Stimulating Sustainable Energy at Maritime Ports by Hybrid Economic Incentives: A Bilevel Optimization Approach

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Abstract

Over the past few decades, maritime ports have faced ever-increasing critiques regarding their significant production of air emissions resulting from their energy activities. To promote sustainability at ports, regulatory authorities have introduced the concept of regulations and economic incentives. In this paper, we analyze the process in which a regulatory authority defines regulations, incentives, and tax policies to motivate one or more ports in the region to initiate energy sustainability and emission-reduction efforts. We model the behaviors of both the regulatory authority and the participating ports in the form of a multi-objective mixed-integer nonlinear bilevel optimization problem to capture the hierarchy of the policy-making process and the existing competitions among the ports. The proposed model finds the optimal incentive and tax policies for the policy-maker in the upper-level and provides the ports in the region with the optimal choice of sustainable energy solutions and service prices in the lower-level. Simulation results show that the proposed approach can effectively reduce the region-wide emission from the port activities while ensuring port entities’ welfare, competitiveness, and sustainable growth as regional energy hubs.

Keywords: Port Energy Systems, Sustainability, Economic Incentives, Policy Analysis, Bilevel Programming

1. Introduction

Maritime transportation accounts for 90% of cross-border world trade, as measured by volume. Ports are considered to be the backbone of this network by connecting value chains and markets in different parts of the world \cite{1}. In 2018, U.S. ports contributed $5.4 trillion to the economy of the country, which accounts for nearly 26% of the nation’s $20.5 trillion economic output \cite{2}. As dependence on these ports grows, so does the severity of challenges against them. The main operation of ports is to load and unload vessels and transport the cargo to warehouses and other destinations, which has made maritime ports to be major energy hubs. The increasing energy demand for port operations has brought forward urgent issues related to the port industry’s substantial impacts on the environment and public health \cite{3}. To satisfy their energy demands, port entities produce a significant amount of environmental pollution through land and sea transportation, waste disposal, and expansion activities \cite{4}. According to the air emission inventory organized by the Port of Los Angeles (POLA) in 2015, the principal sources of airborne emissions at ports are directly linked to the activities of major consumers in the port energy system, such as ocean-going vessels (OGVs), cargo handling equipment (CHE), heavy-duty vehicles (HDVs), harbor crafts, and locomotives \cite{5}. It is reported that approximately 230 million people are directly exposed to emissions originating from the top 100 global container ports. The existence of air pollutants produced by ports is estimated to quadruple by 2050; this equates to approximately 70 million tons of CO\textsubscript{2} and 1.3 million tons of NO\textsubscript{x} \cite{6}. Air emissions directly impact the health conditions of residents living in the communities surrounding ports and cause diseases such as asthma, lung cancer, cardiovascular diseases, and premature mortality \cite{7}. Meanwhile, greenhouse gases (GHGs) are considered to be the primary contributing factor to climate change and global warming \cite{8}. To address these pressing issues, many port entities and authorities are exploring new decarbonization and emission mitigation solutions to the traditional port energy management paradigm in port energy systems. These proposed solutions will allow for the movement towards a port industry that promotes and facilitates renewable energy, sustainable development, steady economic growth, and better quality of life and social welfare for citizens living in the port neighborhood \cite{9,10}.

Existing port sustainable energy solutions embrace technical, operational, and economic dimensions. The abatement measures for OGVs are classified into four categories: alternative fuels or power sources (e.g., liquefied natural gases (LNG), biofuels, solar and wind energy, and nuclear energy), operational measures (e.g., hull conditioning, propeller conditioning, trim and draft optimization), technical measures (e.g., the machinery of main and auxiliary engines, underwater measures for propulsion and hull), and structural changes (e.g., port efficiency, vessel speed reduction, and cold ironing) \cite{10,11,12}. Zero-emission electric transport vehicles and cranes are readily deployable to reduce CHE emission \cite{10,13,14}. Moreover, alternative fuels, speed optimization, idling reduction, and truck

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Preprint submitted to Elsevier

May 8, 2020
platooning can be adopted for HDV’s emission reduction [15][16][17]. Alternative fuels, hybrid, and all-electric harbor craft and locomotives are also available to mitigate emissions [18][19]. Optimizing practices and operational measures at ports in order to mitigate emission has been the topic of various studies in the literature. Vessel speed optimization, berth allocation, crane scheduling, and shipping routing and scheduling are major subjects of these works [20, 21, 22]. Despite the existence of the aforementioned sustainable energy technologies and suggested practices, ports and shipping liners are reluctant to initiate them due to the barriers of implementation cost and time. As profit-driven organizations, port entities are constantly challenged by their stakeholders to justify the pursuit of emission-reduction efforts and the investment of sustainable energy solutions in terms of payback, return on investment, and revenue enhancement. To address this issue, the concept of regulations and economic incentives has emerged to promote emission reductions in the ports’ energy activities [23]. According to the United States Environmental Protection Agency, three types of instruments are available for policymakers: i) mandatory regulations (command-and-control), ii) market-based policies, and iii) hybrid approaches (a combination of command-and-control and market-based policies) [24]. Mandatory regulations refer to the traditional mandates and standards which oblige specific limits, technologies, or processes that polluters must adopt to reduce their emission. Market-based policies, used as performance-based standards, rely on market forces to motivate emission reduction by economic means such as incentives and taxes [25]. Regulatory approaches provide certainty in mitigating emission, while market-based policies

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provide flexibility and willingness to polluters \([26]\) to meet the emission standard. Hybrid approaches combine the certainty and flexibility of these two and hence, are becoming more appealing to policy-makers. However, the design of such policies is not straightforward. Attributes such as operational costs, continuity of operations, regulation compliance, port competitiveness, and regulation attractiveness have to be taken into consideration collectively to form an overall "sensible" solution \([27]\).

