Enabling Smart Ports Through the Integration of Microgrids: A Two-Stage Stochastic Programming Approach

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Abstract

This paper explores microgrids' application at ports and presents a systematic framework for evaluating the benefits of microgrid integration in creating sustainable value through purposeful planning. We focus on demonstrating how a set of Smart Port Index (SPI) metrics can be incorporated into the port microgrid planning process in the proposed framework to holistically improve the smartness of the port. A two-stage stochastic mixed-integer programming model is developed to explain how the use of microgrid at a port can effectively enhance the port's performance in four key activity domains: operations, environment, energy, safety and security under operation uncertainty. The proposed model consists of an investment master problem on the first stage and a multi-objective operation planning subproblem on the second stage. Benders decomposition is implemented for solving the two-stage stochastic model, and Lexicographic Goal Programming is applied to the subproblem to deal with multiple objectives. Simulation results, compared with the minimum cost planning approach, indicate that the proposed framework is capable of guaranteeing an improvement in productivity, sustainability, and reliability of port operations.

Keywords: Maritime Transportation, Ports, Smart ports, Microgrid, Renewable energy, Sustainability

1. Introduction

With the world trade and globalization demanding marine transportation, maritime ports have faced ever-increasing pressure to optimize their performance and deliver more effective and secure flows of goods worldwide. Unlike other industrial systems, as the regional multimodal intersection of global supply chains, a port operates in the context of a complex network of interconnected transportation, industrial, and civil infrastructure, and thus faces multifaceted challenges to provide efficient, cost-effective and sustainable means of transporting goods globally. There is a growing global trend among port entities that new technology-based solutions need to be adopted to facilitate the transformation of conventional ports into high-performance ports to support the ever-increasing import and export tonnage and the resulting traffic while reducing the potential impact on the environment and public health as well as vulnerability to extreme natural and man-made disasters. The port industry is undergoing the transformation to a "smart port" as a result of technological advancements and changing customer expectations. This transformation is an essential step to move the port industry toward a new era of reliability, sustainability, efficiency, and energy dependency that will further contribute to sustaining economic growth and spreading prosperity throughout the world. Molavi et al. [5] introduced a concept of smart port that involves a variety of advanced digital technologies consisting of monitoring, control, automation, and intelligent equipment and applications working together, to optimize the port operations and revitalize the existing infrastructure for a cleaner and strengthened port. Among many, the port industry and researchers have identified microgrids as one of the primary technology enablers for this vision.

A microgrid is a relatively small-scale localized energy network that features an effective integration of high penetration level of Distributed Energy Resources (DERs), such as renewable energy resources, energy storage devices, and controllable loads [14]. A microgrid can operate separately from the larger electrical grid as a self-sustainable entity during extreme weather events or contingencies and reconnect once the contingencies are cleared [31]. Compared with the traditional centralized operation paradigm of bulk power systems, microgrid offers various advantages such as increased efficiency and power quality, reduced cost, enhanced resiliency, and a more reliable, continuous, controllable and clean power supply [12].

It is envisioned that microgrids add the missing "piece" that the port authorities and agencies have been searching for a long time to make traditional ports smart. For the first time, microgrids, as the underlying energy backbone, provides a natural host and a technology hub to support the latest technology-intensive and information-centered economy models that the port entities are actively adopting as a part of the port modernization and electrification initiative. The recent advancement of DERs and their dramatic cost declines have made microgrids both technically and economically feasible and viable. The distributed and localized nature of microgrids, along with the se-

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Nomenclature

Sets

Ω	Set of scenarios
G	Set of dispatchable units
S	Set of energy storage systems
W	Set of nondispatchable units

Indices

ω	Index for scenarios
ch	Superscript for energy storage charging mode
dch	Superscript for energy storage discharging mode
eg	Subscript for the reduced load on the main grid
H	Superscript for high priority loads
i	Index for DERs
L	Superscript for low priority loads
ls	Subscript for the curtailment of low priority loads
rs	Subscript for energy consumption from renewable sources
T	Subscript for total values over the planning horizon
V	Superscript for critical loads
h	Index for hour
m	Index for month
y	Index for year

Parameters

η	Energy storage efficiency
γ	Weight factors in SEgI calculation
κ	Coefficient of present-worth value
λ	Maximum allowable load shedding (% of load)
ρ	Market price
υ	Value of lost load (VOLL)
B	Budget
c	Generation price for dispatchable units
C^{max}	Rated capacity of energy storage systems
CC	Annualized investment cost of generating units
CE	Annualized investment cost of storage - power
COL	Cost of load shedding
CP	Annualized investment cost of storage - energy
D	Load demand
D^{max}	Annual peak load
EM	Emission production
K	Large positive constant
P^{max}	Rated power of DERs
P_M^{max}	Flow limit between microgrid and the main grid
Pr_M^{Outage}	Probability of main grid power outage
q	Number of handled containers
RS	Energy generated or consumed at port from renewable sources as percentage of the total power generated or consumed by port activities
SSI	Number of safety and security incidents due to power loss

Variables

LS	load shedding
P	DER output power
P_M^+	Power bought from main grid
P_M^-	Power sold to main grid
x	DER investment state

Abbreviations

KPIs	Key Performance Indicators
SEgI	Smart Energy Index
SEnI	Smart Environment Index
SPI	Smart Port Index
SSSI	Smart Safety and Security Index
TEUs	Twenty-Foot Equivalent Units

cure, high-quality, and green energy they provide, opens up opportunities for technology integration, capacity expansion, sustainability enhancement, and business continuity to further improve the port's smartness.

In this paper, we discuss how the adoption of microgrids can systematically improve a port's performance in its four main activity domains: operations, environment, energy, safety and security. Then we propose a set of Smart Port Index (SPI) metrics [5] to quantitatively evaluate the benefits that microgrids could contribute to those domains. This index is expected to impact the decision-making process for both the port authorities and government/regulatory authorities. More specifically, the use of this index enables port authorities to measure and investigate a port's performance for different applications, based on which future strategic plans and organizational policies can be developed for long-term growth and resource optimization. For the regional/state government, the potential benefits include regulation and policy success for social well-being, quality of life, and sustainable development, as well as critical insights in managing large consumer-facing businesses that have been impacted by disruptive technological changes. Overall, we are aiming to provide criteria for answering the question of: *for a port entity, is it a meaningful decision to integrate the microgrid?*

A two-stage stochastic mixed-integer programming model is developed to demonstrate how this index can significantly improve the smartness of the port when it is used in the context of port operation and management during port planning. The model consists of two stages: 1) an *investment* master problem to determine the optimal installation status of the DERs, and 2) a multi-objective *operation* planning subproblem to decide on the optimal hourly power generation, load shedding, and power flow between the microgrid and the utility grid (i.e., main grid). The stochastic model considers the inherent operation uncertainties associated with renewable power generation and power outage. Benders decomposition and Lexicographic Goal Programming are proposed to solve the model. Case studies are then performed to evaluate the use of microgrid at the Barbours Cut Terminal in the Port of Houston.

