI that, for all three emission reduction goals, the regulator has to provide a significant portion of their total spending to the port entity to promote the deployment of OPS facilities. In addition, similar to the regulatory approach, the market-based approach provides no additional incentive for the port to further reduce the emission after meeting the emission reduction goal.

Table IV. Performance comparison of different approaches for emission reduction goal α=30%

		RD (million $)	*PD* (million $)	e_c (tons)	e_t (tons)
Regulatory		0.5600	0.09	-	118
Market-based		0.9589	-0.304	-	118
Proposed hybrid approach	case 2.1	0.5796	0.0753	137.9	118
	case 2.2	0.5875	0.0675	137.9	118
	case 2.3	0.5875	0.0675	137.9	118
	case 2.4	1.1674	-0.0417	137.9	65.7
	case 3.1	1.1674	-0.0417	137.9	65.7
	case 3.2	1.1674	-0.0417	137.9	65.7
	case 3.3	1.4193	-0.1875	137.9	57.9
	case 3.4	1.4193	-0.1875	137.9	57.9

Table V. Performance comparison of different approaches for emission reduction goal α=50%

		RD (million $)	*PD* (million $)	e_c (tons)	e_t (tons)
Regulatory		0.95	0.18	-	65.7
Market-based		1.6107	-0.4815	-	65.7
Proposed hybrid approach	case 2.1	0.5402	0.1148	98.5	118
	case 2.2	0.5402	0.1148	98.5	118
	case 2.3	0.7651	0.1252	98.5	92
	case 2.4	1.049	0.0765	98.5	65.7
	case 3.1	1.049	0.0765	98.5	65.7
	case 3.2	1.049	0.0765	98.5	65.7
	case 3.3	1.222	0.0096	98.5	57.9
	case 3.4	1.222	0.0096	98.5	57.9

Table IV. Performance comparison of different approaches for emission reduction goal α=70%

		RD (million $)	*PD* (million $)	e_c (tons)	e_t (tons)
Regulatory		1.02	0.2100	-	57.9
Market-based		1.715	-0.4827	-	57.9
Proposed hybrid approach	case 2.1	0.4929	0.162	59.1	118
	case 2.2	0.4929	0.162	59.1	118
	case 2.3	0.9309	0.1948	59.1	65.7
	case 2.4	0.9428	0.1829	59.1	65.7
	case 3.1	0.9309	0.1948	59.1	65.7
	case 3.2	0.9177	0.208	59.1	65.7
	case 3.3	1.025	0.2067	59.1	57.9
	case 3.4	1.025	0.2067	59.1	57.9

In comparison, we can observe that the proposed hybrid economic approach preserves the flexibility of the market-based approach at a much lower cost for the regulator. For the emission reduction goal of 30%, the results presented in Table IV show that the proposed approach can lower the port's emission level to 118 tons to meet the goal under moderate subsidy and tax rates (Cases 2.1 to 2.3). The resulted regulator spending ($0.5796 million) is slightly higher than that of the regulatory approach ($0.56 million), but well below the market-based approach ($0.9589 million). Furthermore, we can observe that when we further increase the subsidy and tax rates, the port would continue lowering its emission as shown in Cases 2.4 to 3.4. For the emission reduction goal of 50%, Table V shows that the proposed approach can lower the port's emission level to 65.7 tons to meet the reduction goal under moderate/high tax and subsidy rates in Cases 2.4, 3.1, and 3.2. The regulatory spending for these cases is $1.049 million, which is close to the regulatory spending of $0.95 million resulted from the regulatory approach and well below the $1.6107 million regulatory spending for the market-based approach. Similarly, for the emission reduction goal of 70%, Table VI demonstrates that under high tax and subsidy rates (Cases 3.3 and 3.4), the proposed approach is capable of meeting the emission reduction goal at a slightly higher cost ($1.025 million) than the regulatory approach ($1.02 million), while the market-based approach would lead to a regulatory spending of $1.715 million.

The above analysis has clearly shown that proposed hybrid economic approach provides the overall most appealing solution among all three approaches. On one hand, it is cost-effective and reduces the regulatory spending in maximizing OPS installations and emission reduction. On the other hand, it provides financial motivations (i.e., incentives and disincentives) to guide the port entity towards developing its OPS adoption and emission mitigation strategies based on available information such as the assigned emission cap and the tax/subsidy rates. In this way, the port entity has the flexibility and latitude in selecting the best OPS deployment plan via economic decision-making. Overall, the proposed hybrid economic approach strikes a balance between the conventional regulatory and market-based approaches and provides an attractive strategy for the regulator to increase OPS uptake at maritime ports.

5. Conclusions and Future Work

Maritime ports play a crucial role in domestic and international trade and economic growth due to the rapid increase in maritime cargo volume. However, there also exist significant environmental concerns regarding the large volumes of air pollutants occurred near port areas, resulting in adverse impacts on the environment and public health. Hence, this paper introduced a novel hybrid economic approach to jointly aid both the regulatory policymakers and port entities to holistically curb the negative environmental impacts caused by ships at berth by increasing the uptake of OPS. Simulation results show that the proposed approach is capable of capturing the dynamic interactions between the regulatory agency and the port entity involved in the decision-making process regarding OPS deployment and helping both parties determine the most financially feasible and economical investment decisions. For the first time, we have shown the unique advantages of a hybrid economic approach compared to the regulatory and market-based approaches that have been commonly taken by the policymakers. While the proposed approach is developed for the transformation of maritime ports from a major source of pollution to a contributor to the social, economic and environmental well-being being of the coastal communities, we envision that our research effort presented in this paper can be extended to create successful regulations and policies for other large energy-intensive industrial facilities which are subject to governmental/regulatory subsidization.

Future studies can extend the research presented in this manuscript in several potential directions. First, optimal investment and management strategies can be developed to integrate OPS into the port energy system and port microgrids, given its extensive power demand and high demand of continuous, high-quality, and clean power supply. Second, a more generalized incentivization approach can be investigated which treats policy parameters, such as emission tax/subsidy rates used in this manuscript, as decision variables to be optimized as a part of the overall economic policy. Finally, as this manuscript focuses its scope on the interactions between regulator and port entity to promote the OPS deployment on the shore side, one can also study the economic policy to stimulate the vessel retrofitting to enable the connection the OPS facilities while at berth.

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