The necessity of economic regulations for emission reductions at ports has been discussed in the literature \([28, 29]\). In particular, the need for pollution taxes was highlighted and revealed through a survey with port operators and government officials in \([30]\). The results of the survey emphasized the importance of a practical policy-making approach that motivates ports to reduce their emission. The impacts of different environmental policies on air emission mitigation are analyzed in \([31]\). An important regional characteristic that should be incorporated in the design of an effective economic policy is whether there are multiple ports or one port in the region. A market-based approach for pollution control in a region with multiple ports is studied in \([32]\). In regard to environmental regulations, the effectiveness of a unilateral maritime emission regulation versus a uniform maritime emission regulation in the presence of multiple ports has been investigated in \([33]\). The results of this investigation indicated that a unilateral regulation may lead to increased emissions, whereas a uniform regulation always reduces the total emission. The literature has also noted the adoption of bilevel optimization models used to design tax and incentive policies that promote clean energy. In this context, a bilevel optimization model has been developed in \([34]\) to study the renewable incentive design for generation capacity expansion. Moreover, a situation where the government aims to minimize the total \(CO_2\) emissions by using carbon tax and subsidies, and the consumers want to minimize their costs by choosing the optimal combination of energy was considered in \([35]\). As another instance, authors in \([23]\) designed a carbon tax scheme based on the production emission factor via bilevel programming. However, the hybrid economic approach remains largely unexplored in the literature for port energy system design and emission mitigation.

In this paper, we propose a novel hybrid economic approach to aid both the regulatory entities (e.g., government agencies, policy-makers) and the polluting entities (e.g., ports entities, shipping liners) to holistically improve the sustainability of a region consisting of multiple ports. The proposed approach allows the regulatory authority to minimize the emission caused by port energy activities through carbon taxes and subsidies in a way that the port customers’ (i.e., energy consumers) welfare and competitiveness are not noticeably impaired. More specifically, we propose to formulate the problem as a multi-objective bilevel programming model in which the upper-level provides the optimal set of tax and incentive policies for the regulatory entity as well as emission goal, and the lower-level offers the optimal investment decisions regarding the choice of green and sustainable energy solutions and the setting of port service prices for the port entities. Simulation results verify that the proposed approach is capable of simultaneously satisfying the demands of the regulator, ports, and port customers while providing the first two with optimal policies.

The contributions of this paper are highlighted as follows:

- This paper develops a novel hybrid economic approach to stimulate sustainable energy activities at maritime ports. The proposed approach is one of the pioneering research efforts that aim to combine the certainty of command-and-control and the flexibility of market-based economic incentives in the unique context of maritime transportation.
- This paper presents a novel multi-objective bilevel programming model to enable the co-operation of two key stakeholders of the port energy system, the regulatory authority and the competing port entities, based on their points of interest as well as the hierarchy and competition among them.
- This paper presents case studies based on actual port data. The simulation results offer practical insights into the effectiveness of taxes, incentives, and the combination of the two on mitigating emissions with the consideration of the satisfaction of port energy demand.

The remainder of this paper is organized as follows. The methodology section presents the proposed model and its associated solution methodology. Section III illustrates our approach through numerical examples and performance analysis. Finally, Section IV concludes the paper by highlighting the contributions and results of our study as well as insights for future research.

2. Methodology

As set forth above, our problem setting involves two groups of decision-makers: a regulatory authority and competing ports in the associated region. The regulatory authority aims to promote sustainable growth that lowers the combined emission from polluting ports in the region, all while maintaining service availability for the ever-growing energy demand. This is achieved through the establishment of a target emission limit, i.e., an emission cap for each port, to motivate the implementation of sustainable and green energy solutions. The port receives incentives if its emission level is below the cap. Otherwise, the port is penalized by an emission tax. Our approach is hybrid in the sense that it incorporates the certainty of command-and-control by establishing the emission caps while offering economic stimulation to encourage port entities to adopt sustainable energy technologies and meet the assigned emission caps through profitable approaches. The regulatory authority also considers the welfare of the port customers, modeled by the amount of fulfillment of port energy demand. It is noted that in this work, this demand is measured by the total volume of containers handled by the port facility.

The second group of decision-makers is comprised of competing ports in the region that seek to maximize their profits from providing services to port customers (i.e., vessels and ship
liners). This profit is impacted by the choice of sustainable energy technologies, the emission tax, and the potential incentive. Note that in this paper, we consider a fixed cost and a variable cost associated with the implementation of sustainable energy solutions. The fixed cost represents the initial investment that has to be made to support the adoption of the technology, while the variable cost is determined by the unit price of the equipment and the number of units to be purchased. Each solution lowers the emission from the associated energy consumption source by a constant rate \((L_{jk})\) for a given period.

To consider the hierarchical nature of the decision-making process in this problem and the existing competition among the ports, we propose a bilevel programming model. In this model, the regulator acts first as the leader and attempts to make optimal decisions, and then the ports, as the followers, react to the regulator’s decisions in a way that is individually optimal. Due to the consideration of policy transparency, which indicates that both the leader and the followers have access to each other’s objectives and green technology \([56]\), perfect information is assumed in this paper.