The contributions of this paper include:

1. A rigorous process is proposed to evaluate how microgrids can systematically address the current challenges the ports are facing and enhance their performance in different activity domains through a set of SPI metrics. Our work is one of the pioneering research efforts to evaluate and quantify the benefits provided by microgrids to create sustainable values for a smart port.
2. Propose a novel two-stage stochastic mixed-integer programming approach that allows different stakeholders, such as regulators, port authorities, and industrial partners, to evaluate how the incorporation of a microgrid can help a port optimize its performance within a given budget.
3. Without the loss of generality, policy studies are performed in this paper, paired with realistic data, to demonstrate and verify how the utilization of the proposed approach can effectively improve the operation of the Barbours Cut terminal at the Port of Houston compared with the conventional microgrid planning approach that does not consider the domain-specific characteristics of maritime ports.

The remainder of this manuscript is organized as follows. Section II explains the SPI for the port microgrid. Section III formulates the mathematical model. The model is tested under different operation scenarios and policy settings in Section IV. Conclusions are drawn in Section V.

2. Smart Port Microgrid Index

2.1. Background

Electricity has become the dominant medium to integrate, store, and transport energy, and thus is playing a critical role in the global energy supply chain. With large numbers of operations demanding significant power, there are many existing and ongoing efforts around the world to create integrated energy, sustainability, and business solutions that incorporate the concept of microgrids.

In the United States, Port of Los Angeles (POLA) has recently invested $27 million in microgrid development and distributed clean energy resource technologies. As a demonstration project, a microgrid that incorporates a 1 MW solar PV array, an on-shore 2.6 MWh battery storage system, and the associated electrical infrastructure upgrade has been completed in the Omni Terminal and expected to serve as a model for the modernization of 26 other marine cargo terminals at POLA. Port of Long Beach (POLB) has been evaluating microgrid development to support the port's Energy Island Initiative. The evaluation concluded that the development of a microgrid would effectively assist POLB's transition toward renewable energy and serve the port's needs for energy reliability (i.e., the continuity of energy supply), power quality (i.e., free of voltage/frequency deviations and harmonic distortions), and economic stability [1, 22]. In 2018, Port of San Diego was awarded $5 million grant from California Energy Commission for the installation of a renewable-energy-based microgrid at the Tenth Avenue Marine Terminal [6]. The project includes the installation of solar PV panels, battery energy storage, a microgrid controller, and other infrastructure improvements to provide back-up power to port-operated facilities and support military deployment activities.

In Europe, the city of Rotterdam has been partnering with General Electric to transform the Port of Rotterdam into a virtual power plant (VPP) that consisting of a coordinated cluster of microgrids. Built on thermal and renewable power production, the Port is expected to function as a smart energy grid with reduced emissions, enha nced demand-side management, and increased energy efficiency [16]. Microgrids can be especially helpful where shore-to-ship power transfer is offered to reduce the emissions and noise levels of vessels docked in port. As a representative example, Port of Gothenburg has the first 50/60 Hz shore connection in Sweden and shore-side power supply to a vast number of cargo vessels while at berth featuring fully automated power transfer. Port of Dalian in China, Port of Fincantieri in Italy, Port of Ystad in Sweden, and Port of Moin at Costa Rica, among others, are instances of a broader effort to electrify the processes, services, and equipment [29].

2.2. Targeted Port Activity Domains

A smart port consists of four main activity domains: operations, environment, energy, and safety and security. This section shows how the adoption of a well-designed microgrid can potentially enhance the performance of a port in those activity domains.

1. *Operation*: The main operation of the port is to load and unload cargo and containers from received vessels and handle the process of transporting the cargo to warehouses or other destinations. To support the ever-increasing import and export tonnage and cargo transportation resulted from the continuing economic globalization, a smart port microgrid is expected to meet a port's dynamic energy demand in an adaptive, flexible and expandable manner. The abundant generation and distribution capacity assures that the demand of terminal equipment, such as cranes and manifolds can always be met, thus improves the productivity of terminal operators to handle large volumes of cargo and truck traffic, reduce container dwell time and terminal congestion, and thus greatly enhance the throughput of the operation to meet the growing capacity demand [34, 35].
2. *Environment*: Environmental impacts of the port activities reduce social welfare and pose a threat to the survival of living creatures. Therefore, port authorities are facing constant critiques of producing a significant quantity of pollutants and contributing to a range of biophysical problems to the site and the neighboring residential communities [21]. This has caused critical challenges for port

management and menaced the ports' endurance in the future competitive era [23]. Towards this end, a microgrid-based energy infrastructure encourages the collaboration of sustainable initiatives, ecological regenerations, and zero-net energy goals by utilizing renewable and clean energy sources by purposeful planning and preparation. Providing environmentally responsible energy promotes the port's role in meeting the imperative to combat climate change and address the existing environmental problems, and thus minimizes the port's negative impact on the environment and public health ([26], [4]).

3. *Energy*: In the face of ever-increasing energy consumption and costs, a smart port microgrid provides a unique opportunity for integrating the latest smart grid technologies to improve energy functionality and enable advanced management and control of energy consumption [24, 20]. This allows the port to be constantly operated in an efficient and economical way to reduce peak-hour capacity demand, decrease net energy consumption and mitigate peak-hour costs while meeting the power demand and power quality requirements from different sectors and facilities. Additionally, microgrids present opportunities in integrating renewable generations, such as wind generation, solar generation, and on-site bioenergy due to the potential large quantities of biomass accumulate in and around the harbor areas. This is an efficient approach for land use in ports and facilitates the reduction in the consumption of traditional fossil fuels [27, 39].
4. *Safety and Security*: Ports can be vulnerable to a sequence of safety and security issues during a power outage [35, 32]. Equipped with local distributed generation and energy storage resources, a smart port microgrid is able to add significant power safety and security to the ports as it enables continuous and seamless power supply for persistent monitoring and control of facilities, prevents accidents and incidents that may occur during the absence of power, maintains critical loads such as fire stations, information and communication facilities, electricity-dependent security measures (e.g. electric gates, electric fences, surveillance cameras), and emergency transportation systems along the ship channel. Eventually, a microgrid creates redundancy and back-up power to increases port preparedness and resilience to prolonged outages. This is particularly important due to the recent trend that weather-related extreme events are happening in higher frequency and severity which have become the new norm [34, 17].