The port energy demand is modeled as a linear function of \(e^0_i\) and the number of units to be purchased. Each solution lowers the emission from the associated energy consumption source by a constant rate \((R_{jk})\) for a given period.

\[
q_i = \frac{a - p_i}{b}
\]

(1)

\[
q_i = \begin{cases} 
0 & p_i > a \ or \ p_i > p_j, \ i \neq j \\
\frac{a - p_i}{Nb} & p_i = p_j, \ i \neq j \\
\frac{a - p_i}{b} & p_i \leq \min(a, p_j), \ i \neq j
\end{cases}
\]

(2)

The emission level after implementing green solutions at port \(i\) equals the initial emission level at the port \(\left(e^0_i\right)\) minus the mitigated emission (Equation (3)). Tax and incentive for each port are assumed to be linearly dependent on the gap between the associated emission cap and emission level (Equations (4) and (5)).

\[
e_i' = e^0_i - \left(\sum_j \sum_k R_{jk}L_{jk}x_{ijk}q_i\right)
\]

(3)

\[
\tau_i = \bar{\tau}(e_i' - e_i^0)
\]

(4)

\[
s_i = \bar{s}(e_i' - e_i^0)
\]

(5)

We denote the profit of port \(i\) by \(\pi_i\), which is calculated by subtracting the emission tax and the emission abatement costs, if any, from the total port revenue and incentive (Equation (6)).

\[
\pi_i = pq_i = s_i - \tau_i - \left(\sum_j \sum_k F_{jk}y_{ijk} + \sum_j \sum_k VC_{jk}x_{ijk}\right)
\]

(6)

Then, the bilevel model for \(i = 1, \ldots, N\), \(j = 1, \ldots, M\), and \(k = 1, \ldots, U\) can be formulated as follows:

\[
\min_{q_i} \omega_1 \sum_i e_i' + \omega_2 \sum_i \frac{(e_i' - e_i^0)^2}{(e_i^0)^2} + \omega_3 \sum_i \frac{Q - \sum_i q_i}{Q}
\]

\[
\text{s.t.} \sum_i s_i \leq B
\]

(7)

\[
0 \leq e_i' \leq \beta_i
\]

(8)

\[
\sum_i q_i \leq Q
\]

(9)

\[
\min \sigma
\]

(10)

\[
\text{s.t.} \frac{\pi_i' - \pi_i}{\pi_i} \leq \sigma
\]

(11)

\[
x_{ijk} \leq M y_{ijk}
\]

(12)

\[
M \lambda^i_j \leq e_i' - e_i^0 \leq M \lambda^i_j
\]

(13)

\[
\lambda^i_0 + \lambda^i_j = 1
\]

(14)

\[
0 \leq e_i'
\]

(15)

\[
x_{ijk} \in Z^+, y_{ijk}, \lambda^i_0, \lambda^i_j \in [0, 1], 0 \leq p_i
\]

(16)

Equations (7)–(10) define the upper-level model, and Equations (11)–(17) define the lower-level model. Given the regulatory role of the policy-makers, the regulator objective function (i.e., the objective function of the upper-level model) is a convex combination of four normalized terms: 1) the emission level from port activities, 2) the gap between the assigned emission cap and the initial emission level of each port, 3) the gap between the satisfied port service demand and the total demand, and 4) the emission cap assigned to each port (Equation (7)). Note that the second term is included to model a fair regulator which assigns emission caps based on the port’s initial emission level.

The total incentive that the ports can receive is subject to the budget constraint of the regulator (Equation (8)). The assigned emission caps are subject to their respective upper bounds (Equation (9)), and should always be positive. The satisfied demand for port service should be less than or equal to the total market demand (Equation (10)).

In the lower-level model, the goal is to maximize the profit of the ports (Equation (18)).

\[
\max_{x_{ijk}, y_{ijk}, \lambda^i_j} (\pi_1, \pi_2, \ldots, \pi_N)
\]

(18)

To handle the multi-objective lower-level problem, we reformulate Equation (18) into Equation (11) and add Equation (12) to the lower-level model. In Equation (12), \(\pi^*\) is a parameter referring to the maximum profit that each port could potentially receive. Parameter \(\pi^*\) is calculated by Equation (19).

\[
\pi_i^* = p_i q_i^* + s_i^*
\]

(19)

Equation (13) ensures that the fixed cost of implementing solutions will be considered along with the variable cost. Equation (14) decides whether the port entity pays emission tax or
receives incentives according to its emission level and the emission cap assigned to it, respectively. Equation (15) ensures that each port either pays taxes or receives incentives. The emission level associated with each polluting source in the port facility is set to $c_i$ and $\sigma$ for the regulator objective function are set to $+\infty$ and $-\infty$, respectively. At each iteration, the lower-bounding problem (LBD) is solved if feasible, an optimal solution is obtained, and we set $\epsilon_l^{c_i} = \epsilon_l^{c_i^*}$. Then, if the convergence condition is not met, the lower-level model is solved using fixed values for the emission caps (i.e., $\bar{e}_i$). Thus, the parametric upper bound for the lower-level objective function, as well as the new bounds of the emission caps, can be obtained. The last step is solving an upper-bounding problem (UBD) and updating the optimal solution. If the convergence is not met, new constraints will be added to the LBD to direct the algorithm toward the optimal solution. The details for each step are discussed further below.

The lower bound is obtained by solving the LBD, a mixed-integer nonlinear program containing the upper-level objective function, constraints of the lower-level model, and constraints of the upper-level model. The convergence of the LBD is achieved by including a parametric upper bound to the optimal objective function of the lower-level program. This parametric upper bound is enforced by adding a logical constraint (Equation (22)). Note that $D$ is the set of iterations, $d$ is the iteration number, and $E_l^{d_i}$ is the host set obtained at iteration $d$ for the upper-level variable $e_i$.

\[
\begin{align*}
\min_{e_i \in E_l^{d_i}, \lambda_i \in \Lambda} z_{LBD} &= \omega_1 \sum_i \frac{e_i}{e_i^0} + \omega_2 \sum_i \frac{(e_i^0 - e_i)^2}{(e_i^0)^2} \\
 &\quad + \omega_3 \left( \frac{Q - \sum_i q_i}{Q} + \omega_1 \sum_i \frac{e_i}{e_i^0} \right) \\
\text{s.t.} \quad (8) \sim (10), (12) \sim (17) \quad &\Rightarrow \sigma \leq \sigma^d, \forall d \in D
\end{align*}
\]

In the first iteration of the algorithm, Equation (22) considers the initial host set for $e^d$ and $\sigma^d = +\infty$. However, in the following iterations, this set of equations will force a new upper-bound on the lower-level objective function for the associated ranges of $e_i$. The parametric upper bound of the lower-level objective function at iteration $d$ is obtained by solving the lower-level model and obtaining the optimal objective function value.

\[f^l(\epsilon_l^{c_i^*}, \bar{e}_i) \leq f^l(\epsilon_l^{c_i^*}, \bar{e}_i) + \bar{e}_i \]

\[f^l(\epsilon_l^{c_i^*}, \bar{e}_i) = f^l(\epsilon_l^{c_i^*}, \bar{e}_i) + \bar{e}_i \]
The optional upper bound to the optimal solution of the bilevel program is obtained by solving an augmented upper-level problem for fixed upper-level variables. To obtain the upper bound of the optimal objective function, we consider an upper-bounding algorithm for fixed upper-level variables. To obtain the upper bound of the bilevel program is obtained by solving an augmented upper-level problem for a given \( \varepsilon^* \) and the subsets of the host set of \( \varepsilon^* \), for which this solution remains lower-level feasible. Assuming \( r \in (0, 1] \) as a scaling coefficient for updating the bounds of \( \varepsilon_i^* \), the new bounds (i.e., \( \varepsilon_i^{\text{new}} \)) for \( \varepsilon_i^* \) can be obtained from Algorithm 1. This algorithm obtains successively tighter bounds for the upper-level variables (i.e., \( \varepsilon_i^* \)) until all of the potential values for \( \varepsilon_i^* \) within the bounds are feasible for the current lower-level optimal decisions.

Algorithm 1 Finding new bounds for \( \varepsilon_i^* \)

for \( i = 1, \ldots, N \) do
  Set \( r = 1 \).
  repeat
    if \( \varepsilon_i^* - 0.5r(e_i^{\text{up}} - e_i^{\text{LO}}) < e_i^{\text{LO}} \) then
      Set \( e_i^{\text{UD}} = e_i^{\text{dLO}} \).
      Set \( e_i^{\text{dLO}} = e_i^{\text{LO}} + r(e_i^{\text{up}} - e_i^{\text{LO}}) \).
    else if \( \varepsilon_i^* + 0.5r(e_i^{\text{up}} - e_i^{\text{LO}}) > e_i^{\text{UP}} \) then
      Set \( e_i^{\text{dLO}} = e_i^{\text{UP}} - r(e_i^{\text{up}} - e_i^{\text{LO}}) \).
      Set \( e_i^{\text{dUP}} = e_i^{\text{LO}} + 0.5r(e_i^{\text{up}} - e_i^{\text{LO}}) \).
    else
      Set \( e_i^{\text{dLO}} = \varepsilon_i^* - 0.5r(e_i^{\text{up}} - e_i^{\text{LO}}) \).
      Set \( e_i^{\text{dUP}} = \varepsilon_i^* + 0.5r(e_i^{\text{up}} - e_i^{\text{LO}}) \).
    endif
  endrepeat
  Check if the lower-level optimal decisions for all of the realizations of \( \varepsilon_i^* \) within the bounds remain valid.
  if The range is valid then Terminate the loop else Set \( r = 0.5r \) until True.
end

The optimal upper bound to the optimal solution of the bilevel problem is obtained by solving an augmented upper-level problem for fixed upper-level variables. To obtain the upper bound of the optimal objective function, we consider an upper-bounding model for a given \( \varepsilon_i^* \) as follows:

\[
\min_{\text{UBD}} \ z_{\text{UBD}} = \omega_1 \sum_i \frac{e_i^*}{e_i^*} + \omega_2 \sum_i \frac{(e_i^* - e_i^0)^2}{(e_i^0)^2} + \omega_3 \frac{Q - \sum_i q_i}{d} + \omega_4 \sum_i \frac{\sigma_i}{e_i^0} \tag{23}
\]

s.t. (8), (10), (12), (13), (15), (16), (17)

\[
0 \leq e_i^* \leq \beta_i \tag{24}
\]

\[
0 \leq \lambda_i \leq \lambda_i^0 \tag{25}
\]

\[
-M\lambda_i \leq e_i^* - e_i^0 \leq M\lambda_i^0 \tag{26}
\]

As shown in Figure 1 after solving the UBD, the convergence condition is checked. If it is not met, a new logical constraint (Equation (22)) based on \( \sigma^d \) and the new bounds of \( \varepsilon^* \) will be added to the LBD to begin the next iteration.