2.3. Microgrid-Based Smart Port Index

SPI uses four sub-indices for measuring the performance of a smart port in the aforementioned four key activity domains. Those sub-indices are named Smart Operations Index (SOI), Smart Energy Index (SEgI), Smart Environment Index (SEnI), Smart Safety and Security Index (SSSI), respectively. SPI is then formulated as a convex combination of these four sub-indices.

This section provides further context to the specific design attributes of each operation domain concerning microgrid integration. Tables 1, 2, 3, and 4 present the key performance indicators (KPIs) that we use for quantifying the effect of microgrid implementation on the smart port performance.

Table 1
KPIs for quantifying Smart Operations Index

1. Annual twenty-foot equivalent units (TEUs)/Total terminal area
2. Annual cargo tonnage/Total terminal area
3. Annual throughput in TEU per number of cargo handling equipment, trucks, locomotives, and harbor craft
4. Total TEUs per number of container vessels calling the port

Table 2
KPIs for quantifying Smart Energy Index

1. Total energy consumption (primary energy) by port authority per total port area (kWh/m^2)
2. Total energy consumption (primary energy) by the container terminals per total terminal area (KWh/m^2)
3. Percentage of energy from renewable resources
4. Energy saved due to conservation and efficiency improvements

Table 3
KPIs for quantifying Smart Environment Index

1. Emissions from all port activities per total port area
2. Total annual greenhouse gases (GHG) per vessels calling the port

Table 4
KPIs for quantifying Smart Safety and Security Index

1. Annual number of nautical accidents (significant or incidents in areas under the jurisdiction of the port authorities)
2. Annual number of failure to comply (port regulations, industry safety standards, etc.)
3. Annual number of fires and explosions (either nautical or industrial)
4. Annual number of security issues

KPIs should be normalized and preprocessed before being used for the sub-index calculations. Each sub-index is a convex combination of the associated processed KPIs [5]. Here, the KPIs are preprocessed to make sure that sub-indices take values in the range of [0,1]. Hence, SPI always varies between 0 and 1 throughout this paper.

3. Problem Formulation and Solution Methodology

3.1. Modeling the Benefits of Microgrid for the Port Performance

Based on the previous discussion, it is evident that ports are critical infrastructure with significant power demands, and their successful operations heavily rely on high-quality and reliable power supplies. The first benefit of microgrid deployment is that it encourages effective use of electricity and enables better energy management by differentiating types of loads and establishing their priorities [33, 12]. Hence, we divide the port power demand into three types: critical loads (denoted by superscript V), high priority loads (referred to by superscript H), and low priority loads (indicated by superscript L) as follows:

$$D_{hmy} \quad = \quad D^{V}_{hmy} + D^{H}_{hmy} + D^{L}_{hmy} \quad \forall h, m, y \tag{1}$$

Critical loads in ports mainly consist of power demand for safety and security purposes and cannot be shed. These loads are only subject to the power outage. High priority loads include all the essential load that is necessary for the successful operation of the port and handling the containers and cargo (e.g., the power required for electric cranes, onshore power supply, and electric trucks). High priority loads are both subject to load shedding and power outage. Low priority loads are those that are considered non-essential and thus do not impact the throughput and main operation of the port (e.g., extra power consumption in buildings and offices). Same as high priority loads, these can are subject to both load shedding and power outage. However, it is commonly assumed that the value of lost load associated with low priority loads is much lower than the higher priority ones.

For managing the power balance for each type of demand, it is necessary to define the variables associated with each demand type. These variables include power generation from DERs, charged and discharged power from the storage units, power flow between the microgrid and the main grid, as well as the load curtailment. Based on the provided explanations and similar to what is described for D_{hmy} in Equation (1), variables P_{ihmy}, P^{ch}_{ihmy}, P^{dch}_{ihmy}, $P^{+}_{M,hmy}$, $P^{-}_{M,hmy}$ each can be divided into three sets of variables associated with critical, high priority, and low priority loads. The set of variables corresponding to load shedding (i.e., LS_{hmy}) each consists of two sets of variables related to high priority and low priority loads.

For the high priority loads, the on-site generation capacity expansion by deploying microgrid effectively enhances the port operation, which leads to increased annual throughput and can be reflected by the KPIs in Table 1. The throughput of the port operations is commonly measured by either TEU for the number of containers or by cargo tonnage for the weight of the cargo. Cargo tonnage can be estimated by TEUs. Therefore, the Smart Operations Index (SOI) can be represented by the total handled containers (the multiplication of the number of handled containers per supplied power, q_{hmy}, and the total amount of satisfied power demand) divided by the desired value for the total handled containers during the planning horizon (2). Note that Pr is the parameter referring to the probability of main grid power outage. Hence, the total amount of satisfied power demand is $\sum_h \sum_m \sum_y D^{H}_{hmy} - (LS^{H}_{hmy} + Pr^{Outage}_{M,hmy} P^{H,+}_{M,hmy})$.

$$\begin{aligned} SOI \quad = \quad & \frac{\sum_h \sum_m \sum_y q_{hmy} D^{H}_{hmy}}{q^{max}_{T}} \\ & - \frac{\sum_h \sum_m \sum_y q_{hmy}(LS^{H}_{hmy} + Pr^{Outage}_{M,hmy} P^{H,+}_{M,hmy})}{q^{max}_{T}} \end{aligned} \tag{2}$$

Note that the port power demand, D_{hmy}, varies continuously. Therefore, its value can alternate based on specific load growth patterns for each time slot throughout the planning horizon.