Note that bilevel models may not possess a solution even when the functions are continuous, the constraint region of the problem is nonempty and compact, and the follower has some room to respond for all decisions taken by the leader. This happens when the set of all solutions to the follower problem for a fixed leader decision consists of some nontrivial subset of a hyperplane. This means that the follower is indifferent to any point on that hyperplane while the leader might not feel the same indifference with respect to its objective function. However, the leader has no way to induce the follower to change its decisions. The points on this hyperplane are called indifference points which lead to the nonexistence of solutions. A simple way to see whether a solution, \((e_i^*, x_{ijk}, y_{ijk}, p_i^*, \lambda_i^0, \lambda_i^*)\), to the model presented in Equations (7)–(17) is unique is to solve the following problem in which \( S \) is the constraint region of the bilevel problem and \( \sigma \) is the lower-level objective function:

\[
\min \{ \sigma : (e_i^*, x_{ijk}, y_{ijk}, p_i^*, \lambda_i^0, \lambda_i^*) \in S \},
\]

\[
\omega_1 \sum_i \frac{e_i^*}{e_i^0} + \omega_2 \sum_i \frac{(e_i^* - e_i^0)^2}{(e_i^0)^2} + \omega_3 \frac{Q - \sum_i q_i}{d} + \omega_4 \sum_i \frac{\sigma_i}{e_i^0}
\]

\[
= \omega_1 \sum_i \frac{e_i^*}{e_i^0} + \omega_2 \sum_i \frac{(e_i^* - e_i^0)^2}{(e_i^0)^2} + \omega_3 \frac{Q - \sum_i q_i}{d} + \omega_4 \sum_i \frac{\sigma_i}{e_i^0} \tag{27}
\]

If the corresponding solution produces an objective function value that is less than the objective function value associated with \((e_i^*, x_{ijk}, y_{ijk}, p_i^*, \lambda_i^0, \lambda_i^*)\), then the uniqueness condition does not hold.

3. Case Study

In this section, we will demonstrate and evaluate the performance of the proposed approach in reducing emission and designing efficient tax and incentives through two simulation-based case studies: 1) a region with one port, and 2) a region with two ports. For both cases, we consider the following sustainable energy solutions: onshore power supply (OPS) for cold-ironing vessels, LNG-fueled trucks, LNG-fueled yard tractors, hybrid-electric tugboats, and LNG-fueled locomotives. Onshore power supply provides power to vessels at the berth through shore-to-ship power cables in which auxiliary engines on-board can be turned off, which leads to a significant reduction of emissions from diesel fuels. Currently, many industrial ports around the globe, including Port of Antwerp, Port of Gothenburg, POLA, and Port of Seattle, are testing and moving toward integrating OPS technologies into their terminal electricity distribution systems. Alternative fuels such as LNG provide another sustainable and cost-effective way for mitigating GHG emissions and other polluting substances, such as NOx and PM, from traditional, diesel-fueled trucks and tractors. The hybrid-electric tugboat is a recently presented solution recommended by POLA and Port of Long Beach (POLB). The preliminary
Table 1
Information pertaining to sustainable energy solutions for port entities

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<th>Inventory Component</th>
<th>NOx (tons/TEUs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGV</td>
<td>0.002399</td>
</tr>
<tr>
<td>HDV</td>
<td>0.000600</td>
</tr>
<tr>
<td>CHE</td>
<td>0.000674</td>
</tr>
<tr>
<td>HC</td>
<td>0.000184</td>
</tr>
<tr>
<td>Locomotive</td>
<td>0.000298</td>
</tr>
</tbody>
</table>

Table 2
NOx emission rates from different sources at the Port of Houston (2013)

<table>
<thead>
<tr>
<th>Inventory Component</th>
<th>NOx (tons/TEUs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGV</td>
<td>0.002399</td>
</tr>
<tr>
<td>HDV</td>
<td>0.000600</td>
</tr>
<tr>
<td>CHE</td>
<td>0.000674</td>
</tr>
<tr>
<td>HC</td>
<td>0.000184</td>
</tr>
<tr>
<td>Locomotive</td>
<td>0.000298</td>
</tr>
</tbody>
</table>

evaluation results indicated that hybrid-electric tugboats can significantly decrease NOx, CO2, and PM [44]. Finally, LNG-fueled locomotives can also reduce air emissions and are sustainable alternatives to current diesel-fueled locomotives, as suggested by a study conducted by the Port of Tarragona [45]. The specific costs, emission reduction rates, and service capacity associated with these sustainability solutions are provided in Table 1 [43, 45, 41].

The effectiveness of both the economic policies and green solutions is studied for a one-year period. Model (7)–(17) and the solution algorithm have been implemented in GAMS [46]. The Branch-And-Reduce Optimization Navigator (BARON) [47] in GAMS is used for solving the MINLP models at each step of the algorithm [48]. The algorithm has been carried out on a Linux server with 384 GB of RAM and 40 Intel Xeon E5-2690 processors (10 cores per socket) at 3.00 GHz. The time for the algorithm to converge to an optimal solution varies between 1.43 seconds for the single-port case study to 8 hours and 12 minutes for the two-port case study. This convergence time significantly depends on the input parameters such as weights in the government objective function as well as tax and incentive rates.