There are two variables for measuring KPIs in Table 2 that are affected by microgrid installation: net energy consumption and renewable energy generation. Hence, we define the Smart Energy Index (SEgI), as a measure of integrating the latest energy-related functionalities, in the form of a convex combination of the three terms: 1) renewable generation from both DERs within the port microgrid and the main grid, 2) energy consumption reduction as seen by the main grid, and 3) energy efficiency improvement (Equation (3)). Note that the power supply from the main grid is associated with a probability of outage. The first term in Equation (3) refers to the renewable generation from all of the sources divided by the goal value for the total renewable generation (i.e., RS^{max}_{T}). The second term measures the energy consumption reduction during the entire planning horizon due to on-site generation and storage resources as well as net energy usage conservation such as demand-side management techniques, given the microgrid's ability to control electricity imports by utilizing the on-site generation and storage. The third term is the cost resulted from curtailing low priority loads divided by the maximum load shedding cost (COL). Maximizing this term increases the portion of load shedding cost associated with low priority loads to assure the load shedding operation comprises mostly of low priority loads. Coefficient terms γ_{rs}, γ_{eg}, and γ_{ls} in this equation can be determined based on the relative importance of the renewable generation, reduction in the load demand as seen by the main grid, and saving energy by reducing low priority loads. Coefficient terms γ_{rs}, γ_{eg}, and γ_{ls} vary in the range of [0,1] and $\gamma_{rs} + \gamma_{eg} + \gamma_{ls} = 1$.

$$\begin{aligned} SEgI \quad = \quad & \gamma_{rs}\Big(\frac{\sum_h \sum_m \sum_y \sum_{i \in G,W} RS_i P_{ihmy}}{RS^{max}_{T}} \\ & + \frac{RS_M(1 - Pr^{Outage}_{M,hmy})P^{+}_{M,hmy}}{RS^{max}_{T}}\Big) \\ & + \gamma_{eg}\Big(\frac{\sum_h \sum_m \sum_y D_{hmy}}{D_T} - \frac{\sum_h \sum_m \sum_y (1 - Pr^{Outage}_{M,hmy})P^{+}_{M,hmy}}{D_T}\Big) \\ & + \gamma_{ls}\Big(\frac{\sum_h \sum_m \sum_y \upsilon^{L}_{hmy} LS^{L}_{hmy}}{COL^{max}_{T}}\Big) \end{aligned} \tag{3}$$

Under the assumption that each power source is associated with an emission rate per power provided, we define the Smart Environment Index (SEnI) as the mitigated emission rate (Equation (4)). This equation measures the gap between the desired value of SEnI (i.e., $SEnI^{max}$) and the total amount of the emission produced by the different sources per maximum potential amount of emission (i.e., EM^{max}_{T}). Maximizing this sub-index reduces the total emission of a port (second term in the Equation (4)). This equation can be applied to different air pollutants (based on the goals of the port authority) or can be used to measure all of them together by using a simple scaling method (e.g., using CO_2e which is CO_2 equivalent representation of the other greenhouse gasses) [36].

$$SEnI = SEnI^{max} - \frac{\sum_h \sum_m \sum_y \sum_{i\in G,W} \Big(EM_i P_{ihmy}}{EM_T^{max}} + \frac{EM_M(1 - Pr_{M,hmy}^{Outage})P_{M,hmy}^{+}\Big)}{EM_T^{max}} \quad (4)$$

It is expected that the enhanced reliability and resiliency of the power supply by microgrids leads to a reduced number of safety and security incidents caused by power outages. Thus, the Smart Safety and Security Index (SSSI) is quantified by the reduced number of safety and security incidents (Equation (5)). The first term in this equation is the goal value of SSSI (i.e., $SSSI^{max}$) and the second term refers to the number of safety and security incidents that occur due to the loss of power (i.e., SSI) divided by SSI_T^{max}.

$$SSSI = SSSI^{max} - \frac{\sum_h \sum_m \sum_y SSI_{hmy} Pr_{M,hmy}^{Outage} P_{M,hmy}^{V,+}}{SSI_T^{max}} \quad (5)$$

Note that based on our definition, all of the indices presented in Equations (2)–(5) take values in the range of [0,1] and their goal values are 1.

3.2. Uncertain Parameters in Port Microgrid Operation

The error of the renewable generation forecast is a major source of uncertainty. A high degree of renewable energy resources, commonly wind and solar energy, are utilized in microgrids that would produce power that is variable and stochastic [9]. Another source of uncertainty is the probability of disruptions in the main grid. A grid-connected microgrid can switch to island mode to maintain uninterrupted functioning when there is a disturbance in the upstream distribution network. It can switch back to the grid-connected mode and resynchronize with the utility grid when the disturbance is cleared. Such disturbances are often random events, and therefore, in this paper, we use the outage probability to capture the effects of major outages in the main grid to the port.

3.3. Two-Stage Stochastic Mixed-Integer Model

To obtain the optimal decisions while dealing with the uncertainties, we propose an optimization approach in which two optimization stages are solved to address "Investment Planning" and "Operation Planning", respectively (Figure 1). The investment master problem on the first stage is formulated in the form of an integer programming model while the operation planning subproblem on the second stage is formulated as a linear programming model. The master problem determines the optimal installation status of the DERs while the subproblem determines the optimal mix of generation and schedule of the DERs, load shedding, and hourly flow between the microgrid and main grid. Benders Decomposition is implemented and at each iteration, feasibility and optimality cuts are introduced to improve the optimal solution of the master problem.

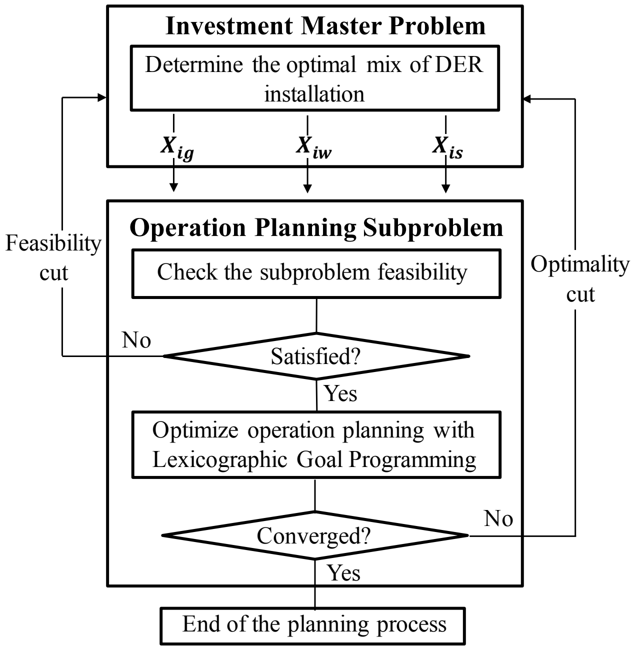


Fig. 1. Microgrid planning with Two-Stage Stochastic Programming and Lexicographic Goal Programming

The investment master problem aims to determine the optimal installation mix of dispatchable, nondispatchable, and storage units as follows:

$$\max_{x_i} \quad E_\omega[Q_\omega(x_i)] \quad (6)$$

$$s.t. \quad D_y^{max} \le \sum_{i\in G,W,S} P_i^{max} x_i \quad \forall y \quad (7)$$

$$x_i \in \{0,1\}, \quad i \in G,W,S \quad (8)$$

The objective of the master problem is to maximize the expected value of the Q_ω over the set of scenarios (6). This term is associated with the subproblem objective function and will be determined by the optimality cuts that will be added to the master problem. Constraint (7) makes sure that the capacity of the installed DERs meets the annual peak load. This constraint is necessary for the self-sustainable operation of the port microgrid as a continually used asset. Constraint (8) states that the variables associated with the installation status of the DERs are binary.

The aim of the operation subproblem on the second stage is to maximize the SPI, which is a convex combination of the four sub-indices defined in Section III.B. However, determining the weight parameters paired with each sub-index is beyond the scope of this paper. In fact, the customizable nature of a microgrid suggests that different priority goals can always be addressed with unique solutions. Therefore, Goal Programming is used in the model formulation to eliminate the need for explicitly specifying the weight parameters. Thus, the objective becomes maximizing multiple goals, which are SOI, SEgI, SEnI, and SSSI (9). In the goal programming, when the goals follow a dominance order, the goal with the highest dominance has to be optimized first. For instance, if there are N goals that follow a dominance order, i.e., goal n should be optimized first, before considering goal m where $n < m$, then we can implement a sequential algorithm (Fig. 2). When the desired values for the goals are known beforehand, this particular model is named Lexicographic [8]. As previously explained, the maximum value for each of the indices (i.e., goals) is known to be 1. Hence, Lexicographic Goal Programming is deemed appropriate for our problem.

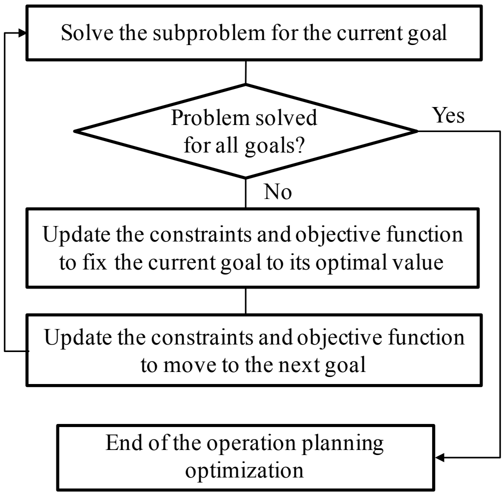


Fig. 2. Lexicographic Goal Programming for the operation planning subproblem

SP objective function given $\hat{x}_i$ (i.e., outputs of the first stage) and for scenario $\omega \in \Omega$ is provided in Equation (9).

$$Q_\omega(\bar{x}_i) = max_{x,P,LS}[SOI_\omega, SEgI_\omega, SEnI_\omega, SSSI_\omega] \quad (9)$$

Budget constraint ensures that total investment cost and operation cost does not exceed the available budget (10). The investment cost of generating units (dispatchable and nondispatchable) depends on their generating capacity. The investment cost of energy storage systems is based on the rated power and rated energy storage capacity. The total operation cost includes: 1) generation cost of dispatchable units, 2) the cost of energy purchase from the main grid, 3) revenue from selling power to the main grid, and 4) the cost of unserved energy. It is assumed that the generation cost of nondispatchable units and energy storage systems are zero due to their renewable nature. The total cost is calculated in the form of present-worth value and incorporates the discount rates. The discount rate refers to the interest rate used to determine the present value and deals with the effect of time on the worth of the money [18].

$$\begin{aligned}&\sum_y \sum_{i\in G,W} \kappa_y CC_{iy} P_i^{max}\hat{x}_i \\ &+ \sum_y \sum_{i\in S} \kappa_y (CP_{iy}P_i^{max} + CE_{iy}C_i^{max})\hat{x}_i \\ &+ \sum_h \sum_m \sum_y \sum_{i\in G} \kappa_y c_i P_{ihmy,\omega} \\ &+ \sum_h \sum_m \sum_y \kappa_y \rho_{hmy}(P^+_{M,hmy,\omega} - P^-_{M,hmy,\omega}) \\ &+ \sum_h \sum_m \sum_y \kappa_y (\upsilon^H_{hmy} LS^H_{hmy,\omega} + \upsilon^L_{hmy} LS^L_{hmy,\omega}) \le B \quad (10)\end{aligned}$$

Constraints (11)-(13) create the hourly power balance for critical, high priority, and low priority loads. The hourly load demand can be either satisfied by power generation from the DERs or through power purchased from the main grid. Storage units can be both charged or discharged during each time slot, but the net discharged quantity counts toward demand satisfaction. The microgrid can either buy power from ($P^+_{M,hmy,\omega}$) or sell power to ($P^-_{M,hmy,\omega}$) the main grid. There is also the option to partially or totally curtail high priority and low priority loads to assure that power balance is always valid.

$$\begin{aligned}&\sum_{i\in G,W} P^V_{ihmy,\omega} + \sum_{i\in S}(P^{dch,V}_{ihmy,\omega} - P^{ch,V}_{ihmy,\omega}) \\ &+ P^{V,+}_{M,hmy,\omega} - P^{V,-}_{M,hmy,\omega} = D^V_{hmy} \quad \forall h,m,y \quad (11)\end{aligned}$$

$$\begin{aligned}&\sum_{i\in G,W} P^H_{ihmy,\omega} + \sum_{i\in S}(P^{dch,H}_{ihmy,\omega} - P^{ch,H}_{ihmy,\omega}) \\ &+ P^{H,+}_{M,hmy,\omega} - P^{H,-}_{M,hmy,\omega} + LS^H_{hmy,\omega} = D^H_{hmy} \; \forall h,m,y \quad (12)\end{aligned}$$

$$\begin{aligned}&\sum_{i\in G,W} P^L_{ihmy,\omega} + \sum_{i\in S}(P^{dch,L}_{ihmy,\omega} - P^{ch,L}_{ihmy,\omega}) \\ &+ P^{L,+}_{M,hmy,\omega} - P^{L,-}_{M,hmy,\omega} + LS^L_{hmy,\omega} = D^L_{hmy} \; \forall h,m,y \quad (13)\end{aligned}$$