3.1. Case 1: Single-Port Region

As an example of a large container port in a region, we consider the Port of Houston, which is the largest U.S. export port. Using the port operating revenue and the energy demand information between 2003 and 2013 [49, 50], we performed a linear regression analysis that considers the inflation rates in order to obtain the y-intercept and the coefficient terms in Equation (1). Specifically, a and b in Equation (1) are set to $123.89 and $3.06 x 10^{-6}, respectively. As an example of a harmful polluting substance that has not been sufficiently mitigated, we focus on the emission of NOx. However, the proposed model, solution approach, and policies are applicable to other air pollutants, as well. The emission production rates for each polluting source at each respective port is given in Table 2. According to this table, ocean-going vessels are accredited as the most polluting sector of the Port of Houston, as they produce a significant amount of NOx. The initial NOx level from OGVs, HDVs, CHEs, harbor crafts, and locomotives amount to 8,115 (tons). In the regulator objective function (Equation (7)), we set the following weight parameters: $\omega_1 = 0.1, \omega_2 = 0.25, \omega_3 = 0.25,$ and $\omega_4 = 0.4$. The selection of these parameters prioritizes the regulator’s role to promote emission reduction through economic incentives. We test the following four combinations of tax and incentive policies:

- Case 1.1 $\tau = 0$ and $\delta = 0$ ($\text{thousands/tons of NOx}$)
- Case 1.2 $\tau = 0$ and $\delta = 10$ ($\text{thousands/tons of NOx}$)
- Case 1.3 $\tau = 10$ and $\delta = 0$ ($\text{thousands/tons of NOx}$)
- Case 1.4 $\tau = 10$ and $\delta = 10$ ($\text{thousands/tons of NOx}$)

Table 3 shows the results for these four test cases. Case 1.1 serves as the performance benchmark where both tax and incentive rates are set to 0. We can observe that despite the assignment of an emission cap (1623 tons), due to the lack of the economic stimulation, the port chooses not to invest in green solutions ($AB = $0) and its emission level remains unchanged from the initial value, i.e., $e_t = e_0 = 8113$ tons. The port’s profit comes from the revenue of handling all of the 1,952,122 containers (Equation (6)). Case 1.2 analyzes the port behavior in the presence of incentive and no tax. We observe that the same results are obtained in this case as Case 1.1. The results suggest that for this particular problem setting when there is no emission tax and the incentive rate is not as competitive, the port will not be motivated to mitigate its emission level to meet the emission cap. Cases 1.3 and 1.4 show that the reduction in emission level can be achieved when the emission tax is enforced, both in the presence and absence of an incentive. In both cases, the port has to invest $32.4 million to provide OPS for 38 container vessels for emission abatement and pay $18.14 million in emission tax for an emission level $e_t$ of 3,436 tons. This investment causes a decline in port profit from $230.2 million to $179.66 million. The optimal port service price per container is obtained to be...
Table 3
Results for the single-port region

<table>
<thead>
<tr>
<th>Case No.</th>
<th>et (tons)</th>
<th>ec (tons)</th>
<th>p ($thousands)</th>
<th>q (# of containers)</th>
<th>π ($thousands)</th>
<th>AB ($thousands)</th>
<th>τ ($thousands)</th>
<th>s ($thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>8113</td>
<td>1622.80</td>
<td>0.12</td>
<td>1,952,122</td>
<td>230,199</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.2</td>
<td>8113</td>
<td>1622.80</td>
<td>0.12</td>
<td>1,952,122</td>
<td>230,199</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.3</td>
<td>3436</td>
<td>1622.80</td>
<td>0.12</td>
<td>1,952,122</td>
<td>179,661</td>
<td>32,400</td>
<td>18,139</td>
<td>0</td>
</tr>
<tr>
<td>1.4</td>
<td>3436</td>
<td>1622.80</td>
<td>0.12</td>
<td>1,952,122</td>
<td>179,661</td>
<td>32,400</td>
<td>18,139</td>
<td>0</td>
</tr>
</tbody>
</table>

$120, and the total port demand is satisfied in all of the four instances.

Additional results are obtained and depicted in Figures 2(a) and 2(b) to further analyze the influence of different combinations of tax and incentive rates ranging from 0 to 20 thousand dollars per tons of NOx emission. Figure 2(a) illustrates the variations of port emission with regards to different tax and incentive rates. We observe that the lowest emission level achieved in this case study is 3,436 tons. It is also noticeable that when the tax rate is low, high incentive rates should be considered to motivate the port (e.g., $\tilde{\tau} = 0$ and $\tilde{s} = 15000$). Meanwhile, the combination of high tax rates and low incentive rates would also stimulate emission reductions (e.g., $\tilde{\tau} = 7000$ and $\tilde{s} = 9000$).

Figure 2(b) presents the payment flow between the port and the regulatory authority for different tax and incentive rates. It can be observed that incentives can only be obtained in a few instances when the tax rates are low, and the incentive rates are high. This indicates that in those few instances, tax by itself cannot sufficiently motivate the port to mitigate its emission. Comparing Figures 2(a) and 2(b), we notice that for lower tax and incentive rates, the port is reluctant to initiate emission abatement and is willing to pay the tax instead. However, with the increasing tax or incentive rates, the port becomes more willing to proactively decrease its emission level to avoid emission taxes and to seek the opportunity of meeting the emission cap to receive incentives.