Equations (14) and (15) control the flow limit between the microgrid and the main grid. The microgrid could benefit from generating power at peak hours to supply local loads and sell the excess power to the main grid at an appropriate price.

$$P^-_{M,hmy,\omega} \le P^{max}_M \qquad \forall h,m,y \quad (14)$$

$$P^+_{M,hmy,\omega} \le P^{max}_M \qquad \forall h,m,y \quad (15)$$

The dispatchable units generation capacity and forecasts for nondispatchable units generation are captured by Equations (16) and (17).

$$P_{ihmy,\omega} \le P^{max}_i \hat{x}_i \qquad \forall i \in G, \forall h,m,y \quad (16)$$

$$P_{ihmy,\omega} = P^{max}_i \hat{x}_i \qquad \forall i \in W, \forall h,m,y \quad (17)$$

The charging (18) and discharging (19) limits of storage units, and the available stored energy at each hour (charged amount minus discharged amount considering the efficiency rate) are also considered (Equations (20) and (21)). The main benefit of the storage units is that they compensate for the variation associated with the renewable power generation. Also, the energy storage system could be charged at low price hours and discharged at high price hours. This assists in revenue generation and cost reduction.

$$P^{ch}_{ihmy,\omega} \le P^{ch,max}_i \hat{x}_i \qquad \forall i \in S, \forall h,m,y \quad (18)$$

$$P^{dch}_{ihmy,\omega} \le P^{dch,max}_i \hat{x}_i \qquad \forall i \in S, \forall h,m,y \quad (19)$$

$$0 \le \sum_{k\le h}\left(P^{ch}_{ikmy,\omega} - \frac{P^{dch}_{ikmy,\omega}}{\eta_i}\right) \qquad \forall i \in S, \forall h,m,y \quad (20)$$

$$\sum_{k\le h}\left(P^{ch}_{ikmy,\omega} - \frac{P^{dch}_{ikmy,\omega}}{\eta_i}\right) \le C^{max}_i \hat{x}_i \qquad \forall i \in S, \forall h,m,y \quad (21)$$

Constraints (22)-(25) establish the relation between the binary variables for DERs installation status and the continuous variables for DERs power generation.

$$\hat{x}_i \le K \sum_h \sum_m \sum_y P_{ihmy,\omega} \qquad \forall i \in G \tag{22}$$

$$\hat{x}_i \le K \sum_h \sum_m \sum_y P_{ihmy,\omega} \qquad \forall i \in W \tag{23}$$

$$\hat{x}_i \le K \sum_h \sum_m \sum_y P^{ch}_{ihmy,\omega} \qquad \forall i \in S \tag{24}$$

$$\hat{x}_i \le K \sum_h \sum_m \sum_y P^{dch}_{ihmy,\omega} \qquad \forall i \in S \tag{25}$$

Constraint (26) and (27) limit the curtailed load for each type of load.

$$LS^H_{hmy,\omega} \le \lambda^H D^H_{hmy} \qquad \forall h, m, y \tag{26}$$

$$LS^L_{hmy,\omega} \le \lambda^L D^L_{hmy} \qquad \forall h, m, y \tag{27}$$

Equations (28) to (39) specify the range of the variables.

$$P_{ihmy,\omega} \ge 0 \qquad \forall i \in G, W, \forall h, m, y \tag{28}$$

$$P^{ch}_{ihmy,\omega} \ge 0 \qquad \forall i \in S, \forall h, m, y \tag{29}$$

$$P^{dch}_{ihmy,\omega} \ge 0 \qquad \forall i \in S, \forall h, m, y \tag{30}$$

$$P^{+}_{M,hmy,\omega} \ge 0 \qquad \forall h, m, y \tag{31}$$

$$P^{-}_{M,hmy,\omega} \ge 0 \qquad \forall h, m, y \tag{32}$$

$$LS_{hmy,\omega} \ge 0 \qquad \forall h, m, y \tag{33}$$

$$P^V_{ihmy,\omega}, P^H_{ihmy,\omega}, P^L_{ihmy,\omega} \ge 0 \qquad \forall i \in G, W, \forall h, m, y \tag{34}$$

$$P^{ch,V}_{ihmy,\omega}, P^{ch,H}_{ihmy,\omega}, P^{ch,L}_{ihmy,\omega} \ge 0 \qquad \forall i \in S, \forall h, m, y \tag{35}$$

$$P^{dch,V}_{ihmy,\omega}, P^{dch,H}_{ihmy,\omega}, P^{dch,L}_{ihmy,\omega} \ge 0 \qquad \forall i \in S, \forall h, m, y \tag{36}$$

$$P^{V,+}_{M,hmy,\omega}, P^{H,+}_{M,hmy,\omega}, P^{L,+}_{M,hmy,\omega} \ge 0 \qquad \forall h, m, y \tag{37}$$

$$P^{V,-}_{M,hmy,\omega}, P^{H,-}_{M,hmy,\omega}, P^{L,-}_{M,hmy,\omega} \ge 0 \qquad \forall h, m, y \tag{38}$$

$$LS^H_{hmy,\omega}, LS^L_{hmy,\omega} \ge 0 \qquad \forall h, m, y \tag{39}$$

4. Numerical Results

In this section, we will demonstrate how the proposed framework can be used to identify the best approach to systematically and holistically improve a port's performance through the integration of the microgrid.

As a particular example, we consider the port microgrid planning for the Barbours Cut terminal at the Port of Houston. As the nation's largest export port, the Port of Houston has a 50-mile long ship channel that moves over 8000 ocean-going vessels and 200K barges each year with over $265 Billion in economic activity in Texas and more than 617 Billion nationwide. As the main deepwater container terminal in the Port of Houston, Barbours Cut is one of the world's busiest ports by cargo tonnage and currently going through the modernization program to increase cargo handling efficiency and capacity. In this paper, we are evaluating the implementation of a microgrid which can support the transformation of Barbours Cut into an all-electric terminal to fulfill the port responsibilities for its public and private partners while achieving the goal of zero emission (Figure 3).

Table 5
Dispatchable units characteristics

Unit No.	Rated Power (MW)	Cost Coefficient ($/MWh)	Annualized Investment Cost ($/MW)
1	5	90	110950
2	5	90	110950
3	3	70	155330
4	3	70	155330
5	2	60	221900
6	2	60	221900

Table 6
Nondispatchable units characteristics

Unit No.	Rated Power (MW)	Cost Coefficient ($/MWh)	Annualized Investment Cost ($/MW)
1	2	0	266280
2	2	0	399419

Table 7
Storage units characteristics

Unit No.	Rated Power (MW)	Rated Energy (MW)	Annualized Investment Cost-Power ($/MW)	Annualized Investment Cost-Energy ($/MW)
1	1	6	133140	66570
2	2	6	66570	66570
3	3	6	44380	66570

We consider the planning horizon to be ten years. Model inputs corresponding to the DERs are given in Tables 5 and 6 and energy storage efficiency (η) is considered to be 90% for all the storage units [3]. The base year peak load is 20 MW, and this peak demand increases by 0.5 MW each year. Load demand varies in the range of [10,24.5] in MW throughout the day [22]. The fraction of critical loads, high priority loads, and low priority loads is set at 30%, 60%, and 10% of the total power demand, respectively. We assume that clean and green sources of energy are not significantly included in the utility grid power supply (i.e., $RS_M = 0$). The coefficient of present-worth value for the first year (κ_1) is 1.02, and for the rest of the years, it is calculated based on the first year value (i.e., $\kappa_y = 1/(1+\kappa_1)^{t-1}$). Market price ($\rho$) fluctuates in the range of [9.87,103.91] ($/MWh) [38]. Parameters associated with SPI calculations such as emission production of the main grid per provided power (EM_M), safety and security incidents per unit of lost power (SSI), energy consumption of the main grid from renewable sources (RS_M) are gathered from the Port of Houston annual reports [10, 28]. The

Fig. 3. Future Barbours Cut terminal in the Port of Houston equipped with microgrid and electric facilities

weight coefficients for SPI calculation based on the four sub-indices are considered to be equal (i.e., *weights* = 0.25). Note that SPI calculation itself is performed only for comparing the results and it is not involved in the optimization model.

Normal probability distribution functions and historical data are used to generate random values for the renewable generation forecasts [40, 11, 37] and probability of power outage [25, 7] at each time slot. 25 scenarios are generated for each uncertain parameter using Latin Hypercube Sampling to represent the uncertainties [19, 2]. Scenario reduction is applied to reduce the computation efforts while maintaining the solution accuracy using the GAMS SCENRED tool [13]. Hence, the initially generated 15625 scenarios were reduced to 25 scenarios using SCENRED.

Model (6)-(39) has been implemented in GAMS [30] and solved by CPLEX 12.6.1.0 [15] on a Linux server with 128 GB of RAM and 24 processors at 2.53 GHz.

Three case studies are designed to study the model performance:

Case 1) Base Case: Planning without microgrid installation

Case 2) Minimum Cost Model: Microgrid planning with the objective of minimizing the cost

Case 3) Maximum SPI Model: Microgrid planning with the objective of maximizing the SPI sub-indices

Tables 8 and 9 present the experiment results including the SPI and SPI sub-indices and detailed information for each case.

4.1. Base Case

As the performance benchmark, the base design case is developed to determine the optimal strategy for the port entity to meet the terminal's power demand through purchasing power from the main grid and performing hourly load shedding at a minimum cost. This case can be viewed as the traditional approach of terminal operation planning without microgrid integration, and the terminal only has a small backup generator (i.e., rated power = 0.5 MW, cost coefficient = 60 \$/MWh, annualized investment cost = 55475 \$/MW) for supporting critical loads when power is not available from the main grid. We assume that with no installation of microgrids, no DERs are deployed in the investment master problem. Thus, the operation subproblem is to find the minimum cost of supplying loads relying on the main grid for the planning horizon. In this case, the port is not able to fully distinguish and control different load types. Hence, decision variables in the model are not determined for each load type. To calculate the sub-indices without having the load-specific variables, we estimate variables for each load type by considering the associated demand ratios (0.3, 0.6, and 0.1 for critical, high priority, and low priority loads).

Additionally, Equations (11)-(13) will be merged into Equation (40).

$$\begin{aligned}
&\sum_{i \in G,W} P_{ihmy,\omega} + \sum_{i \in S} (P^{dch}_{ihmy,\omega} - P^{ch}_{ihmy,\omega}) \\
&+ P^{+}_{M,hmy,\omega} - P^{-}_{M,hmy,\omega} \\
&+ LS_{hmy,\omega} = D_{hmy} \quad \forall h, m, y
\end{aligned} \tag{40}$$

The results in Tables 8 and 9 indicate that the total cost of this case is 72.1556 million dollars, and the resulted SPI is 0.50. A total amount of 18480 MW power is saved (LS^{L}_{T}) which is the lowest compared in all three cases. Under the assumption that the penetration of clean and green sources of energy in the main grid is negligible, relying on the power supply from the main grid results in a low SEgI (0.06). Meanwhile, SOI is maintained at a relatively high level (0.84) due to the high cost associated with the curtailment of high priority loads and the setting of an upper bound for load shedding. SSSI is also high (0.95) due to the existence of the backup generator. With no renewable sources used in this case, the CO_2 emission level is at a high quantity of 7882.646 kilotons. No power is sold back to the main grid (i.e., $P^{-}_{M,T} = 0$). The expected saved power by curtailing low priority loads is 18480 MW.

Table 8
Comparison of indices

Case	SOI	SEgI	SEnI	SSSI	SPI
1) Base case	0.84	0.06	0.141	0.95	**0.50**
2) Minimum cost model	0.87	0.19	0.58	0.98	**0.66**
3) Maximum SPI model	0.99	0.50	0.81	1	**0.82**

Table 9
Comparison of Results for Three Cases

	Case 1	Case 2	Case 3
Cost ($ million)	72.1556	103.3447	137.7110
LS_T^L (MW of saved power)	18480	114480	131184
q_T (# of TEUs)	16397830	16983460	19326000
CO_{2T} (kilotons)	7882.646	6676.235	3063.924
RS_T (MW)	0	174600	732691
SSI_T	6	2	0
$P_{M,T}^{+}$ (MW)	1127026	888078	0
$P_{M,T}^{-}$ (MW)	0	36491	354