3.2. Case 2: Two-Port Region

For the second case study, we consider an instance involving two container ports in the same region: POLA and POLB. These two ports are located side-by-side in San Pedro Bay but are two separate entities and compete with each other for business [51]. According to data for year 2017 ([5],[52],[53]), the number of total containers handled at POLA and POLB, respectively, were 9,343,192 and 7,544,507, while the operating revenue at each respective port amounted to $475 million and $381 million. Hence, in the ports’ demand function (Equation 2), $a$ is set to $90.84$, and $b$ is set to $2.87 \times 10^{-6}$. Details of each ports’ emission inventories are provided in Table 4. Without loss of generality, the weight parameters in the regulator objective function are set for this particular example as follows: $\omega_1 = 0.25$, $\omega_2 = 0.25$, $\omega_3 = 0.25$, and $\omega_4 = 0.25$. Four combinations of tax and incentive rate are considered: Case 2.1: $\tilde{\tau} = 0$ and $\tilde{s} = 0$ (Thousands/tons of NOx), Case 2.2: $\tilde{\tau} = 0$ and $\tilde{s} = 10$ (Thousands/tons of NOx), Case 2.3: $\tilde{\tau} = 10$ and $\tilde{s} = 0$ (Thousands/tons of NOx), and Case 2.4: $\tilde{\tau} = 10$ and $\tilde{s} = 10$ (Thousands/tons of NOx).

Table 4
NOx emission rates from different sources at POLA and POLB (2017)

<table>
<thead>
<tr>
<th>Inventory Component</th>
<th>LA: NOx (tons/TEUs)</th>
<th>LB: NOx (tons/TEUs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGV</td>
<td>0.00033</td>
<td>0.00056</td>
</tr>
<tr>
<td>HDV</td>
<td>0.00016</td>
<td>0.00015</td>
</tr>
<tr>
<td>CHE</td>
<td>0.00005</td>
<td>0.00005</td>
</tr>
<tr>
<td>HC</td>
<td>0.00007</td>
<td>0.00008</td>
</tr>
<tr>
<td>Locomotive</td>
<td>0.00009</td>
<td>0.00008</td>
</tr>
</tbody>
</table>
Table 5
Results for the two-port region: Port of Los Angeles and Port of Long Beach - Equal tax and incentive rates

<table>
<thead>
<tr>
<th>Case No.</th>
<th>eT (tons)</th>
<th>(eT1; eT2) (tons)</th>
<th>(p1; p2) (thousands)</th>
<th>(q1; q2) (# of containers)</th>
<th>(π1; π2) (thousands)</th>
<th>(AB1; AB2) (thousands)</th>
<th>(τ1; τ2) (thousands)</th>
<th>(s1; s2) (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>11,307</td>
<td>(4,886;6,421)</td>
<td>(4,886;3,475)</td>
<td>(0.05;0.05)</td>
<td>(7,691,361;7,691,361)</td>
<td>(354,721;354,658)</td>
<td>(0;0)</td>
<td>(0;0)</td>
</tr>
<tr>
<td>2.2</td>
<td>7,170</td>
<td>(4,515;2,655)</td>
<td>(3,126;6,389)</td>
<td>(0.05;0.05)</td>
<td>(6,979,576;6,979,576)</td>
<td>(354,404;354,404)</td>
<td>(4,400;41,800)</td>
<td>(0;0)</td>
</tr>
<tr>
<td>2.3</td>
<td>5,419</td>
<td>(2,691;2,728)</td>
<td>(3,268;3,484)</td>
<td>(0.05;0.05)</td>
<td>(7,471,608;7,471,608)</td>
<td>(330,687;329,287)</td>
<td>(27,800;29,200)</td>
<td>(0;0)</td>
</tr>
<tr>
<td>2.4</td>
<td>5,298</td>
<td>(2,706;2,592)</td>
<td>(2,760;3,962)</td>
<td>(0.05;0.05)</td>
<td>(7,513,368;7,513,368)</td>
<td>(335,303;335,220)</td>
<td>(23,520;36,760)</td>
<td>(0;0)</td>
</tr>
</tbody>
</table>

(a) Economic performance of POLA and POLB under unilateral tax and incentive rates

(b) Environmental performance of POLA and POLB under unilateral tax and incentive rates

Fig. 3. Analysis of the influence of unequal tax and incentives

Table 5 shows the results obtained for this case study. Case 2.1 serves as the performance benchmark and reflects the ports' optimal decisions when there is no tax nor incentive. The total emission level in the region, denoted by eT, is 11,307 tons of NOx, which is affected only by the number of handled containers in this case. The abatement costs are zero for both ports, and the maximum port profit is achieved by setting p1 = $50. The number of total handled containers in the region is 13,959,152. We observe that in all of the instances, both ports have decided to set similar service prices (i.e., p1 = p2) and satisfy an equal amount of demand (i.e., q1 = q2 = a − p2b). This is in accordance with Equation 2, as its Pareto optimal solution can be achieved when the ports set similar service prices.

In Case 2.2, POLA invests $4.4 million and equips 3 vessels with OPS while POLB invests $41.8 million in providing OPS for 35 vessels, purchasing 50 LNG-fueled tractors, one hybrid-electric tugboat, and providing OPS for 20 vessels. POLB spends $29.2 million to provide OPS to 34 vessels. The overall regional emission is reduced by 32%.

In Case 2.3, the positive tax rate results in a significant reduction of emission levels from both ports. More specifically, POLA mitigates its NOx level by investing $27.8 million in 50 LNG-fueled tractors, one hybrid-electric tugboat, and providing OPS for 20 vessels. POLB spends $29.2 million to provide OPS to 34 vessels. The overall regional emission is further reduced to 5,416 tons, which is about 52% of the initial emission level.

The minimum emission level of 5,298 tons is achieved in Case 2.4. With positive tax and incentive rates, both ports lower their emission levels below the emission cap to receive incentives. POLA provides OPS for 34 vessels and purchases 31 LNG-fueled yard tractors through the investment of $23.5 million in emission abatement. On the other hand, POLB invests $36.8 million in obtaining OPS for 34 vessels and purchasing 48 LNG-yard tractors. This allows both ports to collect incentives.