4.2. Minimum Cost Model

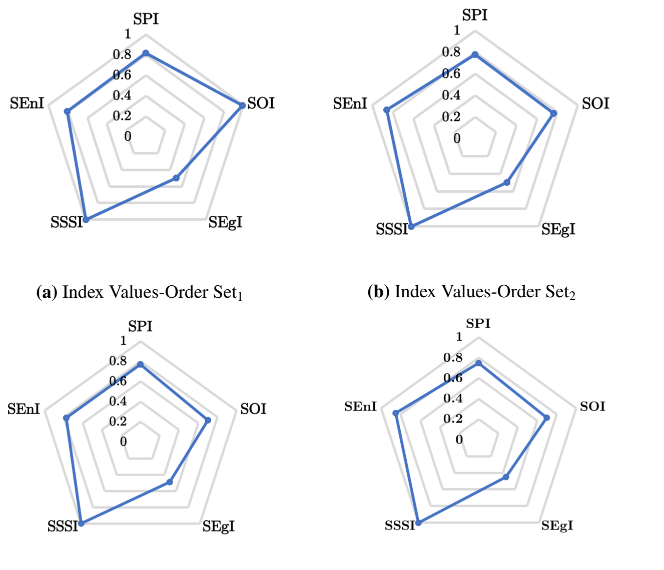
This case presents the conventional approach to microgrid planning with the objective of cost minimization. The objective function of the master problem is the investment cost (i.e., the first two terms in Equation (10)) plus the expected operation cost as defined in Equation (41). The latter is obtained by the optimality cuts that are added to the master problem.

$$\min_{x_i} \sum_{y} \sum_{i \in G,W} \kappa_y CC_{iy} P_i^{max} x_i + \sum_{y} \sum_{i \in S} \kappa_y (CP_{iy} P_i^{max} + CE_{iy} C_i^{max}) x_i + E_\omega [Q_\omega^{'}(x_i)] \quad (41)$$

The constraints of the investment master problem include Equations (7) and (8). The objective function of the operation subproblem is the operation cost. Therefore, the budget constraint, as described in Equation (10), is removed from the set of subproblem constraints. Results obtained from this case indicate that DERs with lowest overall cost (i.e., 5 dispatchable units (units 1, 2, 3, 4, and 6), 1 nondispatchable unit (unit 1), and 2 storage units (units 1 and 3)) are installed to satisfy the annual peak load constraint as described in Equation (7). However, the energy is purchased from the main grid, or the power demand is curtailed whenever the cost of doing such is lower than the cost of the DER on-site generation. We observe that the total cost, in this case, is 103.3447 million dollars. With the installation of renewable DERs, there is an improvement in the energy and environment portion compared with Case 1. However, it is evident that a cost-driven planning approach leads to limited improvement in SPI as it does not fully capture the unique nature and operation characteristics of a port.

4.3. Maximum SPI Model

In this case, we solve the model presented in Equations (6) through (39). This model incorporates all the performance metrics of operational, environmental, energy-related, and safety and security aspects of the port activities as identified and modeled in Section II.C with a pre-specified budget constraint (10). For the preemptive goal programming, we consider that the following dominance order exists in terms of the priorities: SOI ≥ SEgI ≥ SEnI ≥ SSSI. The results of this case study indicate that 4 dispatchable units (units 1, 2, 3, and 4), 1 nondispatchable unit (unit 2), and 3 storage units are installed. The highest index value among the three cases analyzed is obtained with the SPI equal to 0.82. SOI is equal to 0.99, and SSSI is 1, which is its maximum potential quantity. This suggests that the generation capacity is always able to meet almost all of the load demand within the terminal to facilitate the throughput and no security-related incidents occur due to the continuity of the power supply (i.e., $SSI = 0$). SEgI has been enhanced noticeably from 0.19 from Case 2 to 0.50 in Case 3, and SEnI is also increased to 0.81. 732691 (MW) of power is provided through renewable sources, which is 4.20 times the renewable generation decided by the minimum cost model. CO_2 emission is reduced by 54% compared to the minimum cost model and 61% compared to the base case. It can also be observed that while the microgrid still benefits from trading its excessive power back to the main grid, the total power sold to the main grid (P_M^-) in Case 3 is less than Case 2 which is completely cost-driven.



(a) Index Values-Order Set_1 **(b)** Index Values-Order Set_2 **(c)** Index Values-Order Set_3 **(d)** Index Values-Order Set_4

Fig. 4. Index values for different order sets of the goals

To analyze the model behavior with different orders of the goals, we have considered four order sets. The sub-indices and their associated priorities are the elements of the sets: Set_1 = {(SOI,1), (SEgI,2), (SEnI,3), (SSSI, 4)}, Set_2 = {(SOI,3), (SEgI,1), (SEnI,2), (SSSI, 4)}, Set_3 = {(SOI,2), (SEgI,3), (SEnI,1), (SSSI, 4)}, and Set_4 = {(SOI,4), (SEgI,3), (SEnI,2), (SSSI, 1)}. Lower numbers correspond to higher priorities. In each set, a different sub-index has the highest priority. Figure 4 presents the index and sub-index values for all four sets.

Figure 3 indicates that the highest SPI (i.e., SPI = 0.82) can be achieved with Set_1, while the lowest SPI (i.e., SPI = 0.75) is associated with Set_4. SOI is at its peak value (i.e., SOI = 0.99) with Set_1, which is expected because SOI has the highest priority in this set. In Set_2, SEgI is the most important goal and is increased to 0.50 (Figure 4b). Similarly, SEnI is increased to 0.88 when it has the highest priority (Figure 4c). SSSI is given the highest priority in Set 4; however, it has reached its maximum level of 1 with all of the sets.

The results of the analysis suggest that the overall terminal performance is improved most for Set_1 in which the main goal is to increase reliability through the microgrid integration by assuring the continuity and the availability of the power supply.

5. Conclusion

While the economic and environmental viability of microgrids has been well discussed in the literature, ports remain a relatively unexplored segment for microgrid adoption. In this work, we have attempted to fill this gap by evaluating the benefits of microgrid integration and how these advantages can be translated into opportunities for the port industry in particular. Our research findings provide an initial assessment on how to transform a traditional industrialized port into a contributing component of a sustainable eco-system through the use of microgrids. In particular, we have implemented a set of metrics from different key operation domains to facilitate the formation of a holistic approach for planning port microgrids. Case studies and simulation results highlight that through the proposed approach, the port microgrid can contribute to various aspects of port operation and management such as avoiding critical facility downtime (no curtailment of high-priority loads), energy savings (131184 MW curtailment of low-priority loads over the planning horizon of 10 years), energy dependency (no power purchased from the main grid), and emission reduction (reduction of the CO_2 emission from 7882.646 kilotons to 3063.924 kilotons over 10 years).

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