In Case 2.1-Case 2.4, we have analyzed the optimal decisions in the presence of uniform (i.e., equal) tax and incentive rates for the competing ports. However, in practice, governments and regulators might impose unilateral (i.e., unequal) emission policies for port entities such as emission control areas and...
region-specific carbon taxes. In the following discussion, we will investigate the overall optimal operational (i.e., economic and environmental) strategies for POLA and POLB under unilateral emission policies as profit-maximizing decision makers. In this way, the effects of uniform and unilateral emission regulations on the profits, cargo volumes and emissions can be compared in a competitive environment. More specifically, Case 2.5-2.7 are presented in the following discussion to study how port entities would respond to unilateral emission policies when one port has a higher incentive rate, a higher tax rate, and higher incentive and tax rates simultaneously. The results for these cases are shown in Figures 3a and 3b.

- Case 2.5) $r_1 = 10, r_2 = 15, s_1 = 10$ and $s_2 = 15$ ($\text{thousands/tons of NO}_x$)
- Case 2.6) $r_1 = 10, r_2 = 10, s_1 = 10$ and $s_2 = 15$ ($\text{thousands/tons of NO}_x$)
- Case 2.7) $r_1 = 10, r_2 = 15, s_1 = 10$ and $s_2 = 10$ ($\text{thousands/tons of NO}_x$)

It can be observed that in all three cases, the regulatory policies have facilitated the adoption of sustainable energy solutions for both POLA and POLB to reduce their emission levels below their associated emission caps to avoid the emission tax, i.e., $\tau_1$ and $\tau_2$ are both 0. Furthermore, in case 2.5, due to the elevated tax and incentive rates for POLB, the overall emission of the region $\tau_2$ can be reduced to 5276 tons, which is the lowest emission level compared with the other policies for the two-port region. As POLB invests more in emission reduction, it receives more incentive, which results in a increased profit of $336,152,000$ in this case. Moreover, ports set similar service prices and demand (i.e., $p = 50, q = 7,471,609$ TEUs) which is in accordance with our previous discussion.

It can be also observed that under the proposed model, increasing the tax or incentive rate for one port does not significantly impact the overall performance of the other port. This observation is consistent with the port’s revenue model represented in Equation 3. After the optimal service price and energy demand are determined, each port authority attempts to seek its maximum profit (Equation 19) by acting in its own best interest. In this process, a port entity does not have to take into account the rate of tax or incentive allocated to the other port entities or their responses in mitigating emissions. This observation verifies the model presented in Equations 17-19. It also provides the regulatory authority with the flexibility and the option to assign uniform and unilateral tax and incentive rates to different ports, knowing that the required emission level, tax rate, and incentive rate for one port does not significantly impact the other ports in the region.

The results from the single-port region and the two-port region cases indicate that emission tax is capable of reducing emission level on its own; however, the combination of tax and incentive would promote further emission reduction without impairment for the ports. In all of the instances, the most effective choice among green solutions is the onshore power supply. This is due to the fact that the emission mitigation capacity of OPS outweighs its overall investment cost, making it the most appealing green technology choice for port entities to adopt. Contrarily, LNG-fueled locomotives were not chosen in any of these cases despite its high service capacity and high reduction rate. This is in accordance with the fact that vessels are commonly more substantial contributors to $NO_x$ emissions compared to other polluting sources at ports.

4. Conclusion

This paper develops a novel hybrid economic approach to assist both the regulatory authority and the stakeholders of port entities to strike a balance between energy sustainability and fair competition in the competitive environment of a region consisting of multiple ports. Simulation results obtained in Section IV indicate that the proposed approach is capable of effectively promoting green energy and reducing emissions while ensuring port customers’ welfare and sustainable growth. By looking into different combinations of tax and incentive policies in both case studies, we can conclude that emission tax is a more effective approach for emission mitigation than incentive. In fact, higher rates of incentive are required to push the adoption of sustainable energy solutions when there is no tax, while even low tax rates can provide sufficient stimulation for the ports. Furthermore, the combination of tax and incentive can perform better and further motivate emission reduction. In terms of the selection of green solutions, our results indicate that the port tends to invest in solutions that strike the right balance between emission mitigation and overall cost. For instance, ports in our case studies have invested more in implementing onshore power supply due to its significant effectiveness in mitigating emissions with a relatively low investment cost.

There are some limitations in this work that can be addressed as future research. To propose a computationally tractable optimization model for stimulating sustainable energy at maritime ports, this paper assumed a linear relationship (1) between the port service price and the service demand and (2) between the emission level and economic incentives. However, one can investigate further on various factors ports consider in developing sustainable energy solutions and more accurate functions capturing the relationships among them. Furthermore, the proposed model did not consider parameter uncertainty in the model. Hence, one can extend this work to propose an optimization model considering uncertainties on energy demand, service price, and sustainable energy solution cost within the framework of robust optimization or stochastic optimization. Because such models can be difficult to solve, there is a need for a computationally efficient solution algorithm for solving large scale sustainable energy optimization models involving parameter uncertainty.

We envision that our research effort presented in this paper will facilitate the transformation of traditional industrialized ports into an integral contributing component of a sustainable eco-system. The proposed research creates the necessary structural and functional framework not only to strengthen the particular application of maritime ports, as demonstrated in this paper, but also to provide critical insights into revitalizing other
large energy-intensive facilities that exhibit significant impacts on the prosperity and well-being of local communities and are also subject to the ever-changing regulatory environment.

References


power-supply/what-is-ops/


[52] Port of Long Beach, Port of Long Beach: The Green Port URL http://www.polb.com/